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The generation of municipal solid waste (MSW) is increasing globally every year, including in Malaysia. Approaching the year 2020, Malaysia still has MSW disposal issues since most waste goes to landfills rather than being utilized as energy. Process network synthesis (PNS) is a tool to optimize the conversion technologies of MSW. This study optimizes MSW conversion technologies using a PNS tool, the “process graph” (P-graph). The four highest compositions (i.e., food waste, agriculture waste, paper, and plastics) of MSW generated in Malaysia were optimized using a P-graph. Two types of conversion technologies were considered, biological conversion (anaerobic digestion) and thermal conversion (pyrolysis and incinerator), since limited data were available for use as optimization input. All these conversion technologies were compared with the standard method used: landfilling. One hundred feasible structure were generated using a P-graph. Two feasible structures were selected from nine, based on the maximum economic performance and minimal environmental impact. Feasible structure 9 was appointed as the design with the maximum economic performance (MYR 6.65 billion per annum) and feasible structure 7 as the design with the minimal environmental impact (89,600 m3/year of greenhouse gas emission).

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Article

Conversion Technologies: Evaluation of Economic Performance and Environmental Impact Analysis for Municipal Solid Waste in Malaysia

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Abstract: The generation of municipal solid waste (MSW) is increasing globally every year, including in Malaysia. Approaching the year 2020, Malaysia still has MSW disposal issues since most waste goes to landfills rather than being utilized as energy. Process network synthesis (PNS) is a tool to optimize the conversion technologies of MSW. This study optimizes MSW conversion technologies using a PNS tool, the "process graph" (P-graph). The four highest compositions (i.e., food waste, agriculture waste, paper, and plastics) of MSW generated in Malaysia were optimized using a P-graph. Two types of conversion technologies were considered, biological conversion (anaerobic digestion) and thermal conversion (pyrolysis and incinerator), since limited data were available for use as optimization input. All these conversion technologies were compared with the standard method used: landfilling. One hundred feasible structure were generated using a P-graph. Two feasible structures were selected from nine, based on the maximum economic performance and minimal environmental impact. Feasible structure 9 was appointed as the design with the maximum economic performance (MYR 6.65 billion per annum) and feasible structure 7 as the design with the minimal environmental impact (89,600 m^3/year of greenhouse gas emission).

Keywords: optimization; P-graph; municipal solid waste conversion technology

1. Introduction

Municipal solid waste (MSW) is material arising from human activities. It is generated commonly from different areas such as residential, commercial, and institutional zones, as well as public parks [1]. The generation of MSW is drastically increasing globally every year, by a factor of 2.6 [2]. In 2016, the world's MSW generated was around 2.01 billion tons, and this figure is expected to increase to 3.40 billion tons by 2050 [3].

In Asia, MSW generation is expected to reach 1.8 million tons every day in 2025, as more than 1 million tons of MSW is currently being generated every day [4]. Based on a survey conducted by the Malaysian government, MSW generation in Malaysia has increased from 23,000 tons/day in 2008 to 33,000 tons/day in 2012 [5]. The increases of MSW generation in Malaysia are caused by three significant factors: (i) the rapid increase in population; (ii) accelerated urbanization; and (iii) increased industrialization processes [6]. The total population of Malaysia in 2017, as mentioned by the World Bank [7], was 31.62 million. As the population increases, the per capita generation rate also increases. For Malaysia, the MSW per capita generation rate range was of 0.6–0.8 kg per capita per day between 2001 and 2005 [8]. This number is expected to increase to double digits by the year 2020 [9]. Based on the World Bank's report, the waste generation per capita in Malaysia increased by up to 1.00–1.49 kg per capita per day by September 2018 [3]. At present, 54% of the world's population lives in urban areas, and this percentage will increase to 66% or more by 2050 [10].

Increasing MSW generation has become the most prominent environmental issue as MSW may contain dangerous substances that are harmful to our ecosystem and increase the potential risk to our health. MSW must be appropriately disposed of and managed efficiently. Many significant environmental issues may arise from this kind of waste, such as the generation of greenhouse gases (GHGs) released from MSW. Besides, the increasing number of landfills can increase the numbers of rodents and insects that may cause diseases to humans. In recent years, more landfill sites are needed to dispose of all the MSW generated [11]. The main issue we face this traditional disposal method is shortage of landfill sites inland [12]. An essential component of a healthy society and a sustainable environment is an efficient waste management system [13].

The main purpose to manage MSW efficiently include reducing (i) the amount of MSW generated, (ii) the impact on the environment with a lower cost of disposal of MSW, and (iii) the impact on human health [14]. In MSW management in developing countries, five typical problems can be identified: (i) inadequate service coverage, (ii) operational inefficiency of services, (iii) limited utilization of recycling activities, (iv) poor management of non-industrial hazardous waste, and (v) shortage of landfill disposal sites [15]. The present waste management method in Malaysia depends on landfill [11]. Only 5.5% of MSW is recycled and 1% is composted, while the remaining waste goes to landfill [16]. Currently, there are 174 landfills around Malaysia [14]. The recycling rate increased from 5.5% in 2009 to 10.5% in 2012 [17]. Malaysia's recycling rate was 17.5% in 2016, which is still far from the target of 22% by 2020 [18].

One method to solve problems related to landfills is to introduce sustainable and efficient waste management [6]. Integrated waste recycling and various conversion technologies could be effective waste management strategies [19]. There are several steps in sustainable and efficient waste management [20]. Possible waste generation and their conversion technologies are illustrated in Figure 1.

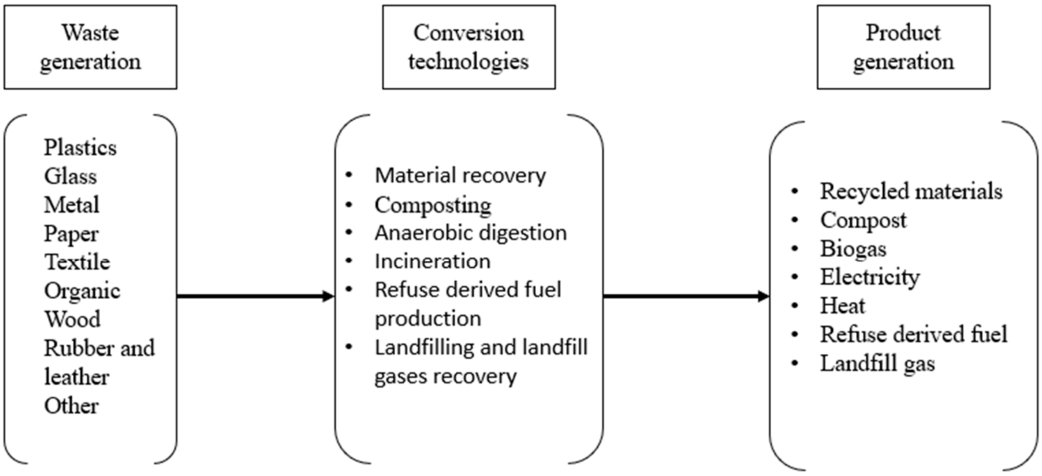


Figure 1. Possible waste generation relationship between their conversion technologies, reproduced with permission from [20]. Copyright Elsevier, 2017.

Based on Figure 1, there are many pathways for conversion technologies to manage MSW after it is collected from residences and processed before being sent to landfills. The three main steps to handle MSW are (i) the collection and transportation of MSW; (ii) the treatment and processing of MSW; and (iii) its final disposal [21]. Each stage has its own investment cost, operating cost, and energy recovery.

However, there are pros and cons to each conversion technology. It is useful to utilize analytical tools to synthesize a promising waste management strategy [22]. There are limited studies on the performance of conversion technology in the context of Malaysia. The optimization of MSW conversion technology will help decide the most favorable and useful method and pathway in managing MSW. Through optimization, we can introduce combined conversion technology to manage Malaysia's MSW.

A process network synthesis (PNS) problem is defined as specifying the raw materials, operating units, and desired products in chemical engineering problem, for example the conversion technologies problem. The PNS problem was developed as a mathematical model in which variables correspond to decisions, such as input and output flow rates, with a limitation corresponding to the mathematical description of the optimization criterion such as the material balance objective function [23]. The common problems in a PNS are (i) the reaction pathway; (ii) process design; (iii) the heat exchangers network; (iv) the water integration system; and (v) the separation unit [24]. The process graph, best known as the P-graph, is one method to solve the PNS problem [25]. The P-graph is a graphical optimization which is available in the software P-Graph Studio [26]. The P-graph is a bi-graph, meaning that its vertices are in disjunctive sets and there are no edges between vertices in the same set [27]. The vertices of the P-graph are denoted as the operating unit (O) and the material (M). This P-graph represents the material flow between the material and the operating unit. The P-graph methodology was originally developed for PNS problems in chemical engineering applications. The P-graph methodology is based on five axioms [28], as follows:

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

To summarize, the P-graph methodology is composed of the following algorithms: (i) maximal structure generation (MSG); (ii) solution structure generation (SSG); and (iii) accelerated branch and bound (ABB) [29]. The MSG algorithm identifies a network structure, which is the union of all possible solution structures of the problem. It can be generated in polynomial time using the information specified in the five axioms. The SSG algorithm generates all combinatorically feasible solution structures or networks. Each solution is a subset of the maximal structure and represents a potential network configuration for the PNS problem. The ABB algorithm identifies the optimal structure based on the solution structures, in conjunction with additional problem-specific information.

The P-graph framework enables rigorous model building and the efficient generation of optimal solutions [29]. The PNS problem primarily utilizes unique information. The P-graph is known as a user-friendly decision-making tool for PNS. This helps in better design and better operations that lead to (i) lower capital and operating cost (CAPEX and OPEX); (ii) higher profitability through increased output and better quality of the product; (iii) reduced technology risk; and (iv) better health, safety, and environmental requirements. These factors may thus help in optimizing MSW conversion technology.

The main objective of optimization is maximizing the efficiency of production by minimizing the cost of production. Therefore, it is essential to optimize MSW conversion technologies using a process graph to evaluate the selected pathway. Table 1 shows different types of optimization models for solid waste management based on previous studies. Data are tabulated based on the optimization method used, the objective of the study, the focus of the study, and the optimization of economic performance (EP) and environmental impact (EI).

Table 1. Optimization models for solid waste management.

Method	References	Objectives	Focus		Optimization on	
			Energy System	**Waste Management**	**Economy**	**Environment**
Linear Programming	[30,31]	To maximize the economic utility of energy consumers	/		/	
Mixed Integer Linear Programming	[32]	To determine the optimal processing network waste-to-energy system	/		/	/
Non-Linear Programming	[33]	To maximize profit, while minimizing waste through source reduction		/	/	
Hybrid Model	[34]	Multi-objective programming and cost–benefit criteria on global warming impact in waste management		/	/	/
P-graph Model	[35]	To utilize organic and dry fractions of municipal waste	/	/	/	/

Although there are various models for optimizing MSW conversion technologies, we still cannot manage MSW efficiently in Malaysia, as there are no integrated conversion technologies for solid waste treatment. Therefore, this study aimed to simulate the feasibility of MSW conversion technologies and analyzed the EP and EI of MSW conversion technologies. The study framework was based on the following factors:

1. Type of resources;
2. Type of product;
3. Selection of conversion technologies;
4. Generation of GHGs;
5. Capital and operating expenses of conversion technologies.

The proposed processing network was designed using the P-graph model. There are a few types of MSW conversion technologies, including landfill, anaerobic digestion, incineration, and pyrolysis. The selected optimized conversion technology for MSW was then further assessed with respect to the impacts on feedstock and products on GHG emissions, demand, and prices. Two different scenarios were considered in this case study, which was designed for maximum EP and design for minimal EI.

2. Materials and Methods

Figure 2 shows the intracellular synthesis procedure for the process graph (P-graph). The procedure starts with the identification of materials and streams to yield the optimal MSW conversion technology network.

The intracellular synthesis procedure started with the identification of materials, streams, and operating units. After that, data input was required to generate the maximal superstructure and solution structure. The procedure ended with an optimal MSW conversion technology network.

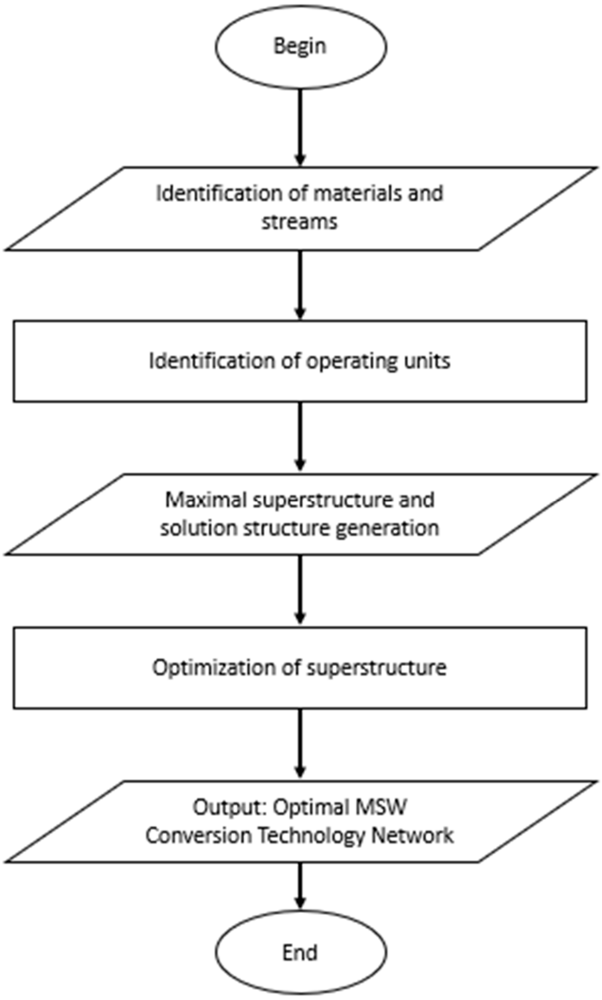


Figure 2. Intracluster synthesis procedure for the process graph (P-graph), reproduced with permission from [36]. Copyright Elsevier, 2010.

2.1. Identification of Materials and Streams

This step produced the details for the inputs and outputs of the system. In this study, there were four types of process feedstock. There are six types of outputs or products, along with their intermediate products, as illustrated in Figure 3.

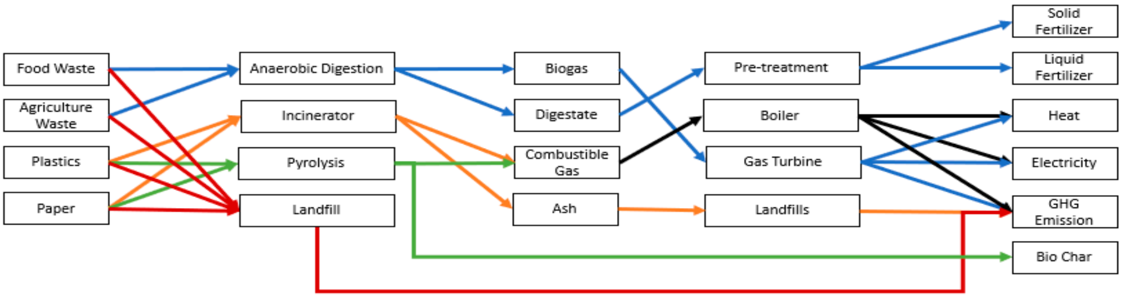


Figure 3. Superstructure for process flow managing MSW in this case study.

Figure 4 shows the circle nodes for the materials and the directed arrows represent as the streams. The number attached on the arrow signifies the consumption or production rate that represents the relationship between a material and an operating unit. Table 2 shows the list of raw materials, intermediate products, and products of the conversion technologies.

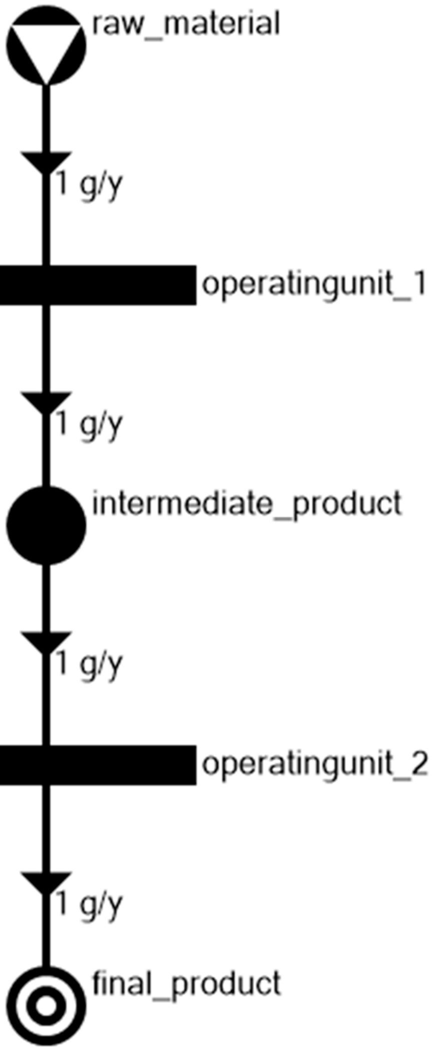


Figure 4. Graphical representation of materials in P-graph.

Table 2. Materials and products for the P-graph.

	Symbols	P-graph Classification	Description
1	Agricultural_Waste	Raw Material	Agricultural waste
2	Ash	Intermediate Product	Ash from plastic and paper in incinerator
3	Bio_Char	Output	Bio char
4	Biogas	Intermediate Product	Biogas production for anaerobic digestion of food and agriculture waste
5	Combustible_Gas	Intermediate Product	Combustible gas from plastic and paper in incinerator and pyrolysis
6	Digestate	Intermediate Product	Digestate of food and agriculture waste
7	Electricity	Output	Electricity generated
8	Food_Waste	Raw Material	Food waste
9	GHG_Emission	Output	Greenhouse gas emission
10	Heat	Output	Heat generated
11	Liquid_Fertilizer	Output	Liquid Fertilizer
12	Paper	Raw Material	Paper
13	Plastic	Raw Material	Plastic
14	Solid_Fertilizer	Output	Solid fertilizer

2.2. Identification of Operating Units

For this case study, 11 operating units were included in the flowsheet-generation problem shown to be solved algorithmically with P-graphs in Table 3. For this case study, anaerobic digestion, incineration, and pyrolysis were identified as the MSW conversion technologies in the model as an operating unit. The relationships between raw materials and operating units involved are shown in Figure 3.

Table 3. List of operating units for the P-graph.

	Symbols	P-graph Classification	Description
1	Boiler	Operating Unit	Boiler of combustible gas from incinerator and pyrolysis of plastic and paper
2	Digester_1	Operating Unit	Anaerobic digester for food waste
3	Digester_2	Operating Unit	Anaerobic digester for agricultural waste
4	Gas Turbine_1	Operating Unit	Gas turbine for anaerobic digestion of food and agriculture waste
5	Incinerator_1	Operating Unit	Incinerator for paper
6	Incinerator_2	Operating Unit	Incinerator for plastic
7	Landfill_1	Operating Unit	Landfill for MSW
8	Landfill_2	Operating Unit	Landfill for from incinerator of plastic and paper
9	Pre-Treatment	Operating Unit	Pre-treatment of digestate for anaerobic digestion of food and agriculture waste
10	Pyrolysis_1	Operating Unit	Pyrolysis of paper
11	Pyrolysis_2	Operating Unit	Pyrolysis of plastic

2.3. Input Data for Waste and Related Conversion Technologies

For this study, four types of MSW were chosen, based on the largest MSW composition generated in Malaysia: food waste, agricultural waste, plastics, and paper. The composition of MSW is shown in Table 4. Organic waste is the main component of MSW in Malaysia, representing up to 50% of the total waste.

Table 4. Composition generation of MSW in Malaysia [5].

	Type of Municipal Solid Waste	Composition of Municipal Solid Waste (%)
1	Food Waste	44.5
2	Plastics	13.2
3	Diapers	12.1
4	Paper	8.5
5	Agriculture Waste	5.8
6	Glass	3.3
7	Cloth	3.1
8	Steel/Metal	2.7
9	Rubber	1.8
10	Other	5.2

The study was conducted using data based on a literature review of MSW generation and MSW conversion technology. Data used were based on different studies and resources. The three types of conversion technologies considered in this case were pyrolysis, incineration, and anaerobic digestion, as limited data were available to be used for the optimization process. All these technologies were compared with the common method of MSW disposal in Malaysia, which are landfills. The allocation of waste to conversion technologies is illustrated in Table 5.

Both types of organic waste (i.e., food and agricultural) undergo an anaerobic digestion process. For inorganic waste, plastics and paper undergo two thermal treatments pyrolysis and incineration. After treatment, all waste is disposed of in landfills.

Table 5. Waste allocation to conversion technology.

	Food	Agriculture	Plastics	Paper
Anaerobic Digestion	/	/		
Incineration			/	/
Pyrolysis			/	/
Landfill	/	/	/	/

2.4. Optimization of Superstructure

The results of the solution structure generated from the previous step are then utilized in the selection of an optimal network using the solution structure generation and linear programming (SSG + LP) algorithm, allowing for the design of optimal process networks based on the solution structures in conjunction with additional problem-specific information, such as flow rates and costs. Consequently, the solution that provides the selected pathways with the best and near-optimum solutions is obtained, as shown in Figure 5. The selected optimized conversion technology for MSW was then further used to access the impacts on feedstock and products on GHG emissions, demand, and prices. Two different scenarios were considered: scenario 1: a design for maximum EP; and scenario 2: a design for minimal EI.

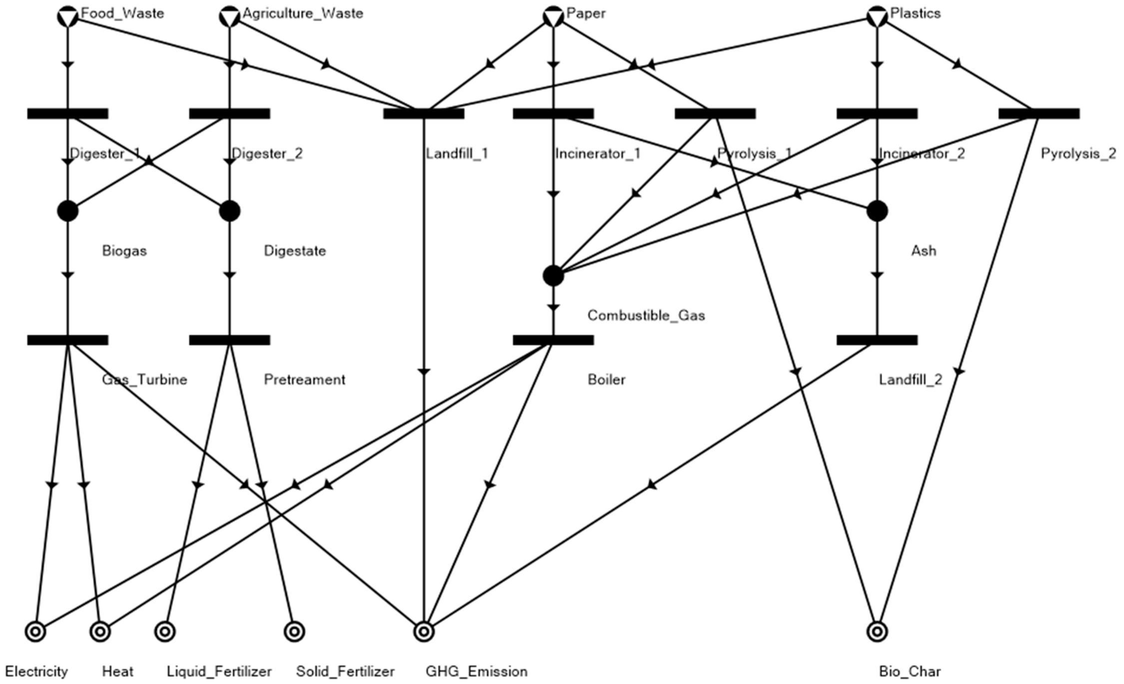


Figure 5. A P-graph representation of the municipal solid waste process network.

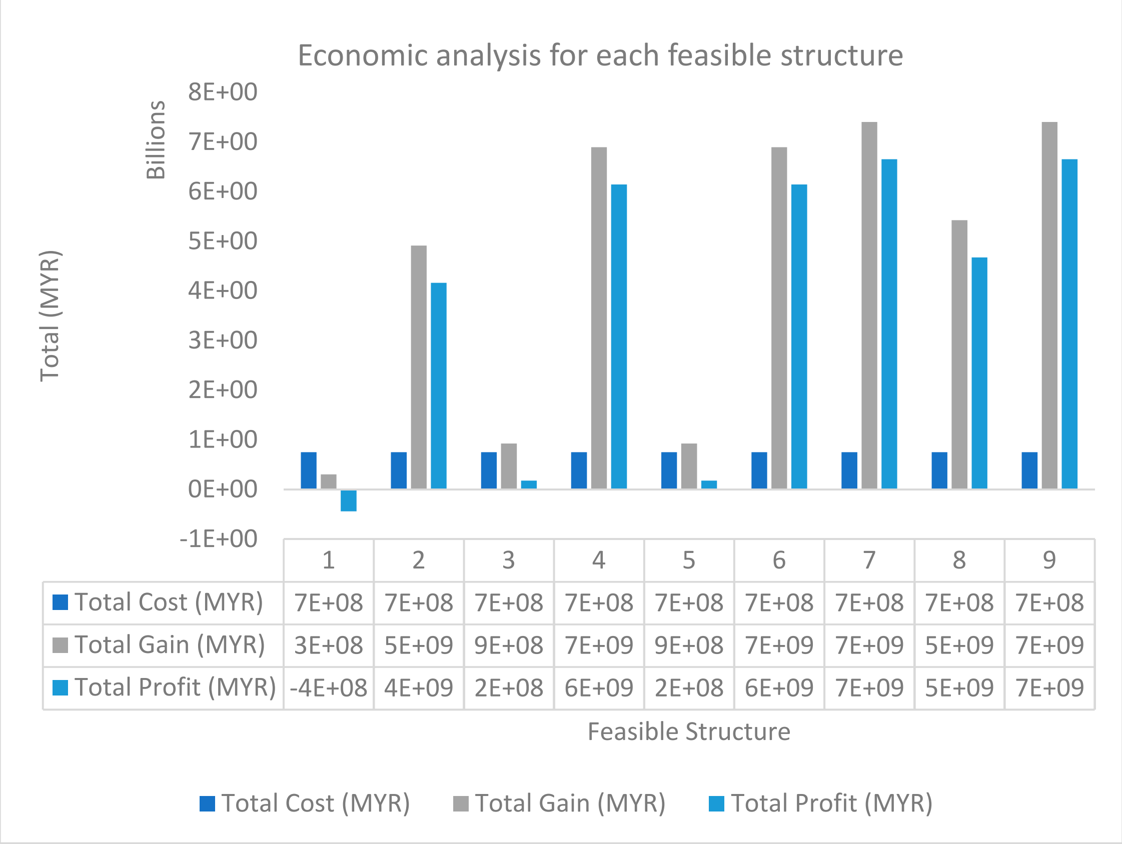
3. Results and Discussion

One hundred feasible structures were generated using the P-graph with the SSG + LP algorithm. The SSG generates all combinatorically, feasible solution structures or networks. Each solution is a subset of the maximal structure and represents a potential network configuration for the PNS problem. The LP is the process of finding the best solution under specific conditions.

Of the 100 feasible structures generated, nine were selected to identify and analyze their EP and EI. These nine feasible structures convert all types of waste into the final products. Four types of MSW (food waste, agriculture waste, plastics, and paper) were converted using three different types of conversion technologies (i.e., anaerobic digestion, incineration, and pyrolysis) to generate six main products, i.e., solid fertilizer, liquid fertilizer, heat, electricity, GHGs, and biochar.

3.1. Comparison of Different Feasible Structures

Figure 6 shows the profit generated for each feasible pathway. The profit generated was calculated by the total gain of the product minus the total cost of raw materials. The highest profit generated was feasible in structures 7 and 9. Both these feasible structures gave the same profit value, which was MYR 6.65 billion per annum. However, as shown in Table 6, feasible structure 7 did not generate two products: electricity and heat. The products generated by feasible structure 7 were solid fertilizer, liquid fertilizer, GHGs, and biochar; while feasible structure 9 generated all six products: solid and liquid fertilizers, heat, electricity, GHGs, and biochar.



	1	2	3	4	5	6	7	8	9
Total Cost (MYR)	7E+08	7E+08	7E+08	7E+08	7E+08	7E+08	7E+08	7E+08	7E+08
Total Gain (MYR)	3E+08	5E+09	9E+08	7E+09	9E+08	7E+09	7E+09	5E+09	7E+09
Total Profit (MYR)	-4E+08	4E+09	2E+08	6E+09	2E+08	6E+09	7E+09	5E+09	7E+09

Figure 6. Economic analysis for each feasible structure.

Table 6. Products generated by each feasible structure.

	Product					
	Electricity	**Heat**	**Solid Fertilizer**	**Liquid Fertilizer**	**GHG Emission**	**Biochar**
Feasible Structure 1	/	/			/	/
Feasible Structure 2	/	/	/	/	/	/
Feasible Structure 3	/	/			/	/
Feasible Structure 4	/	/	/	/	/	/
Feasible Structure 5	/	/			/	/
Feasible Structure 6	/	/	/	/	/	/
Feasible Structure 7			/	/	/	/
Feasible Structure 8			/	/	/	/
Feasible Structure 9	/	/	/	/	/	/

The lowest profit was generated by feasible structure 1. The value gained from the product was much lower than the cost of raw materials. The cost of the raw materials was MYR 746 million, while the value gained from the product was MYR 301 million. There was around a 59.7% loss from this feasible structure because no fertilizer was generated from the digestate (a by-product of anaerobic digestion), as anaerobic digestion has a massive conversion of around 75% from raw materials to digestate before undergoing treatment to convert it into two types of fertilizer: solid and liquid.

For each feasible structure, at least five types of operating units were used. For a feasible structure that generates electricity and heat, at least one operating unit involved either a boiler or a gas turbine. For the generation of liquid and solid fertilizers, the digestate must undergo pre-treatment before it can be sold as products. Table 7 shows the operating units that affected the volume of GHGs generated. The GHG emissions were generated from landfills, gas turbines, and boilers. From landfills, 0.1605 m^3 GHGs per ton of MSW were released into the surroundings. The different types of technology involved in converting MSW gives a different ratio of GHG emissions produced.

Table 7. Operating units that affected the volume of GHG emissions.

	Landfill_1	Landfill_2	Boiler	Gas_Turbine
Feasible structure 1	/	/	/	/
Feasible structure 2	/	/	/	/
Feasible structure 3			/	/
Feasible structure 4			/	/
Feasible structure 5		/	/	/
Feasible structure 6		/	/	/
Feasible structure 7		/		
Feasible structure 8	/	/		
Feasible structure 9			/	

The lowest three structures that generated GHGs were feasible structures 7, 8, and 9 with values of 89,600, 140,000, and 16,500 m^3/year as shown in Figure 7. The GHGs generation was affected by only one piece of operating equipment for feasible structures 7 and 9. Since the conversion of GHG emissions from boilers was only 0.1 m^3 per combustible gas, the generation of GHGs for feasible structure 9 was lower than for feasible structure 7, which was affected by the generation of GHGs from landfills as mentioned earlier. Although feasible structure 8 had two pieces of equipment that affected the generation of GHGs, it was one of the top three feasible structures with a low generation of GHGs. Comparing feasible structures 3 and 4, both had a lower generation of GHGs because both used a gas turbine that affected their GHG generation. The gas turbine had a higher conversion of GHG emission, which was 0.505 m^3 per biogas. The highest GHG volumes were generated from feasible structures 1, 2, 5, and 6. All these feasible structures used three to four operating units, which affected the volume of GHGs generated.

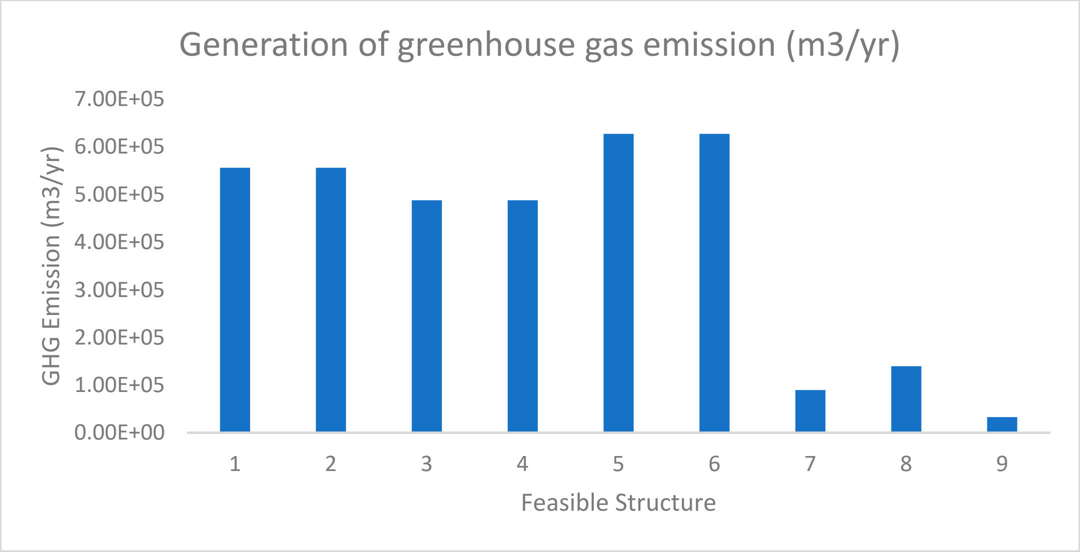


Figure 7. Generation of greenhouse gas for each feasible structure.

3.2. Scenario 1: Maximum EP

Feasible structure 9, as shown in Figure 8, was selected as the structure with the maximum EP. Based on Figure 6, the maximum EP of the selected pathways was estimated to be MYR 6.65 billion per annum or considering the total population of Malaysia in 2017, as mentioned by the World Bank [7] (31.62 million), it was estimated to be MYR 210 per person. For this feasible structure, both organic wastes (i.e., food and agriculture waste) underwent anaerobic digestion in operating units Digester_1 and Digester_2, which produced biogas and digestate. The digestate was separated into two types of fertilizer, liquid and solid, after pre-treatment. However, biogas did not undergo further treatment to convert it into electricity and heat. Plastics were burned in operating unit Pyrolysis_2 to be converted into biochar. Paper was burned in Incinerator_1 to produce both ash and combustible gas. The combustible gas was used in the boiler to convert it into electricity and heat. From this feasible structure, GHGs were produced from the boiler. The highest EP yield products, which were electricity, heat, solid fertilizer, liquid fertilizer, GHG emissions, and biochar, had flow rates of 82,700 kWh/year, 215,000 J/year, 1,030,000 tons/year, 4,110,000 tons/year, 33,100 m^3/year, and 795,000 tons/year, respectively.

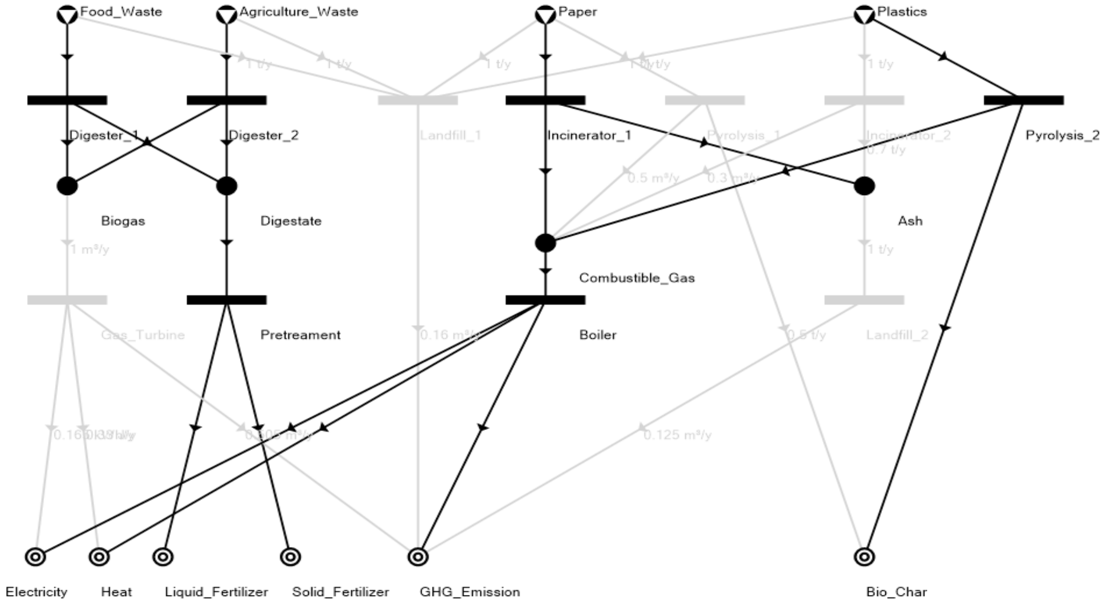


Figure 8. Feasible structure with the maximum economic performance.

The capital cost for a year was estimated to be MYR 123,587,000,000. This capital cost value is for the first year only. The profit margin was calculated as the net profits divided by the revenue. The profit margin for this feasible structure was 89.9%. The payback period of this pathway was 16.7 years. The payback period was calculated to identify the time required to earn back the investment money on the project.

3.3. Scenario 2: Minimal EI

Feasible structure 7, as shown in Figure 9, was selected as the structure with the minimal EI. Based on Figure 6, the minimal EI of the selected pathways was estimated to be MYR 6.65 billion per annum or considering the total population of Malaysia in 2017 as mentioned by the World Bank (31.62 million), it was estimated to be MYR 210 per person. This selected feasible structure was the same as the feasible structure of the maximum EP. However, feasible structure 7 produced less GHGs as GHGs are emitted only from landfills. For this feasible structure, both types of organic waste, food and agriculture waste also underwent anaerobic digestion in operating units Digester_1 and Digester_2, which produced biogas and digestate. The digestate was again separated into two types of fertilizer, liquid and solid, after pre-treatment. However, biogas did not undergo further treatment to convert it into electricity and heat. Plastics were also burned in operating unit Pyrolysis_2 to be converted into biochar. Paper was burned in Incinerator_1 to produce both ash and combustible gas Combustible gas was not converted into electricity and heat, and ash was removed to landfills. From this feasible structure, GHG emissions were produced from landfills only. The highest EP yield products were solid fertilizer, liquid fertilizer, GHG emissions, and biochar at flow rates of 1,030,000 tons/year, 4,110,000 tons/year, 89,600 m^3/year, and 795,000 tons/year, respectively.

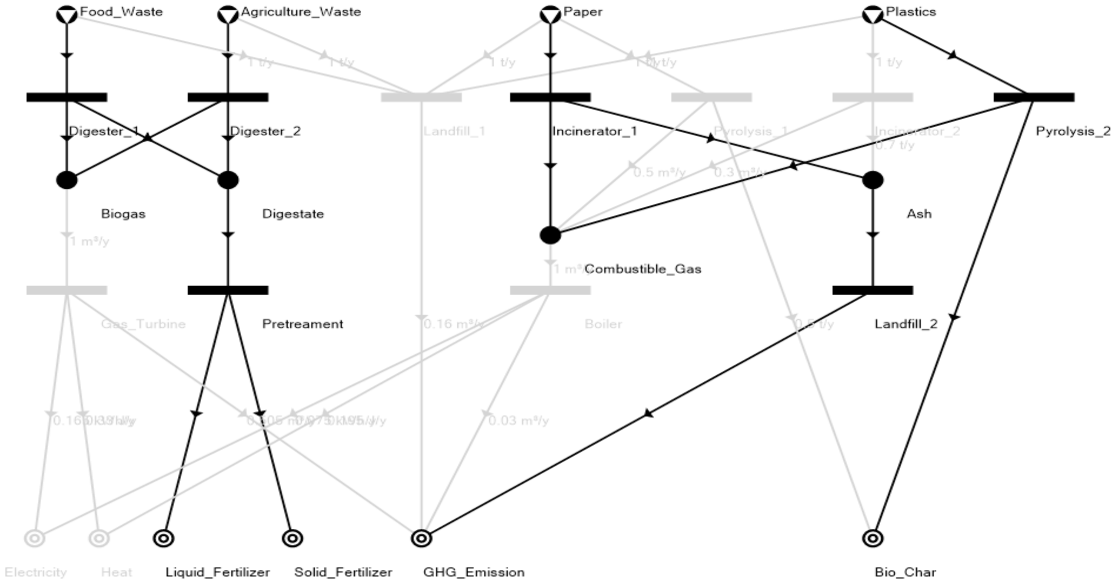


Figure 9. Feasible structure with the least environmental impact.

4. Conclusions

In this study, for the feasibility of MSW conversion technologies by PNS, "process graphs" were simulated. One hundred feasible structures were generated and nine of these were selected randomly for further analysis. Next, the EP and EI of the MSW conversion technologies were analyzed. Feasible structure 9 was chosen as the design with the maximum EP, with a total annual profit gain of MYR 6.65 billion, requiring up to 16 years as the payback period, with a constant flow of products. Feasible structure 7 was chosen as the design with the minimal EI, generating 89,600 m^3/year of GHGs for the whole of Malaysia.

Further studies should be conducted using a real case study. This method of study would be more convenient for optimizing a small case study, focusing primarily on a district rather than on the whole country. This study was a feasible-structure-based preliminary study to treat MSW in the whole country. For example, the payback period of conversion technologies could take up to 16 years because of the high cost of developing conversion technologies to manage the whole country's MSW.

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