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Debottlenecking of the Integrated Biomass Network with Sustainability Index

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This paper is initiated with the discussion on the problems faced in the biomass industry of Malaysia. The supply chain synthesis problem has been extended with recent development of biomass network and sustainability index. Optimisation is no longer sufficient to improve the biomass utilisation. A thorough knowledge of the biomass network is required to identify several bottlenecks that have been hampering the development of the biomass industry. After the identification of the bottlenecks, creative and innovative ideas are needed to suggest debottlenecking approaches by integrating the sustainability index into the biomass network. The integration of sustainability index into the biomass network for debottlenecking is a novel approach in this research paper. This research will help in the development of the nation’s biomass utilisation and industry by using debottlenecking approaches to expand the biomass industry and unlock the underutilised biomass potential.

1. Introduction

The rise of the global population and standard of living have led to an increase in the energy consumption in the world. From the latest International Energy Outlook 2016 released by US Energy Information Administration, projects that the world energy consumption will grow by 48 % over the 28-y period from 2012 to 2040 (EIA, 2016). Aside from this, the raising concern of strengthening the nation’s energy security and increasing global pressure on emissions reduction have driven the worldwide implementation of sustainable development. In Malaysian context, biomass utilisation has abundantly cited as one of the prospective solutions for the mentioned issues due to its extensive biomass resources (Duić et al., 2011). A vast number of research works have been conducted in order to boast the development of biomass industry in Malaysia. Lam et al. (2013) had synthesised an economic-feasible and environmental benign palm oil biomass supply chain in West Malaysia by using a two-stage optimisation model. More recently, Cheah et al. (2016) had conducted a physio-chemical study to discover the feasibility of using Jatropha oil as alternative feedstock for the biodiesel production.

Despite countless efforts have been committed by the Malaysian government and academicians, the development of the biomass industry is still no doubt sluggish. This is due to several underlying bottlenecks, which hamper the development of the biomass industry. Note that the term “bottleneck” should not merely limit to economic dimension but also related to environmental and social dimensions. For instance, community has started to question the actual sustainability performance (e.g., extensive land requirement (Oh, et al., 2010), extensive emission of toxic gas (Asadullah, 2016)) of the production of biomass-derived products. Certainly, economic factor, such as overwhelmingly expensive logistic cost due to low mass density of biomass (Strezov, et al., 2016) and lack of bankability due to new and unproven green technologies (Yatim, et al., 2017) are also the valid hurdles for the development of biomass industry in Malaysia. However, most of the existing bottlenecks detection methods are mainly used to identify bottlenecks that limit the throughput of the process. By using the conventional approaches, bottleneck is often defined as the machine with the (i) longest waiting time; (ii) largest workload; and (iii) longest active duration (Law and Kelton, 1991), which is no longer sufficient to represent the bottlenecks in sustainable development.

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Among the available optimisation tools, P-graph, a powerful graph-theoretic approach shows substantial potential to be applied as debottlenecking approach. One of the key advantageous computing features that offered by this framework is the efficient search of solution space which enables simultaneous generation of multiple solutions - optimal and sub-optimal (Lam et al., 2016). Aside from this, with the aid of the visual interface of P-graph, users are able to formulate their case study easily and efficiently without the need of strong mathematical programming background. To-date, the framework had gained sufficient penetration into chemical engineering literatures (Klemeš et al., 2011) and extensively applied in various forms of research, e.g. optimal biomass processing hubs synthesis (How et al., 2015), redundancy analysis (Bertok et al., 2013), criticality analysis (Benjamin et al., 2017). However, to-date, it has not been applied to develop debottlenecking framework to identify and remove the bottlenecks in the biomass network.

Therefore, this paper presents a novel application of P-graph method in debottlenecking of the biomass network in order to attain higher sustainability. To achieve this, sustainability index, which cover all three dimensions (economic, environmental and social) is integrated into the biomass network, which are formulated through P-graph framework. A case study is carried out to demonstrate the effectiveness of the proposed method.

2. Problem statement

The problem described in this paper aims to determine the optimal biomass utilisation pathway while optimising each sustainability dimension (economic, environmental and social) simultaneously. Debottlenecking process is conducted to further improve the sustainability performance of the biomass utilisation. However, the conventional method that defines “bottleneck” as “the element that limits the system in attaining higher throughput” is no longer suitable to identify all bottlenecks within the huge umbrella of sustainable development. The debottlenecking of the problem is carried out by using the proposed method, which is described in latter section.

3. Method

Figure 1 shows the research flow chart used in this work. The overall research strategy for this paper is: (i) Construction of biomass network; (ii) Formation of biomass network sustainability index (BNSI); (iii) Construction P-graph model; and (iv) Debottlenecking using P-graph framework.

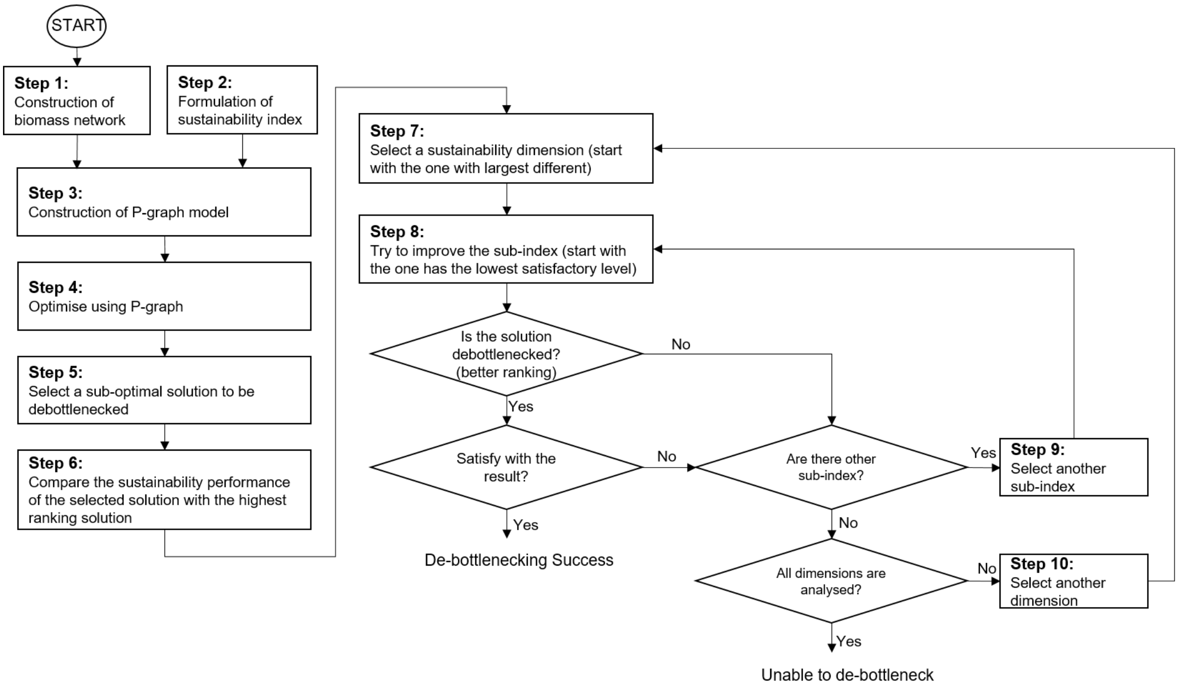

Figure 1: Research flow chart

The description of these components is given in the following subsections:

3.1 Biomass network construction

The construction of biomass network is vital to identify the requirements or considerations of each stage as a whole in a more detailed manner. Moreover, biomass network also serves to provide comprehensive understanding on how one operation affects the others, which in turn affect the sustainability of the biomass network. If the biomass network is well developed and studied, optimisation can be done in a more systematic manner. The activities performed in the network that incorporated in the model are shown in Figure 1.

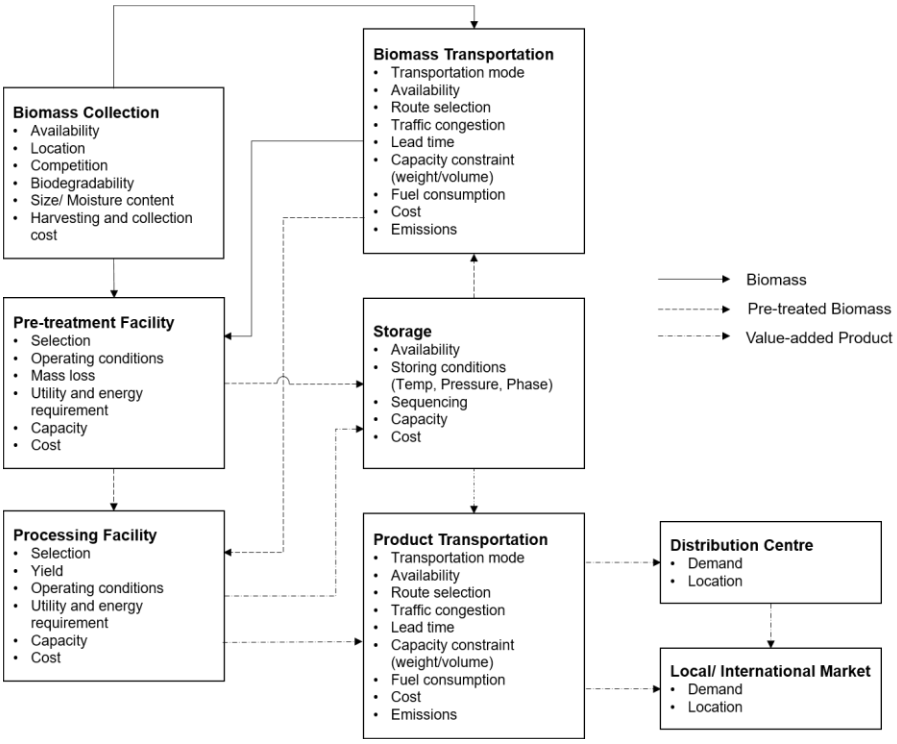

Figure 2: Biomass network (developed from Lam and Ng (2013))

3.2 Biomass network sustainability index (BNSI) formulation

The development of BNSI, an integrated sustainability index consists of three subsequent stages. In the first stage, identification of suitable sustainability indicators is conducted. These indicators are selected based on the preference or concern of various stakeholders, including industry players, shareholders, suppliers, policy makers, customers, etc. In this work, economic index, I^{Ec} concerns on the biomass collection cost, biomass characteristic (related to biodegradability), pre-treatment cost, product price, logistics cost, operating and capital cost of the processing facility. Environmental index, I^{En} encompasses the greenhouse gases emission from each stage of the biomass network (harvesting, transportation, processing, etc.), wastewater generation and toxic wastes disposal rate. Note that the social index, I^{Sc} will only focus on safety issue, i.e., characteristics of the materials involved (toxicity, flammability, explosiveness, corrosiveness, etc.) and operating condition of the process (temperature and pressure).

Then, in order to ensure each sub-index is fairly compared on the same basis, normalization is carried out. It can be done by using Eq(1) and Eq(2), result with a normalised value, $P^{Normalised}$ ranging from 0 (represent worst) to 100 (represent best). Note that Eq(1) is used to normalise the indicators with positive attributes (e.g., product price), while Eq(2) is used to normalise the indicators with negative attributes (e.g., carbon emission).

$$P^{Normalised} = \frac{P - P^{Min}}{P^{Max} - P^{Min}} \times 100 \tag{1}$$

$$P^{Normalised} = \frac{P^{Max} - P}{P^{Max} - P^{Min}} \times 100 \tag{2}$$

where P refers to the value of the indicators, while P^{Min} and P^{Max} refers to the minimum and maximum possible value for P. Finally, Analytical Hierarchy Process (AHP) is introduced to determine the priority scale for each sustainability dimension. In general, AHP is a theory of measurement through pairwise comparisons and relies on the expert’s judgments to derive priority scales (Saaty, 2008). Therefore, the overall objective function can be formulated as:

$$\max \text{BNSI} = w^{Ec} \times I^{Ec} + w^{En} \times I^{En} + w^{Sc} \times I^{Sc} \tag{3}$$

where w^{Ec}, w^{En} and w^{Sc} refer to the priority scale assigned to economic index, environmental index and social index.

3.3 Construction of P-graph model

Figure 3 shows an example of P-graph model with the integration of BNSI in biomass network. This example evaluates the sustainability performance of two stages of the biomass network simultaneously, i.e. pre-treatment process and product conversion. The construction of P-graph model can be decomposed into three parts. Firstly, the formalised score of each sub-index determined from the previous stage is served as an input to the P-graph model (see right column). Then, the O-type vertices in the middle and left columns are used to assign priority scale to each sub-indexes and to each sustainability dimension. Finally, the BNSI of the biomass network is determined. By using the accelerated branch-and-bound (ABB) algorithm, which embedded in the P-graph software, multiple solutions (optimal and sub-optimal) can be generated simultaneously and efficiently. Please note that it does not necessary to be two stages. Decision-makers can decide the size of the model according to their specific needs.

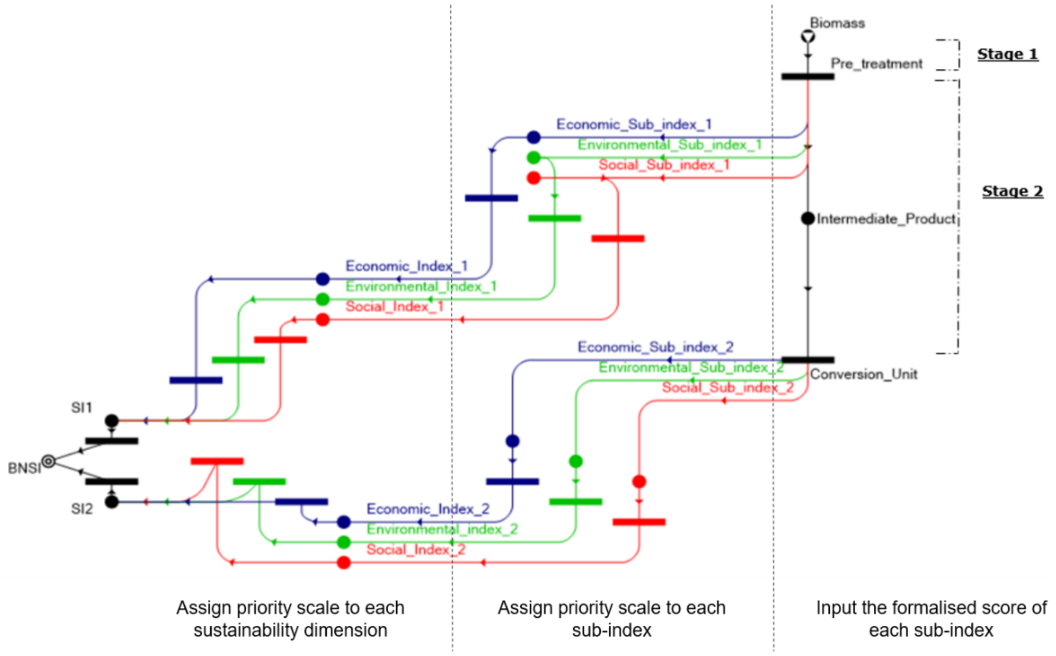

Figure 3: Example of Integration of Sustainability index in biomass network using P-graph framework

3.4 Debottlenecking using P-graph framework

All solutions generated by P-graph is ranked from best to worst based on the BNSI score. Firstly, select one of the sub-optimal solutions that is intended to be debottlenecked. It is benchmarked with the optimal solution. The sustainability dimension that has the largest difference is notified as the potential bottleneck. The sub-index with the lowest score will be the first sub-index to be improved. The improvements may be performed in any stage of the supply chain, from the supply source to the product market (e.g., the processing hub is re-located to reduce transportation cost, alternative technology is implemented for cleaner production, etc.). The remaining sub-indexes will be improved one by one according to score (from lowest to highest), until the selected solution is successfully debottlenecked (increase in ranking) or all the all sub-indexes are analysed. If the result is not satisfied until this stage, the entire process will be repeated by analysing another sustainability dimension.

4. Case study description

To illustrate the proposed approach, a case study of the utilization of two palm based biomass, i.e. empty fruit bunches (EFB) and oil palm fronds (OPF) is used. In this case study, multiple technology options are available for both EFB (fermentation, pyrolysis and combustion), OPF bagasse (gasification) and OPF pressed juice (fermentation and dark fermentation). Figure 4 shows the P-graph model constructed for this specific case study.

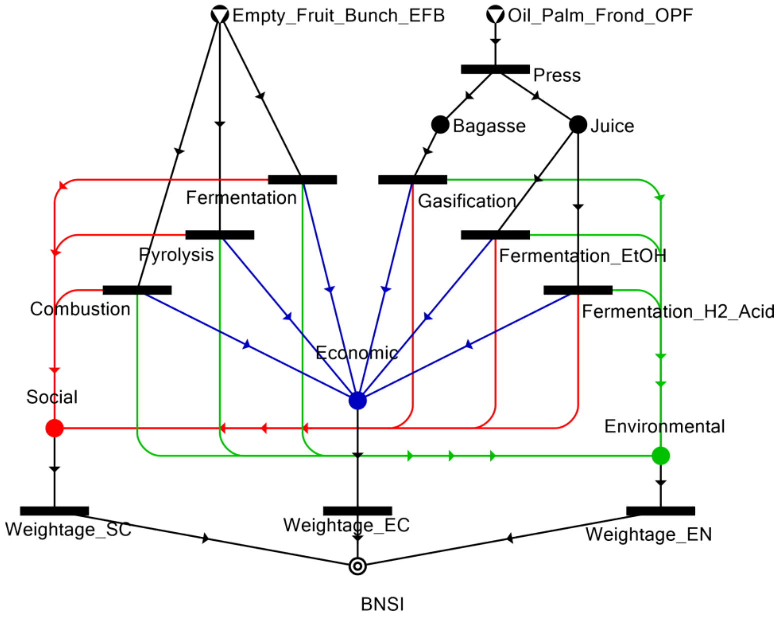

Figure 3: P-graph model for the proposed case study.

5. Results and discussions

The result shows that highest BNSI (78.77) can be attained when EFB is used as pyrolysis feedstock, OPF pressed juice is used to produce bio-ethanol, whereas OPF bagasse is gasified to produce syngas. Lower BNSI is encountered if OPF pressed juice is used to produce bio-diacid (e.g., bio-succinic acid and bio-adipic acid), while others are remained unchanged. This is due to the extensive requirement of CO_2 (372 kg CO_2/t produced bio-succinic acid) for the bio-diacid production (Tan et al., 2016). In order to debottleneck this case, industrial symbiosis between bio-diacid production plant and a huge CO_2 production plant (e.g., bio-ethanol plant) is one of the prospective solutions. Win-win situation is expected as the operating cost for the bio-diacid plant is gradually reduced due to the lower procurement cost for CO_2, while the environmental impact of the CO_2 donor plant can be significantly mitigated with minimal abatement cost. To achieve this, OPF bagasse is used for bioethanol production (see Table 1). It is clearly seen that the bottleneck of the bio-diacid production of OPF pressed juice has been successfully debottlenecked. The increase in economic index is in agreement with the expectation made formerly. The debottlenecking process can be repeated to further improve the sustainability performance of the selected solution as well as the solution, which currently has the lower BNSI, until the decision-makers are satisfied. The case studies presented shows that the proposed approach is applicable for the debottlenecking of biomass network.

Table 1: BNSI score and ranking before and after debottlenecking w^{Ec} = 50 %; w^{En} = 20 %, w^{Sc} = 30 %)

Before debottlenecking			
Technology	Dimension	BNSI	Ranking
OPF bagasse→syngas	I^{Ec}=68.16		
OPF pressed juice→bio-diacid	I^{En}=93.55	78.49	2
EFB→ biochar, bio-oil	I^{Sc}=85.65		
After debottlenecking			
OPF bagasse→bio-ethanol	I^{Ec}=74.73		
OPF pressed juice→bio-diacid	I^{En}=93.30	*83.8*	1
EFB→ biochar, bio-oil	I^{Sc}=92.60		

6. Conclusion

This paper developed a novel debottlenecking approach, which integrates sustainability index into the biomass network. The main contributions are: (i) this work presents the first attempt to pioneer this powerful graph-theoretic method as the potential debottlenecking tools and (ii) a novel framework for the formulation of integrated biomass network sustainability index (BNSI) is presented. The demonstrated case study shows that the proposed debottlenecking approaches are applicable to debottleneck research problem efficiently. Future work will focus on extending application of this approach to debottleneck research problems from other fields. Aside from this, the model structure can be enhanced by considering social impacts other than process safety as job creation, transportation safety, philanthropy involvement.

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