Clean Techn Environ Policy (2013) 15:783–799
DOI 10.1007/s10098-013-0582-x

ORIGINAL PAPER

Systematic approach for conceptual design of an integrated biorefinery with uncertainties

Mei Chee Tang · Markus W. S. Chin · King Ming Lim · Yee San Mun · Rex T. L. Ng · Douglas H. S. Tay · Denny K. S. Ng

Received: 29 October 2012 / Accepted: 18 January 2013 / Published online: 5 March 2013

Abstract The objective of this work is to present a systematic approach for conceptual design of an integrated biorefinery with maximum economic potential accounting for the predefined uncertainties in energy economics. Various parameters commencing from raw biomass feedstock, desired end products, to market price trend, technological constraints and system uncertainties at multiperiods are to be considered. A structural framework, integrated biorefinery pathway map which embeds and interconnects the latest processing technologies is first developed. Then, a robust optimisation model is adopted to determine the optimum network which handles the predefined sets of uncertainties in energy economics. To illustrate the proposed approach, a case study with two different scenarios of uncertainties is solved. Furthermore, a sensitivity analysis is also performed to identify the critical parameters of an integrated biorefinery.

Keywords Biofuel · Design · Integrated biorefinery · Robust optimisation · Uncertainties

M. C. Tang · M. W. S. Chin · K. M. Lim · Y. S. Mun · R. T. L. Ng · D. H. S. Tay · D. K. S. Ng (✉)
Department of Chemical and Environmental Engineering, Centre of Excellence for Green Technologies, University of Nottingham, Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
e-mail: Denny.Ng@nottingham.edu.my

M. C. Tang
e-mail: michelletmc89@gmail.com

M. W. S. Chin
e-mail: mission_my_vision@hotmail.com

K. M. Lim
e-mail: prestonlkm@hotmail.com

Y. S. Mun
e-mail: yeesan.mun@gmail.com

R. T. L. Ng
e-mail: ngtonglip@gmail.com

D. H. S. Tay
e-mail: taydouglas@yahoo.com

R. T. L. Ng
GGS Eco Solutions Sdn Bhd, Wisma Zelan, Suite G.12A & 1.12B, Ground Floor, No. 1, Jalan Tasik Permaisuri 2, Bandar Tun Razak, Cheras, 56000 Kuala Lumpur, Malaysia

List of Symbols

Abbreviations

Btu	British thermal units
$C_nH_mO_p$	C—carbon atom, H—hydrogen atom, O—oxygen atom
CRPM	Chemical reaction pathway map
DEE	Diethyl ether
DME	Dimethyl ether
DTBG	Di-*tert*-butyl ether of glycerol
ETBE	Ethyl-*tert*-butyl ether
FAEE	Fatty acid ethyl esters
FAME	Fatty acid methyl esters
FT diesel	Fischer–Tropsch diesel
HMF	Hydroxymethylfurfural
IBPM	Integrated biorefinery pathway map
MINLP	Mixed-integer non-linear programming
MSW	Municipal solid waste
RMG	Renewable methane gas
RNFA	Reaction network flux analysis
TTBG	Tri-*tert*-butyl ether of glycerol
2015EP	EP achieved under the portfolio of raw biomass feedstock supply in year 2015
2016EP	EP achieved under the portfolio of raw biomass feedstock supply in year 2016

2017EP EP achieved under the portfolio of raw biomass feedstock supply in year 2017
2018EP EP achieved under the portfolio of raw biomass feedstock supply in year 2018
2019EP EP achieved under the portfolio of raw biomass feedstock supply in year 2019
2020EP EP achieved under the portfolio of raw biomass feedstock supply in year 2020
2015/2016EP EP achieved under the portfolio of raw biomass feedstock supply in year 2015 or 2016
2018/2019EP EP achieved under the portfolio of raw biomass feedstock supply in year 2018 or 2019

Sets

b Index for processing technology on biogas platform
c Index for processing technology on carbon-rich chains platform
i Index for raw biomass feedstock
j Index for bioprecursor
h Index for biorefinery platform
k Index for intermediate
k' Index for intermediate other than k
l_1 Index for first reactant in the same processing technology w
l_2 Index for second reactant in the same processing technology w
n Index for special case
p Index for final product
q Index for uncertainty set
s Index for processing technology on sugar platform
t Index for processing technology on thermochemical platform
v Index for conversion operators
w Index for same processing technology

Parameters

C_i^{Bio} Cost of raw biomass feedstock i
C_p^{Fresh} Purchase price of product p
C_p^{Prod} Market price of the final product p
$F_i^{\text{Available}}$ Available supply raw biomass feedstock i
F_i^{Demand} Market demand of product p
n_1 Total number of components in raw biomass feedstock layer in Fig. 1
n_2 Total number of components in bioprecursor layer in Fig. 1
n_3 Total number of components in intermediate layer in Fig. 1
n_4 Total number of components in secondary intermediate layer in Fig. 1
n_5 Total number of components in product layer in Fig. 1
n_6 Total number of components in conversion layer in Fig. 1
x_{ij} Conversion of raw biomass feedstock i to bioprecursor j
$x_{sk}, x_{sk'}$ Yield of chemical reaction in conversion operators of sugar platform
$x_{tk}, x_{tk'}$ Yield of chemical reaction in conversion operators of thermochemical platform
$x_{bk}, x_{bk'}$ Yield of chemical reaction in conversion operators of biogas platform
$x_{ck}, x_{ck'}$ Yield of chemical reaction in conversion operators of carbon-rich chains platform
z Very small real number close to 0
α Probability of occurrence
α_q Probability of occurrence of different uncertainty sets q

Variables

EP Economic potential
F_i^{Bio} Flow rate of raw biomass feedstock i
F_j^{Comp} Flow rate of bioprecursor j
F_h^{Plat} Flow rate of biorefinery platform h
F_k^{Int} Flow rate of intermediate k
F_p^{Prod} Flow rate of final product p
F_p^{Fresh} Flow rate of fresh product p to be purchased
f_{ij} Splitting of raw biomass feedstock i to bioprecursor j
f_{jh} Splitting of bioprecursor j to biorefinery platform h
f_{hs} Splitting of component from platform h to initial feed of processing technology s
f_{ht} Splitting of component from platform h to initial feed of processing technology t
f_{hb} Splitting of component from platform h to initial feed of processing technology b
f_{hc} Splitting of component from platform h to initial feed of processing technology c
f_{ks} Splitting of intermediate k to initial feed of processing technology s
f_{kt} Splitting of intermediate k to initial feed of processing technology t
f_{kb} Splitting of intermediate k to initial feed of processing technology b
f_{kc} Splitting of intermediate k to initial feed of processing technology c
$f_{k's}$ Splitting of intermediate k' to initial feed of processing technology s
$f_{k't}$ Splitting of intermediate k' to initial feed of processing technology t
$f_{k'b}$ Splitting of intermediate k' to initial feed of processing technology b
$f_{k'c}$ Splitting of intermediate k' to initial feed of processing technology c
f_{lw}^1 Flow rate of first reactant l_1 in the same processing technology w

f_{lw}^{2} Flow rate of second reactant l_2 in the same processing technology w

$f_{lw}^{2'}$ Available flow rate of second reactant l_2 in the same processing technology w

$R_{ll'}$ Flow ratio of second reactant l_2 to first reactant l_1 in the same processing technology w

I_n 0–1 binary variable

Introduction

Accounting for the global economic growth and population growth, world energy demand is expected to increase by 49 % projected from 2007 to 2035 (EIA 2010). The projection indicates that global energy consumption will rise from 496 quadrillion British thermal units (Btu) in 2007 to 739 quadrillion Btu in 2035 (EIA 2010). Despite the escalation of energy consumption, worldwide energy is still dependent on limited resources, i.e. fossil fuels which virtually enable all economic domains, wide-ranging from industry, electricity generation to transportation (IEA 2008). Due to the depletion of fossil fuels resources, rise of issues regarding environment, climate change, energy security as well as rural prosperity have captivated the attention of the world. These pressures exert a force to exhibit a transformation towards energy generation that utilises a portfolio of sustainable technologies which mitigate greenhouse gases. In this context, biomass has been identified as one of the viable renewable energy sources. The derived biofuels and biochemical products from biomass have lower inherent carbon footprint (up to 52 %) compared to equivalent energy obtained from conventional fossil fuels (EIA 2019).

In general, biomass can be defined as any organic or inorganic material in which solar energy is or has been stored. It can be briefly represented as $C_nH_mO_p$ (Ng et al. 2009a, Ng 2010). Biomass may vary depending on the different number of atoms, n, m and p of carbon (C), hydrogen (H) and oxygen (O), respectively. As shown in the literature, biomass can be converted into value-added products such as biofuels and biochemical products in processing facilities known as biorefineries. Although biorefineries provide a promising future for fuels and energy, the world is still facing a major challenge in improving the overall performance of biorefineries. Therefore, there is a need to develop a systematic approach to design such systems. In order to facilitate the material and energy recovery, the concept of integrated biorefinery is proposed (Fernando et al. 2006). An integrated biorefinery is a crucial development of biorefinery where several conversion technologies are integrated to reduce the overall cost while increasing the flexibility in product generation (Fernando et al. 2006).

National Renewable Energy Laboratory (NREL) of the United States had categorised the expanded established technologies of biorefineries into five platforms, namely sugar–lignin platform, thermochemical platform, biogas platform, carbon-rich chains platform and plant products platform (NREL 2002). Sugar–lignin platform involves the fermentation of sugars extracted from raw biomass feedstock to produce fuels. Meanwhile, thermochemical platform uses thermal energy to convert biomass into products and energy. Examples of thermochemical platforms are gasification, pyrolysis, combustion and direct liquefaction. Biogas platform focuses on the decomposition of raw biomass feedstock with natural microorganisms in closed

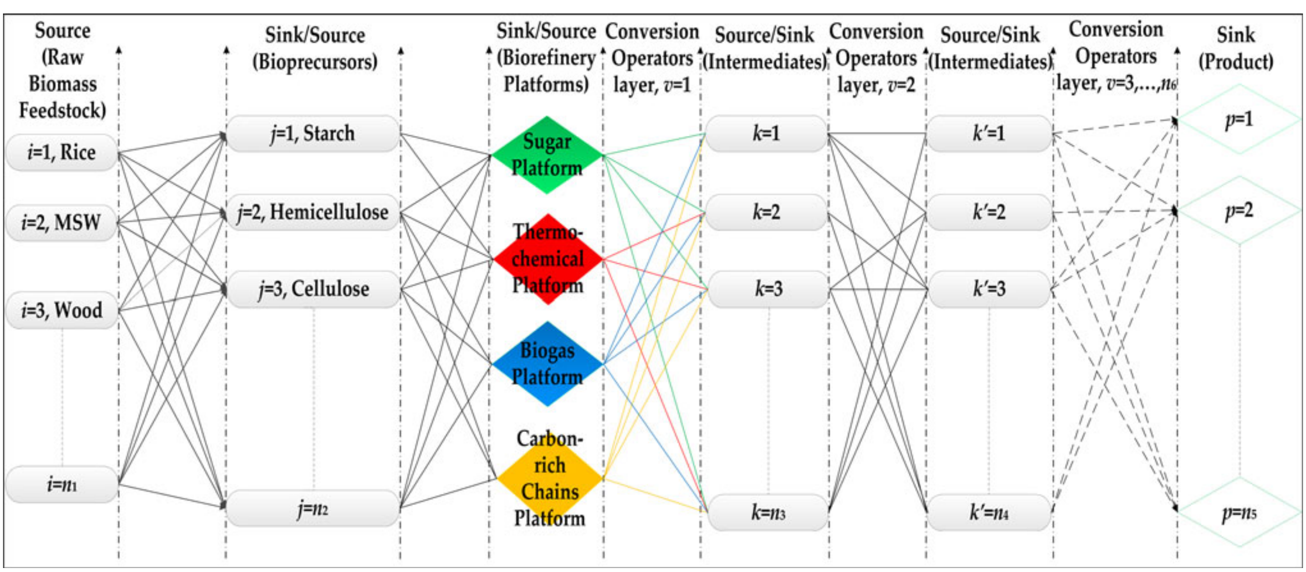

Fig. 1 Superstructure of the Robust MINLP model

tanks (anaerobic digesters) to produce methane and carbon dioxide. Besides, carbon-rich chains platform produces biodiesel (fatty acid methyl esters, FAME) which appears as an important commercial substitute for petroleum diesel through transesterification of vegetable oil or animal fat. Finally, plant products platform develops plant strains that produce greater amounts of desirable feedstock using selective breeding and genetic engineering (NREL 2002).

Since there is substantial number of process alternatives, systematic screening for synthesis of integrated biorefinery is needed. Various systematic tools have been presented to address the design problem covering from screening of chemical reaction (Ng et al. 2009a; Voll and Marquardt 2012; Hechinger et al. 2010) to selection of technologies (Bao et al. 2011), product allocation (Sammons et al. 2008; Mansoornejad et al. 2010) and conceptual design (Kokossis and Yang 2010; Tay et al. 2011a, b; Pham and El-Halwagi 2012). Ng et al. (2009a) presented a quick screening tool, known as chemical reaction pathway map (CRPM), for synthesis of reaction pathway from biomass towards desired products via numerous organic and inorganic chemical reaction conversions. Besides, a rapid screening method known as reaction network flux analysis (RNFA), which systematically identifies alternative reaction pathways prior to analysing and ranking the alternatives, is also introduced (Voll and Marquardt 2012). Hechinger et al. (2010) further extended RNFA to identify and assess production pathways. Most recently, Chemmangattuvalappil and Ng (2013) presented a novel methodology which integrates the molecular design approach with reaction pathway synthesis for design of an integrated biorefinery which produces products that fulfil customer needs.

On the other hand, a mathematical optimisation framework for the evaluation of alternative product allocation to maximise economic performance is presented (Sammons et al. 2008). Mansoornejad et al. (2010) later presented a large block analysis for design of product/process portfolio and supply chain. Meanwhile, Kokossis and Yang (2010) developed a combination of multi-scale formulations with multi-stage problem to solve the complex problem of synthesized biorefineries. Later, Tay et al. (2011a) presented a modular optimisation strategy, which breaks a large optimisation problem into small parts, for synthesis of gasification-based integrated biorefinery. Bao et al. (2011) presented a systematic approach based on technology pathways to generate intermediate chemicals, and then using a tree-branching and searching technique to determine optimum pathways. Recently, Pham and El-Halwagi (2012) introduced 'forward–backward' approach for synthesis of biorefinery. Martin and Grossmann (2012) reviewed the recent works on the integration of production processes, including first, second and third generation of biofuels.

In order to synthesize a sustainable integrated biorefinery, various sustainable measurements, such as economic performance, environmental impact etc. should be taken into consideration simultaneously. Tan et al. (2009) presented a multi-objectives approach for determining the optimal bioenergy system configuration based on the given targets for land use, water and carbon footprint metrics. Besides, fuzzy optimisation model is also extended to synthesize an integrated biorefinery which maximises economic performance along with minimum environmental impacts (Tay et al. 2011b; Shabbir et al. 2012). Recently, Kasivisvanathan et al. (2012) presented a systematic approach for retrofitting a palm oil mill into a sustainable palm oil-based integrated biorefinery. Later, Ng et al. (2012) presented a modular optimisation approach in solving simultaneous process synthesis and heat and power integration problem in an integrated palm oil-based biorefinery. Most recently, Kasivisvanathan et al. (2013) presented a simple mixed-integer linear programming (MILP) model to determine optimal process adjustments due to partial energy systems inoperability.

Other than the mathematical optimisation approaches, Ng (2010) extended the pinch-based automated targeting approach (Ng et al. 2009b, c, 2010) to determine the maximum biofuel production and revenue levels in synthesizing an integrated biorefinery prior to detailed design. Later, Tay and Ng (2012) further extended the approach into consideration of multiple process parameters. On the other hand, Tay et al. (2011c) also presented a graphical approach which was based on C–H–O ternary diagram for synthesis of gasification-based integrated biorefinery.

It is noted that most of the previous works on synthesis of integrated biorefinery do not consider the effects of uncertainties during the early design stage. However, in view of the current volatile market environment and continuous change in consumers' demand, the impact of uncertainties should be considered. Tay et al. (2012) presented robust optimisation approach for synthesis of integrated biorefineries with supply and demand uncertainties. However, the fluctuation or uncertainties of feedstock and product costs is not considered in previous work, which is the subject of this work.

As shown in the literature (Leiras et al. 2010a), robust optimisation is identified as one of the promising approaches to handle uncertainties. Al-Qahtani and Elkamel (2008) presented a robust MILP model to undertake both long-term uncertainties of raw biomass feedstock cost, demand and price of final products. According to Leiras et al. (2010a, b), robust optimisation focuses on models that ensure solution feasibility given the possible outcomes of uncertain parameters. Under this approach, the decision maker is willing to accept a suboptimal solution for the nominal values in order to ensure that the solution remains feasible and near optimal when the data change (Leiras et al. 2010a, b). Based on the advantageous robust optimisation, it is adapted in this work to synthesize a flexible network configuration of an integrated biorefinery that is able to handle the predefined uncertainties.

The objective of this paper is to synthesize an integrated biorefinery with maximum economic potential (EP) accounting for the predefined uncertainties. In this work, various uncertainties such as supply of raw biomass feedstock, demand for desired end products, market price, technological constraints and system uncertainties at multi-periods are to be considered. To address the problem, a graphical framework that analyses and categorises the current potential conversion technologies under four biorefinery platforms is first developed. Next, robust optimisation model is developed based on the graphical framework to determine the flexible network with maximum economic performance. To illustrate the proposed approach, a case study is presented.

Problem statement

The superstructure for the allocation of raw biomass feedstock towards the desired product portfolios is demonstrated in Fig. 1. The synthesis problem of an integrated biorefinery to be addressed is defined as follows: Given a set of raw biomass feedstock $i \in I$ with a flow rate of F_i^{Bio} which can be pre-treated at the conversion of x_{ij} to extract bioprecursor $j \in J$. The total flow rate of extracted bioprecursor j is given as F_j^{Comp}. The bioprecursor j is then further processed via different biorefinery platforms $h \in H$. Based on literature review, four biorefinery platforms h are taken into consideration in this work, which are sugar platform $s \in S$, thermochemical platform $t \in T$, biogas platform $b \in B$ and carbon-rich chains platform $c \in C$. Each platform consists of multiple processing technologies to convert bioprecursor j into various intermediate $k \in K$ at given conversion of x_{sk}, x_{tk}, x_{bk} and x_{ck}, for sugar platform s, thermochemical platform t, biogas platform b and carbon-rich chains platform c, respectively. The total flow rate of intermediate is then determined as F_k^{Int}. Intermediates k can be further processed via various processing technologies in order to produce other intermediate $k' \in K'$at a conversion of $x_{sk'}$, $x_{tk'}$, $x_{bk'}$ and $x_{ck'}$. The intermediate $k' \in K$ can either be sold directly or further processed into final product $p \in P$. The total final product flow rate is given as F_p^{Prod}.

In this work, the optimisation objective is set to maximise the EP of an integrated biorefinery system. EP is a measure of economic performance at the preliminary design stage (Douglas 1985) and it is simple to be determined. The EP of the synthesized integrated biorefinery is determined by the total revenue of sold products $(F_i^{\mathrm{Bio}} C_i^{\mathrm{Bio}})$ deducted from the total cost of raw biomass feedstock $(F_i^{\mathrm{Bio}} C_i^{\mathrm{Bio}})$. In order to consider the predefined uncertainties, probability of occurrence, α_q for different uncertainty sets $q \in Q$ is introduced in synthesizing an integrated biorefinery. To facilitate the formulation of robust optimisation for the synthesis task, a general graphical representation, known as integrated biorefinery pathway map (IBPM), is first developed for illustration.

Integrated biorefinery pathway map (IBPM)

In this work, a novel graphical representation, IBPM which categorises the processing technologies into four prominent platforms and serves as a framework of the generic modelling tool is first developed. Below is the detailed procedure for the development of IBPM:

1. A literature survey is carried out to identify the promising raw biomass feedstock.
2. The characteristics/bioprecursors of the identified raw biomass feedstock, such as starch, hemicellulose, cellulose, lignin, oil/lipids and protein, are identified based on experiment or literature.
3. The processing biorefinery platforms (i.e. sugar platform, thermochemical platform, biogas platform and carbon-rich chains platform) which are able to process respective bioprecursors are determined.
4. Based on the four platforms, all available technologies to convert raw biomass feedstock into intermediates/products are compiled. Besides, the information on process conversion and operating condition is also collected. The selection of technologies focused only on the technology pathways that produce the valuable intermediates (e.g. syngas) and high demand products (e.g. biodiesel, bioethanol) with the highest yield.

Following the proposed procedure, IBPM which based on five biomasses (i.e. rice husk, municipal solid waste (MSW), wood waste, sugar cane bagasse and palm biomass) is constructed and shown in Fig. 2. Note that developed IBPM in Fig. 2 is different from Fig. 1 because the intermediate layer $k \in K$, secondary intermediate layer $k' \in K'$ and product layer $p \in P$ are not separated but merged into a single intermediate and product layer. Note that such design enables the integration networks within four platforms. Based on Fig. 2, the superstructure consists of four layers, i.e. raw biomass feedstock i, bioprecursor j, biorefinery platform h, and intermediate k, and product p. As shown, rice husk, MSW, wood waste, sugar cane bagasse and palm biomass are identified as raw biomass feedstock i. The raw biomass feedstock i was pre-treated to extract useful bioprecursor j (e.g. starch, hemicellulose, cellulose, lignin, triglycerides and protein) for biorefinery processing. Table 1 shows the bioprecursor of the

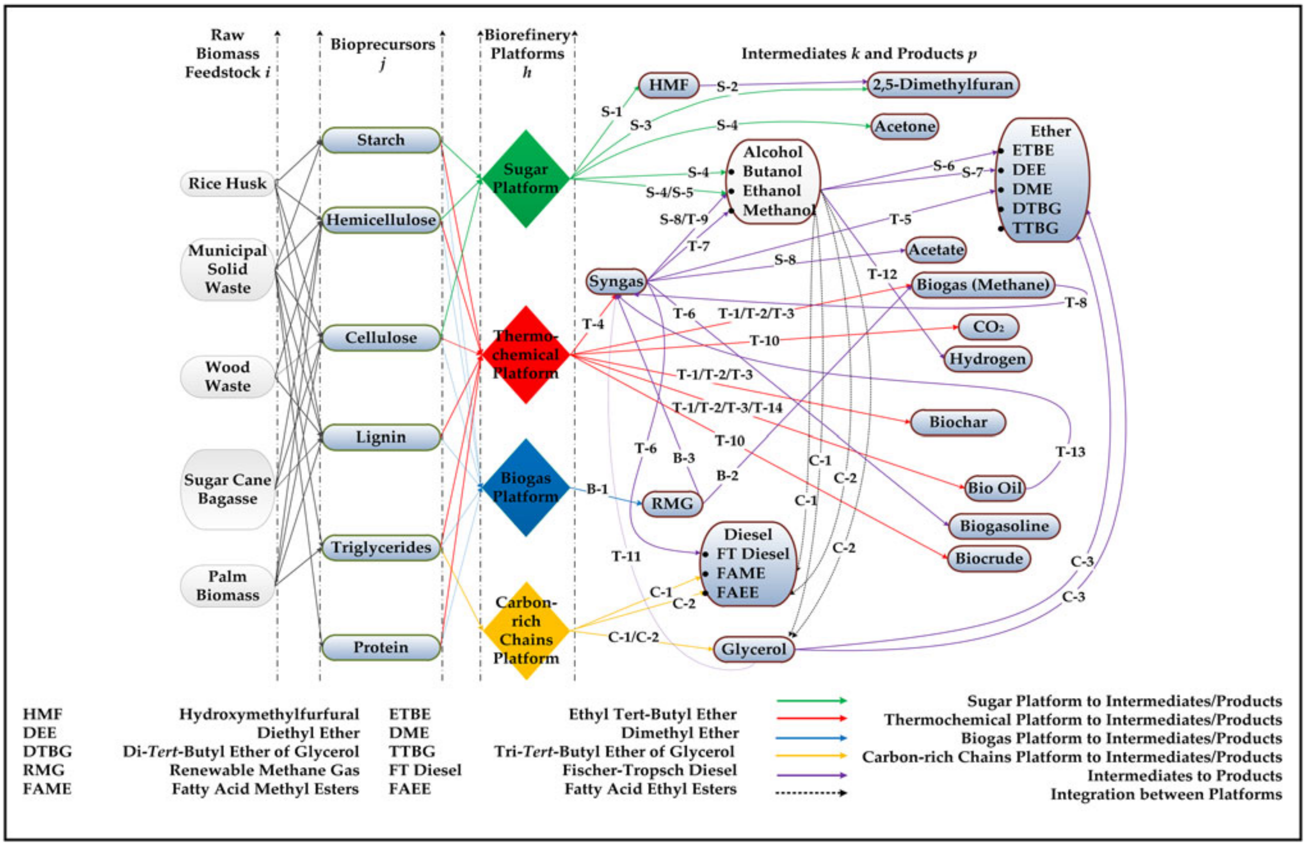

Fig. 2 IBPM

respective compositions of the five raw biomass feedstocks. The bioprecursor *j* are then sent to relevant biorefinery platform *h* for conversion to intermediate *k* via different processing technologies *s*, *t*, *b* and *c*, where *s*, *t*, *b* and *c* denote the processing technologies on sugar platform, thermochemical platform, biogas platform and carbon-rich chains platforms, respectively. The intermediates *k* are either further processed to secondary intermediate k' or sold as the end product *p*.

For better illustration of the superstructure of IBPM, an example of the technology pathway towards the production of ethanol in Fig. 2 is discussed as below. The sugar platform is the sink of bioprecursors such as starch, hemicellulose and cellulose. These three bioprecursors would be processed via two processing technologies S-4 and S-5 to produce ethanol as primary intermediate *k*. Ethanol could be further processed to secondary intermediate k' such as ethyl-*tert*-butyl ether (ETBE) (via S-6), diethyl ether (DEE) (via S-7), fatty acid ethyl esters (FAEE), and glycerol (via C-2). Ethanol could be sold as the end product *p* as well. Nevertheless, the production of ethanol was not restricted to only sugar platform. Integration within platforms enabled ethanol being produced via thermochemical platform and being further processed to hydrogen via pathway T-12.

All the processing technologies on the four biorefinery platforms, including integrated pathways are listed in Table 2, with yields and operating conditions specified. Based on all the literature review (Dry 1996; Struis et al. 1996; Yang et al. 2000; Chynoweth et al. 2001; Chen et al. 2003, 2010; Ji-Hyun et al. 2004; Paolo et al. 2004; Barnard et al. 2007; Varisli et al. 2007; Melero et al. 2008; Demirbas 2009; Favre et al. 2009; Peter 2009; Zhang et al. 2009; Harun and Danquah 2010; Kan et al. 2010; Kim et al. 2010; Krár et al. 2010; Kwak et al. 2010; Mariano et al. 2010; Munasinghe and Khanal 2010; Thananatthanachon and Rauchfuss 2010; Pompeo et al. 2010; Pöschl et al. 2010; Yang et al. 2011), the conversion information of the technologies are summarised in Table 2. It will then serve as the database of the optimisation model and solved in the presented case study.

Formulation of mathematical model

The optimisation of biorefinery network design involves a broad range of aspects varying from material balance to economic analysis to make strategic selection of processes and production capacities. The general deterministic model framework proposed in this paper follows the source–sink

Table 1 Biomass compositions of each raw biomass feedstock

Raw biomass feedstock	Biomass compositions as fraction						
	Starch	Hemicellulose	Cellulose	Lignin	Triglycerides	Protein	Waste
Rice husk	0.000	0.357	0.320	0.223	0.000	0.000	0.100
Municipal solid waste (MSW)	0.067	0.134	0.134	0.134	0.067	0.067	0.397
Wood waste	0.000	0.306	0.395	0.275	0.000	0.000	0.024
Sugar cane bagasse	0.000	0.250	0.420	0.200	0.000	0.000	0.130
Palm biomass	0.000	0.232	0.384	0.267	0.117	0.000	0.000

approach stated by El-Halwagi (2006). The foregoing optimisation formulations are derived equality or inequality constraints from the IBPM framework in Fig. 2 to build the generic mixed-integer non-linear programming (MINLP) model.

The raw biomass feedstock i with the flow rate F_i^{Bio} is split into bioprecursor j with the flow rate of f_{ij}:

$$F_i^{\text{Bio}} = \sum_j^J f_{ij} \quad \forall i \tag{1}$$

The raw biomass feedstock i are converted to bioprecursor j with the conversion of x_{ij}. The total production rate of bioprecursor j is given as:

$$F_j^{\text{Comp}} = \sum_i^I f_{ij} x_{ij} \quad \forall j \tag{2}$$

The total production rate of bioprecursor j can be split into different biorefinery platforms h with the flow rate of f_{jh}:

$$F_j^{\text{Comp}} = \sum_h^H f_{jh} \quad \forall j \tag{3}$$

The total flow rate of each biorefinery platform h, (F_h^{Plat}) is written as:

$$F_h^{\text{Plat}} = \sum_j^J f_{jh} \quad \forall h \tag{4}$$

The splitting of each biorefinery platform h with the flow rate of F_h^{Plat} to processing technologies of s, t, b and c for production of intermediate k:

$$F_h^{\text{Plat}} = \sum_s^S f_{hs} + \sum_t^T f_{ht} + \sum_b^B f_{hb} + \sum_c^C f_{hc} \quad \forall h \tag{5}$$

The total flow rate of intermediate k (F_k^{Int}) is determined by converting the splitting flow rate of each biorefinery platform h at the conversion rate of x_{sk}, x_{tk}, x_{bk}, x_{ck} , respectively. Take note that intermediate k can be also produced from secondary intermediate k' via processing technologies s, t, b and c at the conversion of $x_{sk'}, x_{tk'}, x_{bk'}, x_{ck'}$. The total flow rate of intermediate k $\left(F_k^{\text{Int}}\right)$ is written as:

$$F_k^{\text{Int}} = \sum_s^S f_{hs} x_{sk} + \sum_t^T f_{ht} x_{tk} + \sum_b^B f_{hb} x_{bk} + \sum_c^C f_{hc} x_{ck} + \sum_s^S f_{k's} x_{sk'} + \sum_t^T f_{k't} x_{tk'} + \sum_b^B f_{k'b} x_{bk'} + \sum_c^C f_{k'c} x_{ck'} \quad k \neq k' \quad \forall k \tag{6}$$

The splitting of intermediate k with the flow rate of F_k^{Int} to processing technologies s, t, b and c for the production of secondary intermediate k' or product p. Take note that intermediate k could remain as final product p:

$$F_k^{\text{Int}} = \sum_s^S f_{ks} + \sum_t^T f_{kt} + \sum_b^B f_{kb} + \sum_c^C f_{kc} + F_p^{\text{Prod}} \quad p = k \quad \forall k \tag{7}$$

The total flow rate of final product p:

$$F_p^{\text{Prod}} = \sum_s^S f_{hs} x_{sk} + \sum_t^T f_{ht} x_{tk} + \sum_b^B f_{hb} x_{bk} + \sum_c^C f_{hc} x_{ck} + \sum_s^S f_{ks} x_{sk} + \sum_t^T f_{kt} x_{tk} + \sum_b^B f_{kb} x_{bk} + \sum_c^C f_{kc} x_{ck} \quad \forall p. \tag{8}$$

In special case n where two reactants, l_1 and l_2, are involved in the same processing technology w $(w \in S, T, B, C)$, additional equations (Eqs. 9–11) are introduced to ensure that sufficient amount of both reactants and specific ratio are met to react simultaneously. For example, in order to produce methanol from syngas, the ratio between hydrogen and carbon monoxide has to be greater than two ($H_2/CO \geq 2$) (Ciferno and Marano 2002). Binary variable, I_n is used to denote the existence (or absence) of the second reactant in the process. When first reactant, l_1 with the flow rate of f_{lw}^1 presents in an integrated biorefinery system, $I_n = 1$, the second reactant, l_2 with the flow rate of f_{lw}^2 is available for conversion to intermediate, k and/or final product p; vice versa, when first reactant, l_1 is absent, $f_{lw}^1 = 0$, the binary variable $I_n = 0$. Thus, the second reactant, l_2 will not exist and flow rate of $f_{lw}^2 = 0$, the reaction will not occur.

Table 2 IBPM table

Label	From	Pathway	To	Yield (% of initial convertible feed)	Reference
S-1	Sugar platform	Dehydration	5-Hydroxymethylfurfural (HMF)	62.3 %	Yang et al. (2011)
S-2	HMF	Hydrogenation	2,5-Dimethylfuran	95 %	Thananatthanachon and Rauchfuss (2010)
S-3	Sugar platform	One-pot synthesis	2,5-Dimethylfuran	27.5 %	Thananatthanachon and Rauchfuss (2010)
S-4	Sugar platform	ABE fermentation	Acetone	Ratio (a:b:c)	Mariano et al. (2010)
			Butanol	14.5 %:27.4 %:2.3 %	
			Ethanol		
S-5	Sugar platform	Anaerobic fermentation	Ethanol	52 %	Harun and Danquah (2010)
S-6	Ethanol	Etherification	Ethyl-*tert*-butyl ether (ETBE)	40 %	Yang et al. (2000)
S-7	Ethanol	Dehydration	Diethyl ether	30 %	
S-8	Syngas	Fermentation	Ethanol	Ratio (a:b)	Munasinghe and Khanal (2010)
			Acetate	94.1 %:5.9 %	
T-1	Thermochemical platform	Slow pyrolysis	Biochar	Ratio (a:b:c)	
			Bio oil(tar)	32.6 %:47.2 %:20.2 %	
			Biogas		
T-2	Thermochemical platform	Intermediate pyrolysis	Biochar	Ratio (a:b:c)	Peter (2009)
			Bio oil(tar)	23 %:45 %:32 %	
			Biogas		
T-3	Thermochemical platform	Fast/flash pyrolysis	Biochar	Ratio (a:b:c)	Peter (2009)
			Bio oil(tar)	24 %:64 %:12 %	
			Biogas		
T-4	Thermochemical platform	Gasification	Syngas	39 %	Paolo et al. (2004) (prediction of syngas quality for two stage gasification)
T-5	Syngas	DME synthesis	DME	12.6 %	Ji-Hyun et al. (2004) (DME synthesis from synthesis gas on the admixed catalysts of Cu/ZnO/Al_2O_3 and ZSM-5)
T-6	Syngas	Fischer–Tropsch	Biogasoline	Ratio (a:b)	Dry (1996)
			Biodiesel	45 %:25 %	
T-7	Syngas	Methanol synthesis	Methanol	4.3 %	Struis et al. (1996)
T-8	Thermochemical platform	Steam reforming of methane (SRM)	Syngas	85.3 %	Chen et al. (2003)
			Hydrogen		
			Carbon dioxide or		
			Hydrogen		
			Carbon monoxide		
T-9	Syngas	Catalyzed reaction	Ethanol	13.8 %	Chen et al. (2010)
T-10	Thermochemical platform	Hydrothermal liquefaction	Biocrude	Ratio (a:b:c:d)	Demirbas (2009)
			Gas (>90 % CO_2)	49.5 %:29.7 %	
			Water		
			Dissolved Organic Substance		

Table 2 continued

Label	From	Pathway	To	Yield (% of initial convertible feed)	Reference
T-11	Glycerol	Steam reforming	Syngas H_2 CO CO_2	99.2 %	Pompeo et al. (2010)
T-12	Glycerol	Steam reforming	H_2	100 %	Kwak et al. (2010)
T-13	Bio oil	Gasification	Syngas H_2 CO_2	87.6 %	Kan et al. (2010)
T-14	Carbon-rich chains platform	Hydrotreating	Bio oil	73.9 %	Krár et al. (2010)
B-1	Biogas platform	Anaerobic digestion	Renewable methane gas (RMG) Methane CO_2	36 %	Chynoweth et al. (2001) Pöschl et al. (2010)
B-2	RMG	CO_2 removal	Methane	90 %	Favre et al. (2009)
B-3	RMG	CO_2 reforming/ dry reforming	Syngas H_2 CO	97 %	Zhang et al. (2009)
C-1	Carbon-rich chains platform, methanol	Transesterification	Fatty acid methyl ester (FAME) Glycerol	Ratio (a:b) 93.6 %:5.3 %	Barnard et al. (2007)
C-2	Carbon-rich chains platform, ethanol	Transesterification	Fatty acid ethyl ester (FAEE) Glycerol	Ratio (a:b) 97 %:3 %	Kim et al. (2010)
C-3	Glycerol	Etherification	Di-*tert*-butyl glycerol ether (DTBG) Tri-*tert*-butyl glycerol ether (TTBG)	Ratio (a:b) 54 %:41 %	Melero et al. (2008)

S sugar platform, *T* thermochemical platform, *B* biogas platform, *C* carbon-rich chains platform

$$(z - f_{lw}^{1})(1 - 2I_n) > 0 \quad \forall l \in H, K \quad \forall w \in S, T, B, C \tag{9}$$

$$f_{lw}^{2} = f_{lw}^{2'} I_n \tag{10}$$

$$f_{lw}^{2'} = R_{ll'} f_{lw}^{1} \tag{11}$$

where z is a very small real number close to 0, $f_{lw}^{2'}$ is the available flow rate of second reactant l_2 and $R_{ll'}$ is the flow ratio of the second reactant l_2 to first reactant l_1.

In this work, EP is used to determine feasibility of product portfolios at the preliminary design stage of an integrated biorefinery. The EP is expressed in following equation:

$$\mathrm{EP} = \sum_{p}^{P} F_p^{\mathrm{Prod}} C_p^{\mathrm{Prod}} - \sum_{i}^{I} F_i^{\mathrm{Bio}} C_i^{\mathrm{Bio}} \tag{12}$$

where C_p^{Prod} and C_i^{Bio} are the market price of product p and cost of raw biomass feedstock i, respectively.

As mentioned earlier, an uncertainty parameter would need to be taken into account via pathway configuration presented in IBPM. In this work, the uncertainty sets are considered through a discrete probability distribution with a finite number $q \in Q$ of possible outcomes at different intervals, where q is the number of uncertainty sets (Al-Qahtani and Elkamel 2008). Equation 12 is thus modified as below to create a robust equation:

$$\mathrm{EP} = \sum_{q=1}^{Q} \alpha_q \left[\sum_{p}^{P} F_p^{\mathrm{Prod}} C_p^{\mathrm{Prod}} - \sum_{i}^{I} F_i^{\mathrm{Bio}} C_i^{\mathrm{Bio}} \right] \tag{13}$$

Note that the introduced α_q in Eq. 13 is used to indicate the probability of occurrences α, or uncertainties in different sets q of parameters (e.g. supply trend of raw biomass feedstock, demand trend of biofuel and market price trend of products). In this work, a commercial optimisation software LINGO, version 10, with Global Solver is used to optimise the proposed model. The software uses branch-and-bound (B&B) algorithm that combined with linearisation to find globally optimal solutions in non-linear programming (NLP) and MINLP problems (Gau and Schrage 2003; Lindo Systems, Inc. 2010).

Illustrative case study

To illustrate the proposed approach, a case study is solved. Based on Fig. 2, rice husk, MSW, wood waste, sugar cane bagasse and trash, and palm biomass are taken as the raw biomass feedstocks. To ensure the feed flow rate of raw biomass feedstock to an integrated biorefinery, F_i^{Bio} does not exceed its available supply, $F_i^{\text{Available}}$, Equation 14 is added to the optimisation model.

$$F_i^{\text{Bio}} \leq F_i^{\text{Available}} \quad \forall i \tag{14}$$

On the other hand, the flow rate of product, F_p^{Prod} should exceed the product demand, F_p^{Demand}; thus, additional equation is added.

$$F_p^{\text{Prod}} \geq F_p^{\text{Demand}} \quad \forall p. \tag{15}$$

Note that the available raw biomass feedstock supplies are limited in this case while there is a market demand for the desired biofuels to be fulfilled. Hence, Eq. 8 is modified and F_p^{Fresh} is introduced to represent external supply of products which can be purchased to satisfy the constraints of the product market demand. The modified equation is shown below:

$$\begin{aligned} F_p^{\text{Prod}} = & \sum_s^S f_{hs} x_{sk} + \sum_t^T f_{ht} x_{tk} + \sum_b^B f_{hb} x_{bk} + \sum_c^C f_{hc} x_{ck} \\ & + \sum_s^S f_{ks} x_{sk} + \sum_t^T f_{kt} x_{tk} + \sum_b^B f_{kb} x_{bk} + \sum_c^C f_{kc} x_{ck} \\ & + F_p^{\text{Fresh}} \quad \forall s, t, b, c. \end{aligned} \tag{16}$$

In addition, Eq. 13 is revised by including fresh product to be purchased, F_p^{Fresh} and its purchase price, C_p^{Fresh} to form Equation 17.

$$\text{EP} = \sum_{q=1}^{Q} \alpha_q \left[\sum_p^P \left(F_p^{\text{Prod}} C_p^{\text{Prod}} - F_p^{\text{Fresh}} C_p^{\text{Fresh}} \right) - \sum_i^I F_i^{\text{Bio}} C_i^{\text{Bio}} \right]. \tag{17}$$

In this work, it is assumed that the costs of raw biomass feedstock and the prices of products remained unchanged from 2015 to 2020. The cost and price data of raw biomass feedstocks and products are listed in Table 3. The raw biomass feedstock supply and product demand profiles are divided into four uncertainty sets, as based on yearly portfolio of raw biomass feedstock supply. The supply profile as projected from years 2015 to 2020 is summarised in Table 4. Years with similar raw biomass feedstock supplies would be considered as a singular uncertainty set and assigned a probability of occurrence, α_q. Based on Table 4, each year is assigned a probability of occurrence equally of 0.17 as projected supplies from year 2015 to 2020 are taken into consideration. Note also that both $\alpha_q$of uncertainty sets 1 and 3 are given as 0.33. This is because both sets considered projected supplies for 2 years (year 2015, 2016 and year 2018, 2019 for uncertainty sets 1 and 3, respectively).

Next, four uncertainty sets are further constrained by respective product demand portfolio; however, only three major biofuels: biogasoline, biodiesel (i.e. FAME, FAEE and Fischer–Tropsch (FT) diesel) and bioethanol which cover large shares of global biofuel market are the focal point in all scenarios. Bioethanol and biodiesel (i.e. FAME and FAEE) account for approximately 85 % and 15 % of the global biofuel market, respectively; and there is a rising demand for the development of biogasoline and FT-diesel from non-food biomass (Tramoy 2008). The projected product demand portfolio from years 2015 to 2020 is summarised in Table 5.

In this work, two projected uncertainties are analysed. The first scenario focuses on uncertainties in raw biomass feedstock supply and product market demand; while the second scenario considers uncertainties in product cost with consideration for raw biomass feedstock supply and product market demand. In the first scenario, both uncertainties are considered to investigate their effects on the EP of the proposed integrated biorefinery system. However, the monetary variability is not considered in Scenario 1, which is the subject of Scenario 2. A detailed analysis of product and raw biomass feedstock historical cost data is summarised in Tables 6 and 7. As this scenario is primarily affected by the cost of products, the raw biomass feedstock supply no longer affects the probability distribution. Therefore, the probability distribution in this case study is revised to a general guideline of the possible fluctuation to all product cost based on crude oil price trend. The uncertainty defined in this case study is the inability to determine if crude oil prices will either overshoot or undershoot the mean price. The occurrences for product price overshoot is a measure of number of years at which crude oil prices pass the high upper control limit of US$90 per barrel, and for product price undershoot is a measure of years below the low control limit of US$70 per barrel. Figure 3 shows the trend of crude oil prices from 2000 to 2005. As shown, timeline ranging from 2000 to 2001 shows most prices of the highly demanded biofuels below the low control limit. Meanwhile, timeline ranging from

Table 3 Products market price and raw biomass feedstock cost

Product	Market price (US$/tonne)	Product	Market price (US$/tonne)
Hydroxymethylfurfural (HMF)	508.33	Syngas	1,124.33
2,5-Dimethylfuran	2,260	Carbon dioxide (CO_2)	75
Acetone	393.67	Hydrogen	4,000
Butanol	1,223	Biogas	251.67
Ethanol	1,098.67	Biochar	70
Methanol	221.33	Bio Oil	1,289
Ethyl-*tert*-butyl ether (ETBE)	1,005.33	Fischer–Tropsch (FT) diesel	1,000
Diethyl ether (DEE)	377.33	Biogasoline	822.67
Dimethyl ether (DME)	377.33	Biocrude	360
Di-*tert*-butyl ether of glycerol (DTBG)	166.67	Fatty acid methyl esters (FAME)	1,019.67
Tri-*tert*-butyl ether of glycerol (TTBG)	166.67	Fatty acid ethyl esters (FAEE)	1,019.67
Acetate	7,900	Renewable methane gas (RMG)	251.67
Glycerol	220.33		
Raw Biomass Feedstock	**Cost (US$/tonne)**	**Raw Biomass Feedstock**	**Cost (US$/tonne)**
Rice husk	300	Sugar cane bagasse	459.33
Municipal solid waste (MSW)	333.33	Palm biomass	443.33
Wood waste	450		

Table 4 Projected supply of raw biomass feedstock

Uncertainty set	Probability of occurrence, α_q	Rice husk	MSW	Wood waste	Sugar cane bagasse	Palm biomass
		(million tonne/year)				
1 (year 2015/2016)	0.33	0.36	5.80	2.20	1.60	34.60
2 (year 2017)	0.17	0.40	6.40	2.20	1.60	38.40
3 (year 2018/2019)	0.33	0.50	7.10	2.50	1.50	42.70
4 (year 2020)	0.17	0.50	7.10	3.00	1.30	47.40

Table 5 Projected demand of bioethanol, biodiesel and biogasoline

Uncertainty set	Probability of occurrence, α_q	Bioethanol (million tonne per year)	Biodiesel	Biogasoline
1 (year 2015/2016)	0.33	0.30	0.015	0.015
2 (year 2017)	0.17	0.45	0.030	0.030
3 (year 2018/2019)	0.33	0.60	0.045	0.045
4 (year 2020)	0.17	0.75	0.075	0.045

2002 to 2003 shows most prices of biofuels in between the mean of US$80–100 per barrel crude oil. For timeline between 2004 and 2005, most prices of biofuels rose above the upper control limit of US$90 per barrel. Based on the above-mentioned information, it is noted that α is equal to two per six each metrics evaluation whereby the occurrences of product price overshoot and undershoot fragmented throughout 6 years is equivalent to two occurrences out of 6 years. The probability distribution, α for 2015–2020 is determined based on the same trends as year 2000–2005. Meanwhile, the crude oil price is assumed to be the same as previous years.

Scenario 1: uncertainties in both raw biomass feedstock supply and product market demand

Solving the model with Equations 1–7, 9–11 and 14–17 and parameters given in Tables 3, 4 and 5, the average EP obtained under uncertainties in both raw biomass feedstock supply and product market demand is located as US$11.29 billion/year. Table 8 summarises the global optimal solution to the robust optimisation problem of Scenario 1 and provides the design parameters for an integrated biorefinery. Note that the design of equipment, piping and instrumentation shall be based on the maximum capacity

Table 6 Biofuel historical cost data

Biofuel	Timeline per two concurrent years (US$/tonne)		
	2000–2001	2002–2003	2004–2005
Acetate	5,183.19	6,399.00	7,900.00
Acetone	258.28	318.87	393.67
Biochar	45.93	56.70	70.00
Biocrude	236.20	291.60	360.00
Biogas	165.12	203.85	251.67
Biogasoline	492.08	607.50	750.00
Bio oil	845.71	1,044.09	1,289.00
Butanol	802.41	990.67	1,223.00
Carbon dioxide	49.21	60.75	75.00
Diethyl ether (DEE)	247.57	305.67	377.33
Dimethyl ether (DME)	247.57	305.67	377.33
Dimethylfuran (DMF)	1,482.79	1,830.60	2,260.00
Di-*tert*-butyl ether of glycerol (DTBG)	109.35	135.00	166.67
Ethanol	529.41	653.67	806.91
Ethyl-*tert*-butyl ether (ETBE)	659.60	814.33	1,005.33
Fatty acid ethyl esters (FAEE)	669.00	825.93	1,019.67
Fatty acid methyl esters (FAME)	669.00	825.93	1,019.67
FT-diesel	640.00	800.00	1,000.00
Glycerol	144.56	178.47	220.33
Hydrogen	2,624.40	3,240.00	4,000.00
Hydroxymethylfurfural (HMF)	333.52	411.75	508.33
Methanol	145.22	179.28	221.33
Renewable methane gas (RMG)	164.45	203.85	251.67
Syngas	737.67	910.71	1,124.33
Tri-*tert*-butyl ether of glycerol (TTBG)	109.35	135.00	166.67

Table 7 Raw biomass feedstock historical cost data

Raw biomass feedstock	Timeline per two concurrent years (US$/tonne)		
	2000–2001	2002–2003	2004–2005
Rice husk	196.67	243.00	300.00
Municipal solid waste (MSW)	218.67	270.00	333.33
Wood waste	295.33	364.67	450.00
Sugar cane bagasse	301.33	372.00	459.33
Palm biomass	291.00	359.00	443.33

determined under the uncertainty set 4 ‘year 2020’. Based on the optimised result, it is noted that the optimised flow rate of desired products is determined as 35.12 million tonne/year bioethanol, 0.071 million tonne/year FAEE, 0.0042 million tonne/year FT-diesel and 0.0075 million tonne/year biogasoline. Note also that only additional 0.038 million tonne/year of biogasoline needs to be purchased externally to fulfil the market demand. Therefore, this provides opportunity to produce more bioethanol, which has the highest market price (US$1,098.67/tonne). This is attained through an optimum pathway configuration towards the production of bioethanol as illustrated in Fig. 4. As shown, four pathways producing intermediates (syngas) are selected; which are steam reforming of methane (T-8), gasification of bio oil (T-13) and steam reforming of glycerol (T-11). The produced intermediate (syngas) is then fully converted to end products via two pathways, which are FT process (T-6) to produce FT-diesel and biogasoline, and fermentation process (S-8) to produce bioethanol and acetate. Besides, transesterification process (C-2) which converts ethanol and triglycerides to FAEE and glycerol is identified as another alternative pathway. In addition, pyrolysis (T-2) is also used to convert all bio-precursors to biogas, biochar and bio oil.

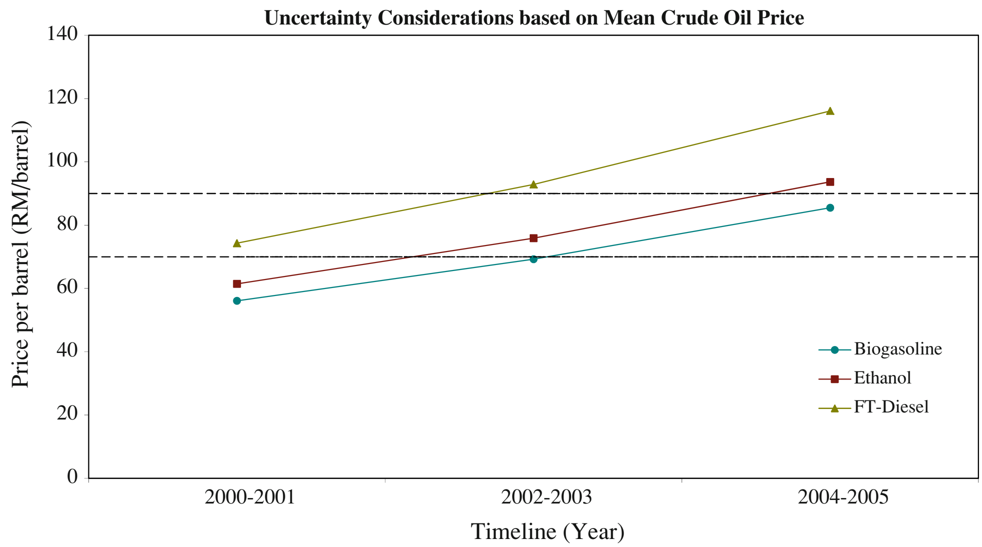

Fig. 3 Uncertainty Considerations based on mean crude oil price of 80 ± 10 US$/barrel

Table 8 Global optimal solution for Scenario 1

Uncertainty sets	Product flow rate (million tonne/year)							Economic potential (billion US$/year)
	Bioethanol	Biochar	Acetate	FAEE	FT-diesel	Biogasoline		
						Production	Fresh	
1 (year 2015/2016)	26.32	9.65	1.65	0.014	0.0014	0.0025	0.013	9.83
2 (year 2017)	28.96	10.62	1.82	0.027	0.0028	0.0050	0.025	10.83
3 (year 2018/2019)	31.98	11.73	2.01	0.041	0.0042	0.0075	0.038	11.99
4 (year 2020)	35.12	12.88	2.20	0.071	0.0042	0.0075	0.038	13.23
Design parameters	35.12	12.88	2.20	0.071	0.0042	0.0075	0.038	11.29

Scenario 2: uncertainties in product cost with considerations of raw biomass feedstock supply and product market demand

With equal objectives to maximise EP, Eqs. 1–7, 9–11 and 14–17 are solved globally with parameters in Tables 3, 4, 5, 6 and 7. The optimum pathway configuration for this case study is showed in Fig. 5; while, Table 9 summarises the optimal solution of Scenario 2. As shown, the average EP is targeted as US$5.90 billion per two concurrent years. The average EP is obtained by the product of probability distribution equivalent to one over three per metric with addition of EP of the concurrent years. The EP parameters are assumed to be an approximate equal to projected timeline of 2015–2020 as market trends continuously increase and decrease with time. With trend conditions where the cost of raw biomass feedstock is increased as compared to the selling price per product, therefore, the maximum EP reduces. This has resulted in a lower EP as compared to Scenario 1. Figure 5 shows the optimum pathway configuration for Scenario 2.

Overall, the highest yield from the optimised three sets of metrics is bioethanol of values 38.4, 44.7 and 49.8 million tonne per two concurrent years from 2000 to 2005. This is due to the relatively high demand of ethanol ranging from 0.3 to 0.75 million tonne per year (see Table 5). The configured network optimised production of biogasoline is from 0.03 to 0.09 million tonne; biochar is from 15.2 to 19.7 million tonne; acetate is from 2.61 to 3.39 million tonne; FAEE is from 7.85 to 10.2 million tonne and FT-diesel is from 0.0028 to 0.0083 million tonne per two concurrent years.

Sensitivity analysis

The above robust solution to all two scenarios are further investigated with a sensitivity analysis of EP towards the cost of raw biomass feedstock and the prices of biofuels, for the purpose of enabling stakeholder evaluation of the key drivers of the overall EP of the proposed model. Although robust optimisation is developed to handle uncertainties, however, it will not be able to determine the key drivers which affect the overall solution. The key drivers can only be determined via sensitivity analysis; therefore, sensitivity analysis is conducted in this work.

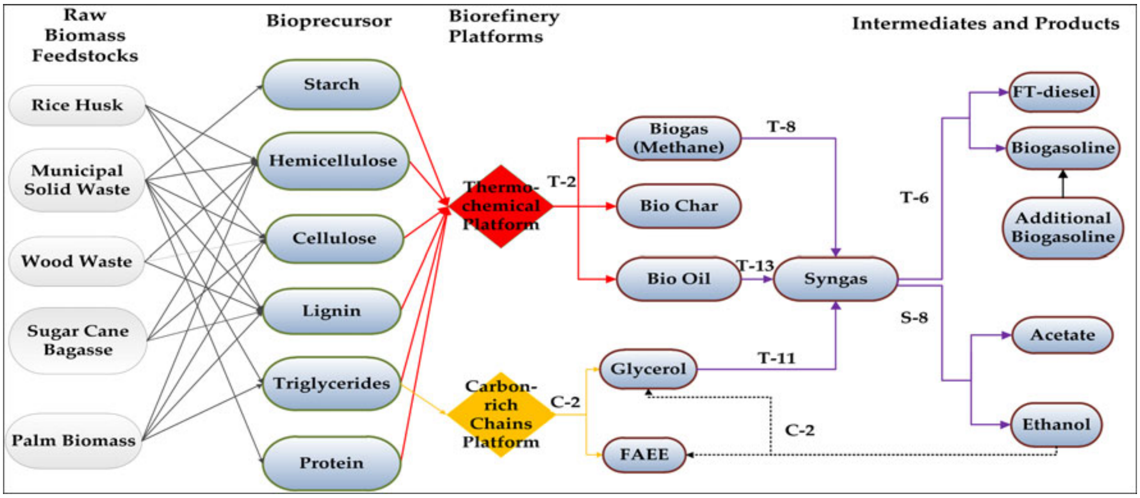

Fig. 4 Optimum pathway configuration for Scenario 1

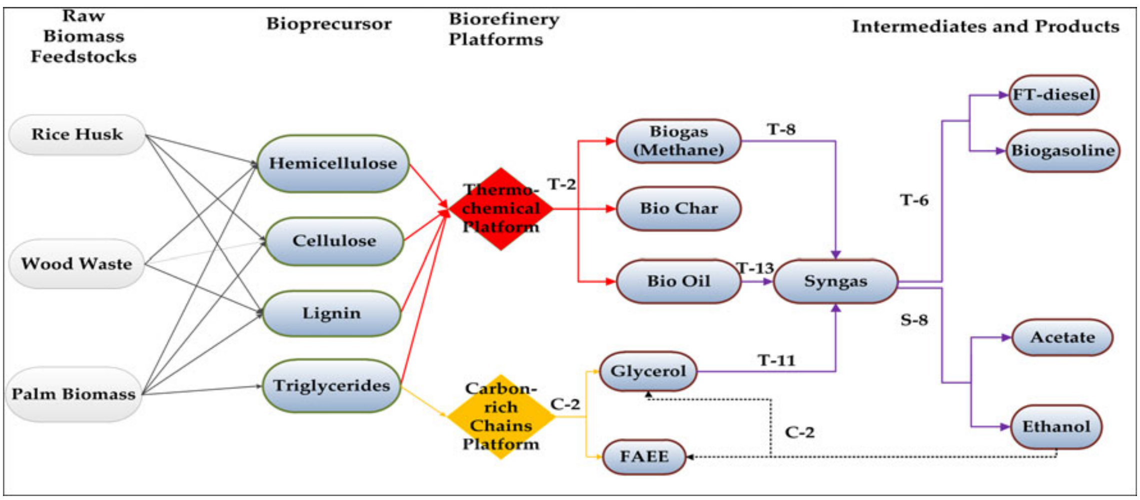

Fig. 5 Optimum pathway configuration for Scenario 2

Table 9 Global optimal solution for Scenario 2

Timeline	Product flow rate (million tonne/2 years)							Economic potential (billion US$ per 2 years)
	Ethanol	Biochar	Acetate	FAEE	FT-diesel	Biogasoline		
						Production	Fresh	
2000–2001	38.4	15.2	2.61	7.85	0.0028	0.030	0.025	3.99
2002–2003	44.7	17.7	3.04	9.20	0.0069	0.075	0.063	5.79
2004–2005	49.8	19.7	3.39	10.20	0.0083	0.090	0.075	7.92
Design parameters	49.8	19.7	3.39	10.20	0.0083	0.090	0.075	5.90

Effects of changes in costs of raw biomass feedstock and prices of biofuels on the overall EP are assessed by varying the cost and price parameters by a 10 % decrease and increase. The mentioned analysis is known as one-way sensitivity analysis because only one parameter is changed at one time to locate the variations of EP. The percentages of change in the overall EP are illustrated graphically by a radar chart, represented by Figs. 6 and 7 for Scenario 1 and 2, respectively.

Upon analysing the radar chart for the effect of changes in costs of raw biomass feedstock, the overall EP is mostly sensitive to a small change in palm biomass cost in both

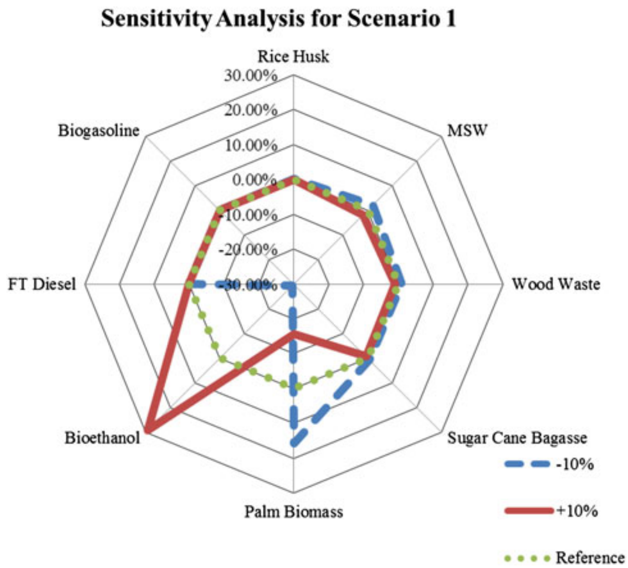

Fig. 6 Radar diagram for Scenario 1

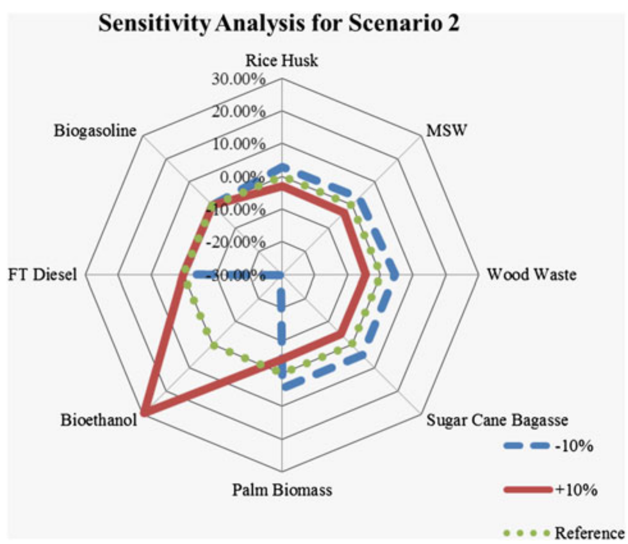

Fig. 7 Radar diagram for Scenario 2

scenarios. In both Scenarios 1 and 2, it is noted that the overall EP rose and fell by 15.74 and 50.34 %, respectively, for the 10 % changes in the cost of palm biomass. This is due to the highest availability of palm biomass for the proposed model (at the range of 34.60–47.40 million tonne per year). It could be seen from Table 4 that the available supply of palm biomass far outweighed that of the other raw biomass feedstock. The solved model inputs all the palm biomass supply into an integrated biorefinery system in order to maximise production rate of biofuels. Hence, a 10 % change in palm biomass cost largely affects the total cost of the raw biomass feedstock supply in the Eq. 17 as well as the overall EP. Similarly as the available tonnage supplies of other raw biomass feedstock are less (i.e. less than 8 million tonne per year) than that of palm biomass, fluctuations in the raw biomass feedstock cost excluding palm biomass will barely influence the cost term of the Eq. 17, and thus a slight change to the overall EP. The overall EP with a ±10 % change in prices of MSW, wood waste, sugar cane bagasse, and rice husk are negligible. The differences in overall EP changes among these four types of raw biomass feedstocks are due to the differences in their available supplies.

In examining the radar chart for the effect of changes in market prices of biofuels, it is noted that the overall EP is tremendously sensitive to a small change in bioethanol market price. A variation of ±10 % in bioethanol market price results in a ±29.35, and ±53 % change in the overall EP, for Scenarios 1 and 2, respectively. Note that such significant sensitivity is observed because the market price of bioethanol is the highest among the other four (i.e. US$1,098.67 per tonne for the base case); the proposed model tended to produce bioethanol only with all amounts of raw biomass feedstock in order to maximise the overall EP. Therefore, due to the highest bioethanol flow rate, a 10 % change in bioethanol market price would significantly affect the revenue (Eq. 17), and so, affect the overall EP. The overall EP with a ±10 % change in prices of other products (e.g. FT-diesel, Biogasoline, MSW, wood waste, sugar cane bagasse etc.) only affected the overall EP by not more than 0.1 %. The production of FT-diesel, FAME, FAEE and biogasoline are merely to meet the demand specifications. Hence, the overall EP had negligible effects due to their low production rate.

The above sensitivity analysis dictated the importance of the availability of raw biomass feedstock and the market prices of biofuels to conceptual design of an integrated biorefinery. Biorefining industries may focus their research and development on enhancing the availability of biomass feedstock and the production of high-value biofuels in order to improve the overall economic profitability. Other than that, stakeholders must constantly be attentive to the deviations in economic trends to sustain the desired economic profitability.

Conclusion

In this work, a graphical representation IBPM and a robust optimisation model were presented to serve as a systematic approach for synthesis of an integrated biorefinery. The uncertainties in biofuel(s) market demands, raw biomass feedstock supply and economic evaluation of both products and feedstock are considered in the generic model to provide a more robust and practical analysis of the problem. Manipulation of probability bounded constraints enables decision makers to make flexible choices in projecting the design parameters of an integrated biorefinery. In future work, the proposed model can be extended to be more flexible, creating preferences towards specific pathways. In addition, integration of heuristics in biorefinery synthesis will also be considered. Meanwhile, it is noted that the presented generic model can be adapted to different objective functions for more detailed analyses.

Acknowledgments The financial support from University of Nottingham Research Committee through New Researcher Fund (NRF 5021/A2RL32) is gratefully acknowledged.

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