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Automated targeting for the synthesis of an integrated biorefinery

Denny Kok Sum Ng*

Department of Chemical and Environmental Engineering, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia

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ABSTRACT

Biorefineries are processing facilities that convert biomass into value-added products such as biofuels, specialty chemicals, and pharmaceuticals. Integrated biorefineries which consist of various processing facilities (e.g., digestion, fermentation, pyrolysis, gasification, etc.) have been proposed in order to enhance the energy efficiency and material recovery. This work presents an optimisation-based, automated targeting procedure to determine the maximum biofuel production and revenue levels in an integrated biorefinery. The approach is based on pinch analysis and allows targets to be determined prior to detailed design of the biorefinery flowsheet. A hypothetical case study is shown to illustrate the proposed approach.

1. Introduction

According to the *Annual Energy Outlook 2007* [1], total world consumption of energy is projected to increase from 472 trillion MJ in 2004 to 590 trillion MJ in 2015 and eventually to 741 trillion MJ in 2030. Throughout the projected period, fossil fuels (i.e., coal, oil and natural gas) are expected to continue to supply a large share of energy use worldwide [1]. Thus, the gradual depletion and rising costs of fossil fuels will soon become a major global problem. As a result, there is an increased attention to the issues of energy security, resource diversification, and efficiency enhancement.

At the same time, the increase of public awareness towards environmental sustainability is also motivating a shift from fossil fuels to renewable energy sources. Biofuels are recognised as some of the most promising forms of alternative energy because of the renewable nature of biomass. The sequestration of carbon dioxide during photosynthesis and crop growth results in an inherently low-carbon fuel cycle. Furthermore, a wide variety of biomass is available depending on local geographic conditions (e.g., traditional agricultural crops, energy crops, forestry waste, municipal solid waste, etc.), and these may be converted into a range of products other than fuel. Biorefineries are processing facilities that convert biomass into value-added products such as biofuels, specialty chemicals, and pharmaceuticals. In order to enhance overall energy efficiency and material recovery within the processing facilities, an integrated biorefinery is needed. An integrated biorefinery is comprised of various processing facilities such as digestion, fermentation, pyrolysis, gasification, thermal conversion, etc. which allows energy exchange within processes and material reuse/recycling to increase the overall biochemical production with minimum energy requirement. Via in-plant material recovery, generation of waste (i.e., carbon dioxide, wastewater, etc.) can also be minimised. Furthermore, the residual of biomass can be used as fuel to generate steam and electricity to fulfil the processes requirement. Thus, the overall energy consumption of an integrated biorefinery will be lower as compare to the process that operates independently.

Much research has been done in the area of chemical process synthesis. Westerberg [2] described process synthesis as the step to determine the optimum interconnection of different processing units to form a flowsheet that meets the process design requirement. The aim of process synthesis is to optimise the logical structure of a chemical process, particularly the sequence of steps (reaction, distillation, extraction, etc.), the choice of chemical employed and the source and destination of recycle streams [3]. In the late 1960s, process synthesis research was initiated by Rudds and his co-workers [4,5]. Since then, there have been extensive developments in process synthesis subtopics, such as synthesis of heat-exchange networks (HEN) [6,7], mass-exchange networks (MEN) [8,9], separation networks [10], reaction pathways [11–13], reactor networks [14–18], and property-based networks [9]. In the past decade, water [19–27] and hydrogen [28,29] network synthesis emerged as special cases of mass integration for industrial resource conservation and pollution prevention.

Process integration is recognised as one of the most important elements in process synthesis. It is especially vital for effective waste minimisation and reduction of raw material usage for a process plant. Many successful applications of process integration for

* Tel.: +60 3 89248606; fax: +60 3 89248017.
E-mail address: Denny.Ng@nottingham.edu.my.

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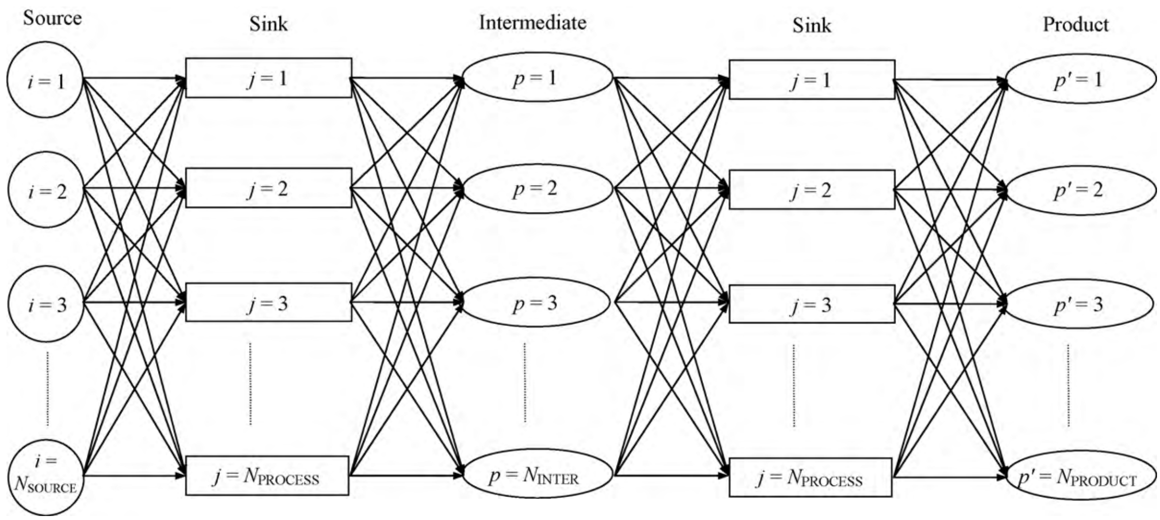

Fig. 1. Graphical representation for an integrated biorefinery.

waste minimisation efforts in various chemical process industries have been reported (e.g., fuel production [8], oil refinery [29], petrochemical [30], pulp and paper mills [31] and agrochemicals [32]). In many cases, the environmental benefits have been accompanied by economic gains from the efficiency enhancements.

It is important to note that due to the complexity of the chemical structure and variation in composition of biomass, there are many challenges in designing an integrated biorefinery. In addition, the unique features of an integrated biorefinery make the process design more difficult than the conventional chemical processes. For example, the thermodynamic properties (e.g., Gibbs free energy, enthalpy, entropy, etc.) of biomass are not well established compared to conventional chemicals. In addition, there is lack of established information related to the rates of reaction for biomass conversion (particularly for biochemical processes), which makes process synthesis of biorefineries even more challenging. Therefore, many existing approaches for the synthesis and design of chemical processes may not be directly applicable for the synthesis of integrated biorefineries.

According to Bridgwater [33], a biorefinery will be inherently multifunctional and produces various products such as biofuels, electricity and chemicals from biomass inputs. Detailed techno-economic analysis and optimisation on the well-established biomass-to-energy conversion technologies such as heat and power generation [34,35], biodiesel production [36–40] and bioalcohol [41] have been conducted.

Recently, Ng et al. [42] proposed a hierarchical approach to the synthesis and analysis of an integrated biorefinery. Two process screening tools (Evolutionary technique and Forward-Reverse Synthesis Tree) were presented to analyse and reduce the number of process alternatives. In addition, Kokossis and Yang [43] identified the challenges of synthesis and design a sustainable biorefineries. These authors proposed a total system approach to combine multi-scale formulations with multi-stage problem solving capabilities for problems involving novel processes [43]. On the other hand, Sammons et al. [44] introduced a flexible framework to evaluate the profitability of different possible production pathways within an integrated biorefinery. Later, Sammons et al. [45] extended their previous work to determine the optimal process pathway based on economic potential and environmental performance. In addition, Sammons et al. [46] proposed a general systematic framework for optimising product portfolio and process configuration in integrated biorefinery. Mansoornejad et al. [47] then further extend the previous work by introducing market aspects, supply chain network design and flexibility manufacturing design in the framework. Tan et al. [48] developed an extended input-output model using fuzzy linear programming to determine the optimal capacities of distinct process units given a predefined product mix and environmental (carbon, land and water footprint) goals.

Despite these recent developments, it is notable that significant amount of research has been carried out in the area of synthesising and designing conventional chemical processes, but much less research has been carried out in the new area of biorefineries. According to the philosophy of pinch analysis, the overall performance targets (minimum fresh resource requirement, total annualised cost, etc.) can be located prior to the detailed network design, which is essential for gaining insight into process bottlenecks. Therefore, it is important to develop a systematic procedure to find production and economic targets prior to the detailed design of an integrated biorefineries.

In this work, pinch based automated targeting approach that was originally developed for the synthesis of resource conservation networks [49–52] is extended to determine the maximum biofuel production and revenue targets for an integrated biorefinery. In addition, based on the resulting targets, the detailed allocation of raw material (biomass) and intermediate products (e.g., alcohol, syngas, etc.) for different processes to produce final products can be determined. It is interesting to note that the biofuel production and revenue targets for a given feedstock can be determined prior to the detailed process flowsheet and network design of an integrated biorefinery.

2. Problem statement

In most cases, the efficiency of biomass processing facilities is assessed using the mass-based conversion of raw material to the desired products. Since carbon is the key element in organic matter (i.e., biomass), tracking carbon content from raw material (biomass) to final products is very important. By recovering the carbon content in raw material that may be lost from conversion processes in the form of gases (e.g., carbon dioxide and carbon monoxide) and solid waste (e.g., fermentation residues, charcoal, etc.), the overall mass efficiency of a biorefinery can be increased. In addition, the total amount of carbon that is converted to products or waste from biomass remains the same as in the given biomass when no additional carbon is added in the process. However, hydrogen and oxygen contents may change significantly by adding oxidants (e.g., steam, air, etc.) and water for thermal and biological conversion

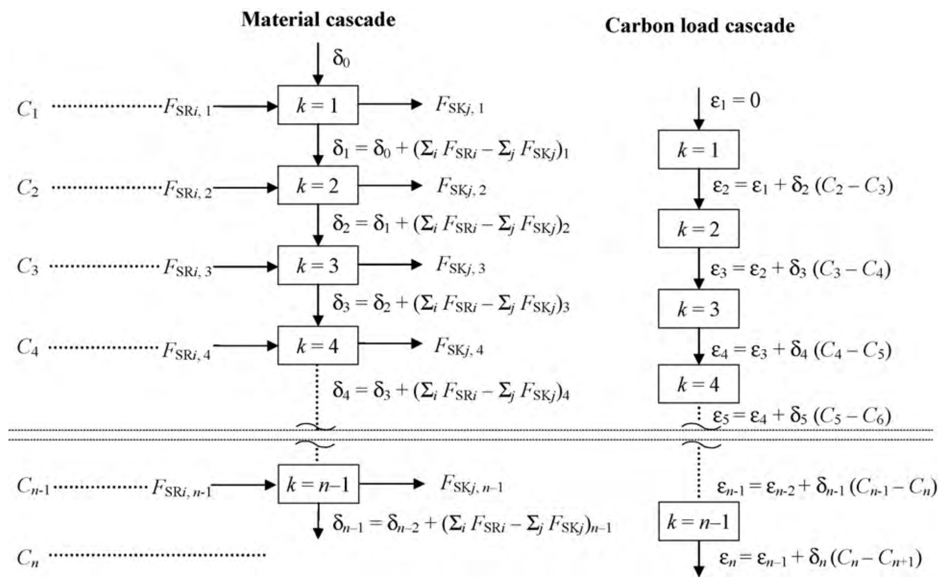

Fig. 2. Generic biorefinery cascade diagram (BCD).

processes. In order to determine and enhance the performance of an integrated biorefinery, in this work, carbon content is thus used as the dominant quality parameter for resources, intermediates as well as processes.

The problem of synthesis of an integrated biorefinery may be formally stated as follows. Given a set of biomass sources, SR_i that may be converted to intermediates p, $INTER_p$ or products p', $PD_{p'}$. Each source has given a flowrate, F_{SR_i} and is characterised by carbon fraction, C_i. A set of sinks, SK_j which are process units that can convert sources i into intermediates p, and products p', is specified. Each sink is characterised by a predefined minimum carbon fraction requirement (C_j^{min}). In addition, the process conversion factors of sources i to intermediates p (X_{ijp}) and intermediates p to products p' ($X_{pjp'}$) via SK_j are also specified.

In order to reduce the complexity of an integrated biorefinery, only single-stage or two-stage processes that convert a given source i to any product p' are taken into consideration. The problem structure may be summarised as shown in Fig. 1. The objective of the methodology is to determine maximum production of single product (biofuel), or alternatively, revenue from a mix of multiple products, from a given available biomass feed; and, to determine the network design of the integrated biorefinery that meets these targets.

3. Automated targeting

The automated targeting technique was originally developed for MEN synthesis [53]. It was then extended to the synthesis of resource conservation network (RCN) for cases with reuse/recycle [49], interception [50,51] and waste treatment [52] based on cascade analysis [23,31]. Later, automated targeting was also used to find targets for minimum amount of CO_2-neutral or low-carbon energy sources for segregated energy planning problems [54]. Note that in the previous works of MEN and RCN syntheses [49–52], concentration of contaminants and stream flowrate are used to measure the quality and quantity of process streams respectively. Based on the extracted data, MENs and RCNs with maximum recovery or minimum total annualised/operating cost can be synthesized. For carbon constrained energy planning, carbon intensity and amount of energy are selected to measure quality and quantity of energy stream to determine the optimum allocation of energy source to the energy demand sectors. As presented previously, tracking carbon content is important in synthesis of integrated biorefinery; hence, carbon content and material flowrate are used as the dominant quality and quantity parameters respectively. It is noted that the previous analogies for MENs and RCNs syntheses as well as energy planning are not longer applicable for synthesis of integrated biorefinery. Therefore, automated targeting is further extended in this work, to the synthesis of an integrated biorefinery with production and revenue targets. In addition, the model can also determine the network design of the integrated biorefinery.

Based on these previous works [49–52], the technique involves arranging sources/sinks in descending sequence, with highest quality (lowest impurity concentration or emission factor) located at the top of the cascades. Since carbon content is used as the dominant quality parameter in this work, the sources, sinks, intermediates and products should be arranged based on carbon fraction. These are arranged in a descending order based on carbon fraction level (C_k), from the highest level $k = 1$ to the lowest level $k = n$. This step of procedure is called as the construction of a *biorefinery cascade diagram* (BCD) as shown in Fig. 2. The highest value of carbon fraction is added as the first level, if this does not already exist among the process sinks and sources. For example, 100% is added in first level ($C_1 = 100\%$) if the carbon fraction is measured as percentage. In addition, a final fictitious level of zero ($C_n = 0$) is added at the bottom of the cascade to allow the calculation of residue carbon load (ε). Next, material flowrate cascading is performed across all levels. At each level k, the difference between the total available material sinks ($\sum_j F_{SK_j}$) and sources ($\sum_i F_{SR_i}$) is determined. Next, the *net material flow* cascaded from the earlier level $k-1$ (δ_{k-1}) with the flow balance at level k form the net material flowrate of each k-th level (δ_k), given as in Eq. (1).

$$\delta_k = \delta_{k-1} + (\Sigma_i F_{SR_i} - \Sigma_j F_{SK_j})_k \tag{1}$$

To ensure that no additional biomass flow is generated from the final level n, as that level is only used for the calculation of residual carbon load, a new constraint (as shown in Eq. (2)) is needed.

$$\delta_k = 0 \tag{2}$$

Carbon load cascading is performed next. Within each interval, the carbon load is given by the product of the net material flow from level k and the difference between two adjacent levels. As in the material flow cascade, residual of the carbon load of each level k (ε_k) is cascaded down to the next level. Hence, carbon load balance

Table 1
Conversion table of biomass to intermediate and final products.

Process sink j	Raw material	Intermediate p/product p'	Conversion, X_{ijp} or $X_{pjp'}$ (kg product/kg raw material)
Digestion	Biomass	Methane (CH_4)	0.147
		Biomass residual	0.79
Fermentation	Biomass	Ethanol	0.27
		Biomass residual	0.61
Gasification	Biomass	Syngas (CO)	0.18
Pyrolysis	Biomass	Bio-oil	0.54
Dehydration	Ethanol	Biofuel	0.65
Synthetic fuel	Methane	Biofuel	0.286
Synthetic fuel	Bio-oil	Biofuel	0.1425
Fischer–Tropsch	Syngas	Biofuel	0.9

at the k-th level is determined by Eq. (3).

$$\varepsilon_k = \varepsilon_{k-1} + \delta_k (C_k - C_{k+1}) \tag{3}$$

where ε_{k-1} is the residue carbon load that is cascaded from level $k-1$.

Conversely, the residual impurity load, ε must take a positive value, which implies that a feasible carbon load cascade is achieved [23,31,49–52]. As such, the maximum allowable carbon load of sink in each level is fulfilled. Therefore, Eq. (4) is included as a constraint in the formulation of the model.

$$\varepsilon_k \geq 0 \tag{4}$$

It is interesting to note that, when the residual carbon load is determined as zero in the model solution at level k ($\varepsilon_k = 0$), a pinch point occurs. In physical terms, the zero carbon load means that, at the optimal solution, the minimum carbon load requirement of all sinks above the pinch point are fulfilled by the sources in order to operate the process sinks [23,31,49–52]. The identification of the pinch point provides valuable insights to decision makers. Its primary value is that it identifies the system bottleneck. Thus, the "golden rule" of pinch analysis can be applied to this problem in order to meet all the specified process requirements in the integrated biorefinery, the fresh resources (i.e., biomass) must be supplied only to the process sinks below the pinch point. Allocation of this resource to the process sink(s) above the pinch point will lead to an infeasible solution, or lower production rate/revenue than the targeted quantity identified by pinch analysis.

Note also that the above formulation is a linear programming (LP) model that can be solved easily to yield global optimal solution if a solution exists. In this work, the LP models were solved using Lingo v10.0. However, in practice the automated targeting can be implemented using any LP solver, which can be found even in common spreadsheet environments. In addition, in some cases, non-linear programming may result due to additional case-specific process constraints or objectives. Such variants can be optimised using appropriate optimisation software.

In order to determine the maximum production of desired products (F_{PD}), the BCD (Fig. 2) is used, with the optimisation objective formulated as follows:

$$\text{Maximise } F_{PD} \tag{5}$$

Alternatively, the maximum revenue solution can be obtained for cases with multiple products, in which case the optimisation objective is set as

$$\text{Maximise } \Sigma_{p'} (\text{REV}_{p'} F_{\text{PD}p'}) \tag{6}$$

where $\text{REV}_{p'}$ and $F_{\text{PD}p'}$ are the revenue and flowrate of product p' respectively. In this work, a hypothetical case study is solved to illustrate the proposed automated targeting for synthesis of integrated biorefinery.

4. Case study

Tables 1 and 2 show the conversion table and data for a hypothetical case that are used to illustrate the application of the automated targeting approach to the synthesis of an integrated biorefinery. Three scenarios are analysed in this work. In the first scenario, the optimisation objective is to determine the maximum production of single product (biofuel) from a given amount of biomass. In the other scenario, maximum revenue target for cases with multiple products is presented. Next, synthesis of an integrated biorefinery with multiple feedstocks and products that achieve maximum revenue target is further analysed.

In this work, an idealised biomass [55] that contains 31.7% lignin ($CH_{1.12}O_{0.377}$) and 68.3% polysaccharides ($C_6H_{10}O_5$) on an ash-free basis is assumed as raw material. Based on the given information above, the carbon fraction of the biomass is calculated as 0.477. As shown in Table 1, four processes that convert raw material (biomass) to intermediates such as methane, ethanol, syngas and bio-oil via digestion, fermentation, gasification and pyrolysis, respectively. In addition to these, four other processes that further convert the intermediates to biofuel are also included. Theoretical or empirical conversions of raw material to intermediates/products for these processes are also included in Table 1.

Table 2
Data for a hypothetical case study.

Source		Available source (kg)	Carbon fraction (C_i)	Sink		Minimum requirement of carbon fraction ($C_j^{\min}$)
SR1	Ideal biomass	10,000	0.477	SK1	Digestion	0.477
SR2	Digested residual biomass	79% inlet biomass to digestion	0.474	SK2	Fermentation	0.477
SR3	Fermented residual biomass	61% inlet biomass to fermentation	0.170	SK3	Pyrolysis	0.250
				SK4	Gasification	0.250

Since the residuals of biomass from digestion and fermentation processes contain high carbon content and energy potential; hence, further recovery these residues allow the enhancement of the production of biofuel. Thus, both biomass residues are extracted as sources as shown in Table 2. The carbon fraction of biomass residues can be estimated based on theoretical or experiment data that reported in the literature. In this work, the carbon fractions of digested and fermented biomass residues are given as 0.474 and 0.17 respectively.

On the other hand, four processes (digestion, fermentation, pyrolysis and gaisification) that accept similar raw materials (i.e., biomass, biomass residue, or mixture of both) to produce various intermediates are taken as sinks (see Table 2). As shown, the minimum requirements of carbon fraction ($C_j^{\min}$) of the sinks to produce intermediates/products are also specified for each sink. It is noted that the processes that further convert intermediates to final products are not taken as process sinks in Table 2 because such processes are not constrained by the carbon fraction of intermediates. Also, those processes require different raw materials or intermediates to produce final product (biofuel). Examples include Fischer–Tropsch, dehydration and synthetic fuel processes require syngas (carbon monoxide and hydrogen), alcohol and methane/bio-oil, respectively, to produce biofuel.

To locate the maximum production target, Eqs. (7) and (8) are included in the automated targeting formulation (Eqs. (1)–(4)).

$$F_{\text{INTER}p} = X_{ijp} F_{\text{SK}_j} \quad (7)$$

$$F_{\text{PD}p'} = X_{pjp'} F_{\text{INTER}p} \quad (8)$$

Based on above equations, the flowrates of intermediates p ($F_{\text{INTER}p}$) and final product p' ($F_{\text{PD}p'}$) can be determined. Since the biomass residues are taken as SR_i and the flowrates of these sources can only be determined via Eq. (7) once the model is optimised. Thus, F_{SR_i} of biomass residues are included as variables in the automated targeting.

4.1. Scenario 1: Maximum production of single product (biofuel) from a given biomass

Solving Eq. (5) subject to the constrains in Eqs. (1)–(4), (7) and (8) yields the solution in the BCD shown in Fig. 3. Note that 8230.6 kg of biomass is fed to the fermentation process (SK2), and the balance of the biomass (1769.4 kg) is gasified via SK4. Solving Eq. (7) based on the given conversion in Table 1, 2222.3 and 5020.7 kg of ethanol and biomass residue (SR3) are generated, respectively, when 8230.6 kg of biomass is fermented in SK2. As shown in Fig. 3, 1769.4 kg of SR1 (δ_3) and 5020.7 kg of SR3 (δ_4) are used to produce syngas via gasification. According to Table 1, the conversion of syngas from biomass (X_{ijp}) is given as 0.18; hence, 1222.2 kg of syngas is generated from the 6790.1 kg of biomass mixture. As the biomass is processed via fermentation and gasification, two intermediate products (ethanol and syngas) are generated. Since the objective of this scenario it to find the maximum conversion of biomass to biofuel, both intermediates are further processed via dehydration and Fischer–Tropsch processes respectively. Based on the optimisation model and conversion data in Table 1, 2544.5 kg of biofuel is produced, where 1444.5 and 1100 kg are derived from ethanol and syngas, respectively. In line with the detailed allocation of fresh resource (biomass) and intermediates (residual biomass, ethanol and syngas), a network design for Scenario 1 is shown in Fig. 4. In order to simplify the network design, the unrecovered solid and gas wastes are not shown in Fig. 4.

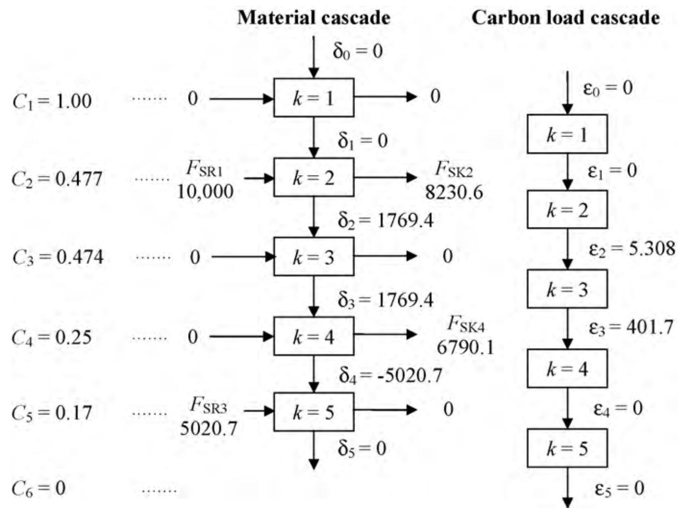

Fig. 3. Biorefinery cascade diagram for Scenario 1 (maximum production of biofuel).

Table 3
Revenues of intermediates and final products.

Intermediates/final products	Revenue, $\text{REV}_{p'}$ ($/kg)
Biofuel	0.93
Methane (CH_4)	1.02
Ethanol	0.78
Bio-oil	0.008

4.2. Scenario 2: Maximum revenue for cases with multiple products

A second scenario with multiple products is illustrated next. Here, the objective is to maximise revenue from the product portfolio given a fixed raw material cost. Table 3 shows the revenues of intermediates and final products which are typical based on historical data. Since each intermediate p has a market value, it can be considered as final product. To determine the flowrate of multiple products, the mass balances of processes (Eq. (9)) are included in the model.

$$F_{\text{PD}p'} = F^{I}_{\text{PD}p'} - F^{I}_{\text{INTER}p} \quad (9)$$

where $F^{I}_{\text{PD}p'}$ is the flowrate of product p' that produced from first process. Meanwhile, $F^{I}_{\text{INTER}p}$ denotes the flowrate of product p' that

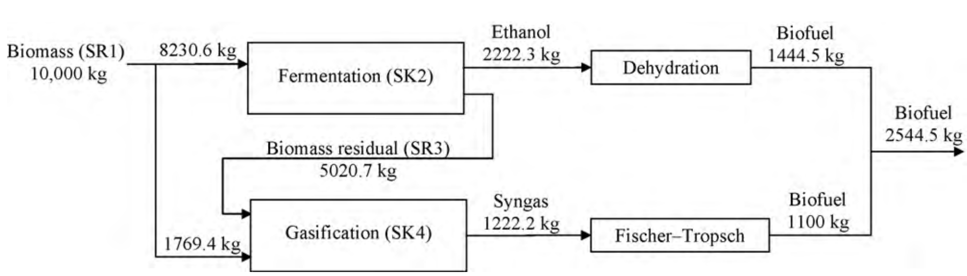

Fig. 4. Network design for Scenario 1.

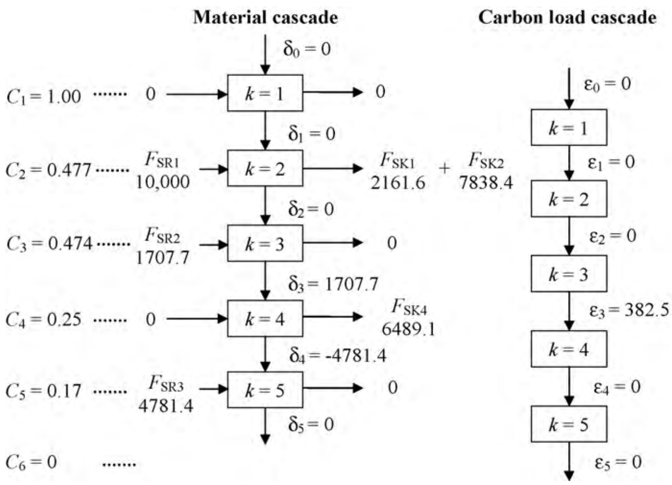

Fig. 5. Biorefinery cascade diagram for Scenario 2 (maximum revenue for cases with multiple products).

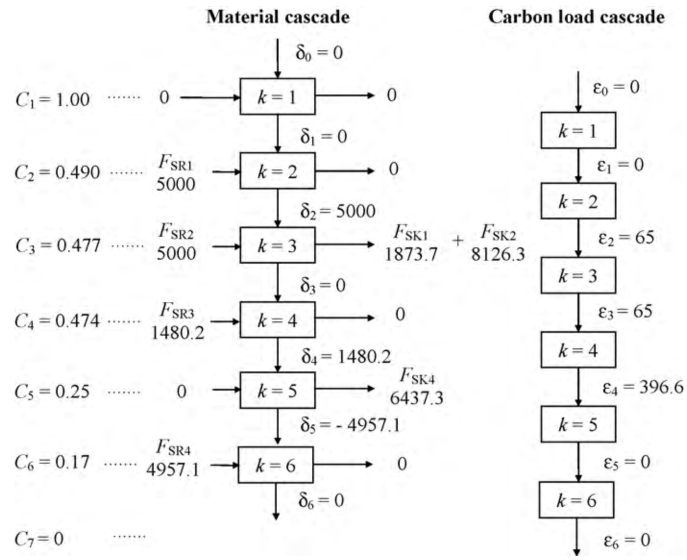

Fig. 7. Biorefinery cascade diagram for Scenario 3 (maximum revenue for cases with multiple feedstocks and products).

require further processing (which also considered as intermediate *p*).

Solving the model with the objective function in Eq. (6), subject to Eqs. (1)–(4) and (7)–(9), yields the results shown in Fig. 5. Note that digestion (SK1), fermentation (SK2) and gasification (SK4) processes are involved in this scenario. As shown in Fig. 5, 2161.6 and 7838.4 kg of biomass are digested into methane and fermented to ethanol, respectively. In this scenario, there are two types of residual biomass (SR2 and SR3) are generated from digestion and fermentation processes. Based on Eq. (7) and Table 1, flow of SR2 and SR3 are determined as 1707.7 and 4781.4 kg respectively (see Fig. 5).

In addition, the maximum revenue target is found to be $ 2953 when 10,000 kg of biomass is processed. Based on the optimised model, 2116.4 kg of ethanol and 317.8 kg of methane from fermentation and digestion processes, respectively, are taken as final products. Meanwhile, 6489.1 kg of biomass residues from both processes are gasified to 1168 kg of syngas, and then further converted to 1051.2 kg of biofuel via Fischer–Tropsch process. The network design for Scenario 2 is shown in Fig. 6. As in the previous scenario, the unrecovered waste streams are neglected and not included in Fig. 6. It is notable that the network design of Scenario 2 is different from Scenario 1. As shown in Fig. 6, an additional process (digestion) is used to produce methane which is not found in Scenario 1 (Fig. 4). Note also that the allocation of materials (biomass and intermediate) in network design of Scenario 2 (Fig. 6) is different from the Scenario 1 (Fig. 4). Thus, based on different optimisation objective, alternative network design of an integrated biorefinery is obtained.

4.3. Scenario 3: Maximum revenue for cases with multiple feedstocks and products

In Scenario 2, single feedstock (biomass) is used to produce multiple products and an integrated biorefinery with maximum revenue is synthesized. In this scenario, the case study is further analysed for multiple feedstocks. Two types of biomass (energy crop, SR1 and wood waste, SR2) are to be given in Table 4. Based on the ultimate analysis, the carbon fraction of SR1 and SR2 are calculated as 0.477 and 0.490 respectively. Note that similar process

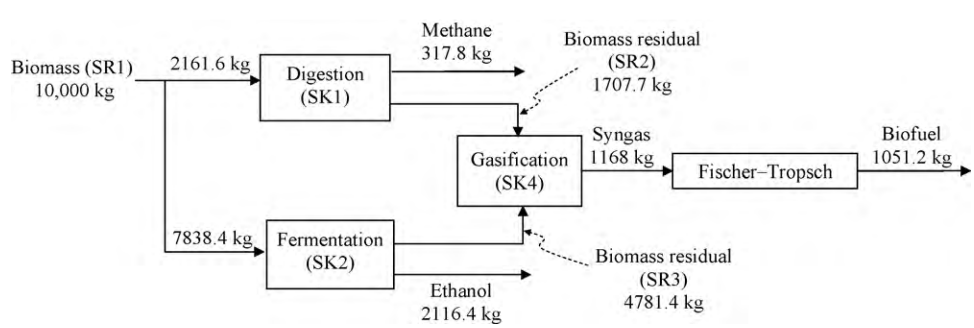

Fig. 6. Network design for Scenario 2.

Table 4
Hypothetical case study for Scenario 3.

Source		Available source (kg)	Carbon fraction (C_i)	Sink		Minimum requirement of carbon fraction (C_j^{min})
SR1	Wood waste	5000	0.490	SK1	Digestion	0.477
SR2	Energy crop	5000	0.477	SK2	Fermentation	0.477
SR3	Digested residual biomass	79% inlet biomass to digestion	0.474	SK3	Pyrolysis	0.250
SR4	Fermented residual biomass	61% inlet biomass to fermentation	0.170	SK4	Gasification	0.250

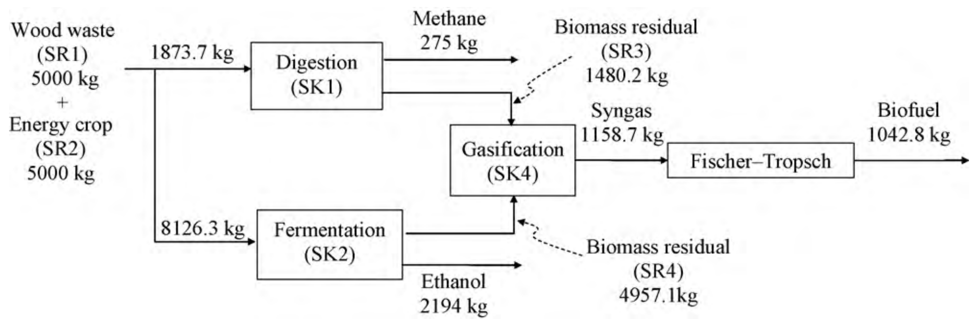

Fig. 8. Network design for Scenario 3.

sinks requirement and residual biomass with previous scenarios are included in Table 4. In addition, similar conversion and revenue data presented in Tables 1 and 3 are also included in this scenario. Since multiple feedstocks are available in this scenario, in order to ensure total consumption of process sink is not higher than available fresh resources (SR1 and SR2), Eq. (10) is included in the model.

$$\Sigma_j F_{SKj} \le F_{SR1} + F_{SR2} \quad (10)$$

Following the similar approach in Scenario 2, the model is solved with the objective function in Eq. (6), subject to the constraints in Eqs. (1)–(4) and (7)–(10), yields the results shown in Fig. 7. Note that similar processes with Scenario 2 (i.e., digestion, SK1; fermentation, SK2 and gasification, SK4) are involved. In this scenario (Fig. 7), 1873.7 and 8126.3 kg of biomass (total of SR1 and SR2) are digested into methane and fermented to ethanol via SK1 and SK2 respectively. Based on Table 1, 1480.2 kg of SR3 and 4957.1 kg of SR4 are generated, when 1873.7 and 8126.3 kg of biomass are digested and fermented respectively. The maximum revenue target is located as $ 2962 based on the given wood waste and energy crop. In addition, 2194 kg of ethanol and 275 kg of methane are produced from fermentation and digestion processes are taken as final products. Meanwhile, all residual biomass from SK1 and SK2 (6437.3 kg) are gasified to 1168 kg of syngas, and then further converted to 1042.8 kg of biofuel via Fischer–Tropsch process. The network design for the case study is shown in Fig. 8. Note that network configuration for this scenario is similar with Scenario 2 (Fig. 6).

It is worth mentioning that the presented values in Tables 1–4 may be vary based on market price, advancement of technologies and various operating condition as well as type of feedstocks. Besides, price fluctuations and feedstock quality variations are bound to be encountered in biomass supply chains. Hence, with such variations and uncertainties, the production and revenue targets as well as network design may change. However, the proposed automated targeting can be easily revised and formulated to locate the targets and identify processes that involved in the integrated biorefinery. In the future work, sensitivity analysis of abovementioned variations is to be considered to synthesize a robust and flexible integrated biorefinery.

5. Conclusion

In this work, an automated targeting approach for finding maximum biofuel production and revenue targets of an integrated biorefinery is presented. These targets can be found prior to detailed process network design, which is essential for gaining insight into process bottlenecks. Besides, the network design of an integrated biorefinery that achieves the targets is also can be determined from the proposed approach. In addition, the proposed approach can be easily revised and formulated to handle uncertainties in feedstock quality, market conditions or process yields. Further work is still needed, to develop a unified approach to design a robust and flexible integrated biorefinery that handle different types of feedstock. In addition, extension of current model to account for seasonality and supply chain of biomass is to be considered.

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