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Biomass Processing Network Optimisation Using P-graph with Pareto Screening

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A global movement is working towards emission reduction. Despite its availability, biomass is generally under-utilised due to various challenges, including financial factors. Convincing economic and environmental performances of biomass waste-to-wealth processing networks are needed to motivate investors and boost the implementation of biomass projects. In this work, the P-graph is combined with Pareto visualisation to optimise and screen biomass waste-to-wealth processing network to generate optimal models for investors' selection. The selected optimal solution generates an annual gross profit of MYR 210 M and a total carbon emission of 69 kt CO_2. This work aims to motivate the development of the biomass industry by providing a convincing statement to the palm industry and investors for investment and development.

1. Introduction

Palm oil, renowned for its high melting point and stability at high temperatures, is widely used in the food industry as an edible oil. Palm oil segment has been dominating the global vegetable oils consumption market, at ~78 Mt/y (Statista, 2024). The huge production of palm oil also raises concerns about the significant volume of biomass generated by the palm oil industry, averaging at 9 t of biomass generated per t of crude palm oil produced (Loh and Choo, 2013). The palm biomass generated stems primarily from two sources: the oil palm plantation and the palm oil mill. The oil palm plantation yields Oil Palm Frond (OPF) and Oil Palm Trunk (OPT), while the palm oil mill produces Empty Fruit Bunch (EFB), Palm Kernel Shell (PKS), Palm Mesocarp Fibre (PMF), and Palm Oil Mill Effluent (POME).

The large volume of palm biomass has created disposal and environmental issues due to poor waste management. In fact, these biomass can be processed into value-added products through various technologies. To tackle the waste disposal issues, the concept of circular economy (CE) can be applied. CE is defined as the system of regeneration that minimise waste generated by closing and extending the loops of supply chain and improving eco-efficiency technologies while maintaining and maximising its value in the economy based on three principles: eliminate waste and pollution, circulate products and materials at their highest value and regenerate nature. To achieve CE in palm oil industry, the concept of waste to wealth is the key to extend the loop of supply network by using palm biomass to produce valuable products through different technologies. If unutilised, palm biomass ends up in landfilling, which emits ~400 kg CO_2e/t biomass (Nordahl et al., 2020).

Different techniques are available for the synthesis and optimisation of biomass processing network. The application of P-graph in process synthesis was first used for mass exchange network synthesis (Lee and Park, 1996). The effectiveness of P-graph application in generating feasible structure compared to conventional mathematical programming approach was demonstrated. The application of P-graph was then extended for heat exchanger network (HEN) and biomass supply chain syntheses (How et al., 2019). These applications proved the capability of P-graph framework in process synthesis. As a graph-theoretical approach, P-graph displays a visual interface which enables users to construct the case study in an easier manner and allows audience without strong mathematical programming background to understand the case study easily. However,

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P-graph is typically used for single objective optimisation. The combination of P-graph and Pareto visualisation enables another objective of different dimension to be included for solution screening.

Palm biomass has great potential to be processed into value-added products and biomass energy, this approach mitigates environmental issues stemming from the unattended biomass in the palm oil industry. Many processing methods (e.g. enzymatic hydrolysis, fermentation, chemical extraction, etc.) have been developed and tested to produce various valuable products (Hau et al., 2022). The main challenge impeding the advancement of the biomass industry is the economic factor, manifested in additional capital requirement and the lack of convincing evidence regarding the profitability of biomass products. The initiative to evaluate the economic and environmental performances of the biomass waste-to-wealth supply network is crucial to stimulate the adoption of technologies for generating biomass-based products. A positive outcome from this evaluation could increase the possibility of attracting potential investors for biorefinery technologies and the deployment of biomass energy. This work aims to develop an optimisation model using the P-graph coupled with Pareto visualisation to assess the economic and environmental performances of a palm biomass supply network. The model identifies both the optimal and sub-optimal solutions across various process pathways using P-graph with Pareto visualization to screen the optimised solutions for further decision making.

2. Methodology

The study initiates by establishing a biomass network and defining economic and environmental indicators. Then, a P-graph model is constructed, employing the Mixed Integer Linear Programming (MILP) and Accelerated Branch-and-Bound (ABB) algorithm within the P-graph framework. The P-graph superstructure is constructed by mapping the available biomass resources to the available biomass conversion technologies and ending with the production of respective biomass products from the processes. By utilising P-graph, the study ascertains feasible technologies and end-products for palm biomass processing, evaluating different pathways' feasibility and their corresponding economic and environmental impacts. The solutions are later visualised in Pareto chart for environmental performance screening. The economic performance of the biomass processing network is quantified by the gross profit of the pathway which includes biomass cost, transportation cost, operating expenditure (OPEX) and capital expenditure (CAPEX). In terms of environmental dimension, the environmental performance is quantified based on the total carbon emission.

2.1 Economic Dimension

The biomass is sourced from palm oil mill and palm oil plantation. Raw material cost includes the biomass cost and the transportation cost, as shown in Eq(1).

$$C^{RM} = C^{Biomass} + C^{Transport} \tag{1}$$

Where C^{RM}(MYR/t) is the total raw material cost, $C^{Biomass}$(MYR/t) is the cost of biomass and $C^{Transport}$(MYR/t) is the biomass transportation cost from the source to the processing plant.

The biomass processing plant is assumed to be set up next to palm oil mill. EFB, PKS and POME are collected at palm oil mill and fed directly to the processing plant. OPF and OPT are collected in oil palm plantation, the average distance for biomass transportation from oil plantation to palm oil mill is 31 km (Arshad *et al.*, 2019). The biomass transportation cost is determined using Eq(2).

$$C^{Transport} = FC \times D \times C^{Fuel} / 8 \tag{2}$$

Where $C^{Transport}$ (MYR/t biomass) is the biomass transportation cost from the source to processing plant, FC(L/km) is the fuel consumption rate of vehicle, D(km) is the distance from source to the plant, C^{Fuel}(MYR/L) is the cost of diesel fuel.

The cost function forms the economic indicator and is evaluated to be maximised:

$$Profit = C^{Product} - C^{RM} - C^{OPEX} - C^{CAPEX} \tag{3}$$

where $Profit$ (MYR/y) is the gross profit, $C^{Product}$ (MYR/y) is the revenue received from product sales, C^{RM} (MYR/y) is the total raw material cost, C^{OPEX} (MYR/y) is the operational expenditure and C^{CAPEX} (MYR/y) is the capital expenditure.

2.2 Environmental Dimension

Total carbon emission, as shown in Eq(4), serves as the environmental indicator and measures the environmental performance of the biomass processing network. In the model, the environment indicator is input into P-graph by considering it as a product outlet for all the technologies. This allows P-graph model to evaluate the total carbon emission of the selected pathway. The carbon emission rate of each technology is determined with Eq(4).

$$Total\ carbon\ emission = E^{Process} + E^{Transport} + E^{Utility} \tag{4}$$

where $Total\ carbon\ emission$ (t CO_2/y) is the total carbon emission, $E^{Process}$ (t CO_2/y) is the carbon emitted by the process, $E^{Transport}$ (t CO_2/y) is the carbon emitted during the transportation of biomass and $E^{Utility}$ (t CO_2/y) is the indirect carbon emitted considering the consumption of electricity generated using fossil fuel.

2.3 Demonstration Case Study

A demonstration case study is developed based on the annual production rate of an operating palm oil company in Malaysia. In this study, biomass from the oil palm plantation, i.e. OPF and OPT, and biomass from the palm oil mill, i.e. PKS, EFB and POME, are considered as sources of biomass. The integrated palm biomass supply network is designed to produce bioethanol, biochar, biooil, syngas and bio-methane through different technologies. Table 1 shows the conversion ratio of all the available technologies used for biomass processing.

Table 1: Conversion ratio of all technologies for each biomass

Technology	Feedstock	Output	Conversion	Reference
Fermentation	EFB	Bioethanol	0.09 t/t	(Nurul Adela et al., 2014)
	OPF		0.32 t/t	(Kumneadklang et al., 2015)
	OPT		0.223 t/t	(Eom et al., 2015)
Slow Pyrolysis	EFB	Biochar	0.109 t/t; 0.099 t/t; 0.116 t/t	(Kong et al., 2014)
	OPF	Biooil	0.099 t/t; 0.090 t/t; 0.105 t/t	(Kong et al., 2014)
	OPT	Syngas	0.079 t/t; 0.072 t/t; 0.084 t/t	(Kong et al., 2014)
	PKS		0.290 t/t; 0.264 t/t; 0.308 t/t	(Kong et al., 2014)
Fast Pyrolysis	EFB	Biochar	0.040 t/t; 0.248 t/t; 0.043 t/t	(Kong et al., 2014)
	OPF	Biooil	0.036 t/t; 0.225 t/t; 0.039 t/t	(Kong et al., 2014)
	OPT	Syngas	0.029 t/t; 0.18 t/t; 0.031 t/t	(Kong et al., 2014)
	PKS		0.106 t/t; 0.660 t/t; 0.114 t/t	(Kong et al., 2014)
Anaerobic Digestion (AD)	EFB	Bio-methane	45 m^3/t	(Suksong et al., 2020)
	OPF		42 m^3/t	(Suksong et al., 2020)
	OPT		35 m^3/t	(Suksong et al., 2020)
	POME		10 m^3/t	(Madaki and Seng, 2013)
Gasification	EFB	Syngas	2,178 m^3/t	(Sukiran et al., 2011)
	OPF		2,223 m^3/t	(Konda et al., 2012)
	OPT		2,105 m^3/t	(Nipattummakul et al., 2012)

The annual working hour and payout period for the system is 8,000 h/y and 10 y. The annual biomass input is calculated based on 205,882 t/y FFB, which gives a maximum available biomass of 347,735 t/y. Table 2 shows the conversion ratio of FFB (fresh fruit bunch), biomass availability and their cost and emission parameters. Table 3 shows the selling price of biomass products and the capital expenditure (CAPEX) and operational expenditure (OPEX) of biomass processing technologies.

Table 2: Conversion ratio of FFB, availability of biomass, cost of biomass, and emission parameter of biomass

Biomass	Conversion Ratio[1] (t output/t of FFB)	Available Biomass (t/y)	Total Raw Material Cost (MYR/t)	Carbon Emission[2] [kg CO_2 / t biomass transported]
PKS	0.069	14,206	250.40	0.519
EFB	0.230	47,353	50.40	0.519
POME	0.599	123,323	0	0
OPT	0.100	142,264	254.17	5.367
OPF	0.691	20,588	54.17	5.367

Source: [1]Yeo et al. (2020), [2]Wang and Yang (2022)

Table 3: Biomass product selling prices and cost of biomass processing technologies

Product	Unit	Price (MYR/ur	Technology	CAPEX (MYR/t)	OPEX (MYR/t)
Bioethanol[1]	t	2661.6	Fermentation[4]	159.00	260.00
Biochar[1]	t	1260	Slow Pyrolysis[4]	173.00	108.00
Bio-oil[2]	t	917	Fast Pyrolysis[4]	141.00	171.00
Syngas[2]	m^3	0.6	Anaerobic Digestion[3]	261.10	2.69
Bio-methane[3]	m^3	1.13	Gasification[4]	150.00	180.00

Source: [1]MacRelli et al. (2012); [2]How (2018); [3]How et al. (2018); [4]Yeo et al. (2020)

The environmental dimension is measured according to the total emission of carbon dioxide from the process and transportation of biomass. Table 4 tabulates the steam and electricity requirement of each technology.

Table 5 shows the carbon emission parameters for biomass transportation and processing technology. The emission rate of transportation is 2.77 kg CO_2 per L of Diesel (Wang and Yang, 2022). The rate of carbon emission from power generation is 1.18 kg CO_2 per kWh of electricity consumed. Pyrolysis process generally offers negative carbon emission (Hammond et al., 2011).

Table 4: Scale factors of steam and electricity demand for each technology

Technology	Steam (t MPS/t biomass)	Electricity (kWh/t biomass)	Reference
Fermentation	-	62.46	(Kumar and Murthy, 2011)
Slow Pyrolysis	-	150	(Humbird et al., 2011)
Fast Pyrolysis	-	180	(Humbird et al., 2011)
Anaerobic Digestion	-	-	-
Gasification	0.45	280	(Humbird et al., 2011)

Table 5: Carbon emission rate of conversion technology

Technology	Feedstoc	Emission rate [t CO_2 / t biomass]		Technology	Feedstock	Emission rate [t CO_2 / t biomass]	
		Proces	Power generatior			Process	Power generatior
Fermentation	EFB	0.084	0.074	Anaerobic	EFB	0.079	0
	OPF	0.300		Digestion	OPF	0.074	
	OPT	0.079			OPT	0.043	
Slow Pyrolysis	EFB	-	0.177		POME	0.036	
	OPF	-		Fast Pyrolysis	EFB	-	0.212
	OPT	-			OPF	-	
	PKS	-			OPT	-	
Gasification	EFB	-	0.330		PKS	-	

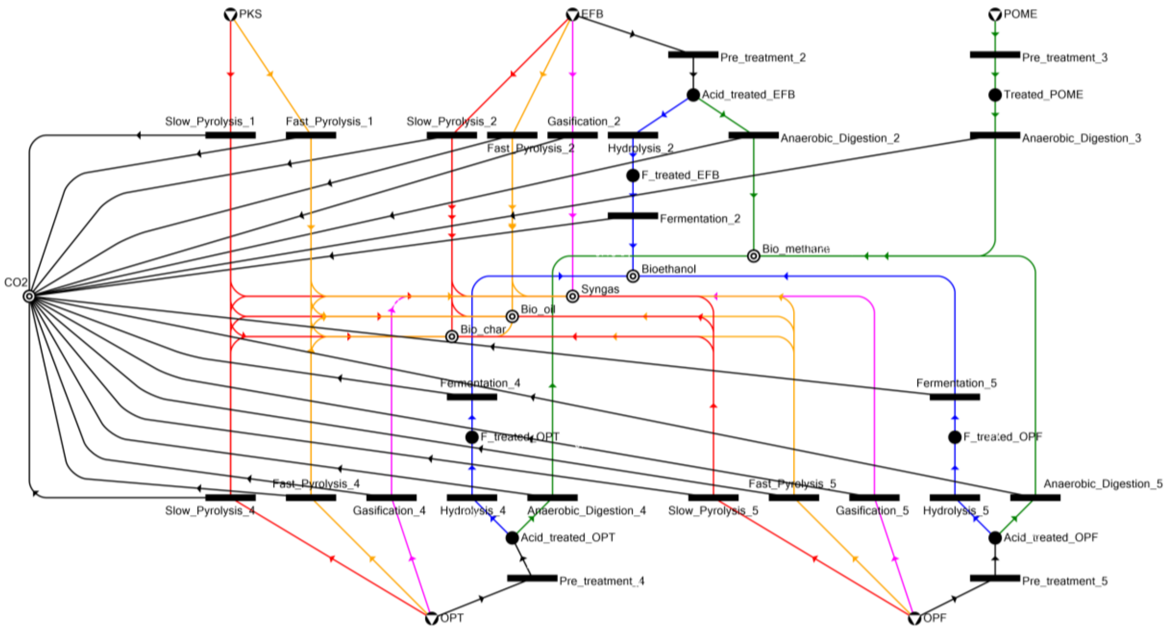

Figure 1: P-graph model of the case study (blue box represents the total carbon emission)

The benchmark of total carbon emission allowance is set based on the estimated carbon emission from landfilling palm biomass at a rate of 400 kg CO_2eq/ t biomass. The total carbon emission allowance of the biomass conversion process is assumed to be 50 % of the total carbon emission from landfilling process, which takes the value of 69,547 t CO_2eq/y. Figure 1 shows the P-graph model of the case study constructed using P-graph Studio.

3. Results and discussion

3.1 Optimization using P-graph model

The optimisation in P-graph is performed using ABB algorithm. The optimal solution gives a profit of 225,447,000 MYR/y. PKS, EFB, OPT and OPF were utilised to produce 1,619 t/y of biochar, 9,376 t/y of bio-oil, and 462,728,000 m^3/y of syngas with POME not being utilised. Table 6 summarises the top 5 solutions generated by the P-graph model.

3.2 Pareto visualisation

The solutions derived from P-graph is portrayed using Pareto chart (as shown in Figure 2) which allows the simultaneous display of economic performance and environmental performance for each solution. As the most optimal solution may not be the most ideal solution in practice, the Pareto chart allows the selection of solution(s) according to a company's emission target.

Table 6: Top 5 results generated by P-graph model

Rank	Profit (MYR/y)	Total Carbon Emission (t CO_2/y)	Pathway Selection		
1	226,476,000	73,286.0	PKS → Fast Pyrolysis EFB → Gasification	OPT → Gasification OPF → Gasification	POME → Unutilised
2	225,641,000	72,788.8	PKS → Slow Pyrolysis EFB → Gasification	OPT → Gasification OPF → Gasification	POME → Unutilised
3	222,018,000	70,267.0	PKS → Unutilised EFB → Gasification	OPT → Gasification OPF → Gasification	POME → Unutilised
4	221,027,000	69,641.9	PKS → Fast Pyrolysis EFB → Gasification	OPT → Fermentation OPF → Gasification	POME → Unutilised
5	210,192,000	69,144.7	PKS → Slow Pyrolysis EFB → Gasification	OPT → Fermentation OPF → Gasification	POME → Unutilised

Typical optimisation objectives are to maximise the profit and minimise the total carbon emission. These two objectives are generally opposed to each other, as total carbon emissions typically increase with profit. The optimal solution is determined by finding the maximum profit achievable within the given carbon emission allowance. If the CO_2 emission allowance is set to 50% (69,546.94 t/y) of what would be caused by landfilling biomass, the Rank 1 solution does not meet the specification, but Structure 5 solution does. The results indicate that converting palm biomass into value-added products releases less carbon into the atmosphere compared to landfilling biomass. In short, the model is capable of generating solutions that meet the objectives of this study for both economic and environmental indicators (i.e., a positive gross profit and an acceptable reduction in total carbon emissions). The results prove the feasibility of a palm biomass waste-to-wealth processing network and provide a convincing note regarding economic and environmental performance to the industry and investors.

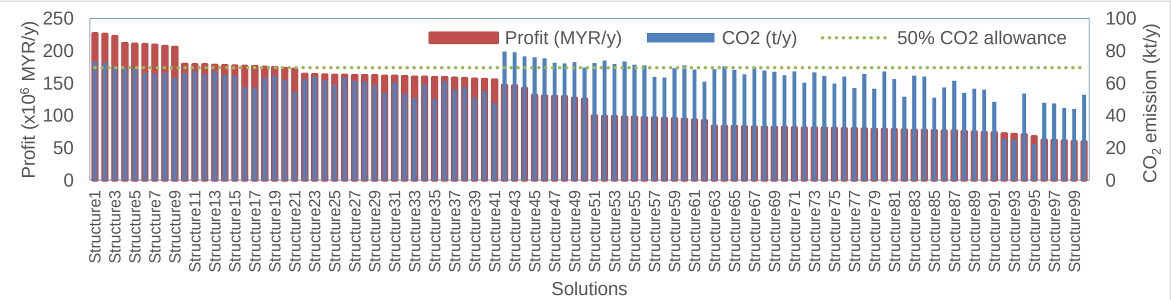

Figure 2: Pareto chart plotted for top 100 solutions in descending profit

4. Conclusions

An optimisation model for palm biomass waste-to-wealth processing network was constructed through P-graph approach. The biomass conversion technologies available for PKS, EFB, POME, OPT and OPF were considered to convert biomass into valuable products with their potential carbon emissions evaluated. With the generated solutions using P-graph, Pareto chart was used to screen solution with acceptable total carbon emission allowance benchmarked at 50 % of the carbon emission caused by biomass landfilling. Solution Structure 5 was identified as the feasible solution meeting the emission criteria while generating positive income.

The feasible outcome of the study provides a convincing statement to the industry and investors to explore further the biomass waste-to-wealth supply network. Future work can include the social dimension to enhance the study scope. More indicators can also be considered in the evaluation of existing dimensions to consider the long-term sustainability of solutions. Circular economy concept can be implemented to achieve a closed loop, self-sustaining biomass processing network. Further study can also integrate biomass sources from different industries to generate a comprehensive biomass processing network.

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