Journal of Cleaner Production 34 (2012) 38–48

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Multiple-cascade automated targeting for synthesis of a gasification-based integrated biorefinery

Douglas H.S. Tay, Denny K.S. Ng*

*Department of Chemical and Environmental Engineering, Centre of Excellence for Green Technologies, The University of Nottingham, Malaysia Campus, Broga Road, 43500 Semenyih, Selangor Darul Ehsan, Malaysia*

ARTICLE INFO

*Article history:*
Received 5 July 2011
Received in revised form
8 November 2011
Accepted 8 November 2011
Available online 17 November 2011

*Keywords:*
Biofuel
Gasification
Integrated biorefinery
Optimization
Automated targeting

ABSTRACT

In this work, a novel multiple-cascade automated targeting (MCAT) approach is proposed for determining the maximum economic performance of a gasification-based integrated biorefinery. Since multiple process parameters (i.e., heat input of biomass gasifier, syngas specification for downstream synthesis process, gasification temperature, etc.) should be taken into consideration simultaneously in order to optimize such system, this work extends the previously developed single-cascade automated targeting (SCAT) to allow such problems to be dealt with more effectively. This proposed approach, is based on pinch analysis, and can be used to identify the performance targets based on different optimization objectives prior to detailed design of the integrated biorefinery. An industrial case study is solved to illustrate the approach.



## 1. Introduction

According to EIA (2010), the total world consumption of energy is projected to increase from $5.22 \times 10^{11}$ GJ in 2007 to $7.80 \times 10^{11}$ GJ in 2035. However, the gradual depletion and rising cost of fossil fuel supplies have initiated the onset of numerous energy policies that promote biofuel production worldwide (Martin and Eklund, 2011; Narodoslawsky et al., 2008), from the highly successful USA and Brazil to upcoming biofuel producers such as Tanzania (Martin et al., 2009), Japan (Kaizumi, 2011) and Nepal (Khatiwada and Silveira, 2011). Other than promoting sustainable development, biofuels are also among the promising forms of renewable energy sources because biofuels can be produced from a wide variety of feedstocks. In addition to having good potential for reducing greenhouse gases emissions, biofuels can also enhance energy security, improve trade balance and create job opportunities in countries that are net energy importers.

As reported in the literature, there are many mature processes and technologies that convert specific biomass to value-added products through thermal, biological and physical conversions (i.e., heat and power generation, biodiesel, bioethanol, charcoal and solid fuel pellets production). These options have been systematically analyzed in previous works. For example, Mohan and El-Halwagi (2007) and Qin et al. (2006) performed targeting on the extractable power from biomass for heat and power generation. Besides, economic and environmental analyses were also carried out in the targeting process (Mohan and El-Halwagi, 2007; Qin et al., 2006). Various analyses also have been performed for biodiesel production, such as optimal feedstock selection (i.e., Pokoo-Aikins et al., 2009, 2010), production process optimization (i.e., Fischer and Iribarren, 2011; Myint and El-Halwagi, 2009) and production scheduling based on the type and availability of the feedstocks (Elms and El-Halwagi, 2009, 2010). Bioethanol production processes have also been widely analyzed and optimized. Various works have been carried out to determine cost effective and environmental friendly bioethanol production technologies (e.g., Piccolo and Bezzo, 2009), as well as design and optimize bioethanol production with the consideration of both economic and environmental performances (e.g., Chouinard-Dussault et al., 2011; Zamboni et al., 2009a,b). However, in most cases even optimized single pathway processes exhibit poor energy efficiency (Pham and El-Halwagi, 2011; Martin and Eklund, 2011).

As shown in Demirbas (2009), the diversification of feedstocks and products through integration of multiple biomass conversion technologies can improve the overall economic and environmental performances of a biorefinery. To further enhance the overall process and economic performances, the concept of integrated

* Corresponding author. Tel.: +60 3 89248606; fax: +60 3 89248017.
*E-mail addresses:* douglas.tay@nottingham.edu.my (D.H.S. Tay), denny.ng@nottingham.edu.my (D.K.S. Ng).

0959-6526/$ – see front matter 
doi:10.1016/j.jclepro.2011.11.006

biorefinery that further integrates multiple conversion platforms is highlighted in various literatures (e.g., Liu et al., 2011; Ragauskas et al., 2006).

Various process systems engineering (PSE) techniques have been developed to aid in the conceptual design of an integrated biorefinery, addressing issues in biomass logistics, conversion kinetics, process energetics, and raw material selection and product allocation (Kokossis and Yang, 2010; Narodoslawsky, 2003). Current research and development efforts in the synthesis of integrated biorefineries focus on integrating the wide spectrum of thermal, biological and physical biomass conversion technologies to generate multiple value-added products. The base problem of product allocation in an integrated biorefinery has been extensively analyzed based on different objectives, such as economic performance (Zondervan et al., 2011; Bao et al., 2011; Sharma and Romagnoli, 2011; Sammons et al., 2008), environmental performance (Nemet et al., 2011; Zondervan et al., 2011), energy conversion efficiency (Mizsey and Racz, 2010). Besides, optimization of production with consideration of both economic and environmental performances simultaneously also have been investigated (Santibanez-Aguilar et al., 2011; Tay et al., 2011a; Gwenhenberger et al., 2007). Most recently, Tay et al. (in press) presented a robust optimization approach for the synthesis of integrated biorefineries that deals with uncertainties in raw material supply and product demand.

As biomass supply chain design is a crucial aspect in securing biomass supply for biorefinery (Gold and Seuring, 2011), integration of supply chain design with synthesis of a biorefinery should be considered simultaneously. Bowling et al. (2011), Mansoornejad et al. (2010), Lam et al. (2010) and Čuček et al. (2010) have presented optimization approaches for simultaneous synthesis of supply chain networks and biorefinery configuration. Most recently, some research works have been conducted in the area of process design and integration, focussing on material and energy integration between processing facilities within an integrated biorefinery (e.g., Liu et al., 2011; Ng and Sadhukhan, 2011; Tock et al., 2010); specifically, integration with conventional fossil fuels facilities such as coal and natural gas facilities (Baliban et al., 2011; Elia et al., 2010), combined heat and power facility (Sadhukhan and Ng, 2011; Tous et al., 2011) have been presented. On the other hand, Tay et al. (2011b) presented a graphical targeting approach for the evaluation of gas phase equilibrium composition of biomass gasification. Based on the targeted composition, a conceptual design of an integrated biorefinery can be systematically developed.

As reported in the previous works (Koukios et al., 2010; Fernando et al., 2006), another key feature of an integrated biorefinery is its ability to handle multiple feedstocks (biomass) and convert them into a range of desired intermediates. Thermal-conversion processes, such as gasification and pyrolysis, are the attractive technologies for the initial processing of biomass because of their robustness (Demirbas, 2009). Gasification process usually operates in a temperature range of 600–1400 °C to convert biomass into a gaseous mixture of carbon dioxide ($CO_2$), steam ($H_2O$), methane ($CH_4$), carbon monoxide (CO) and hydrogen ($H_2$). The gaseous mixture is also known as syngas (Ciferno and Marano, 2002). Syngas can be used for the generation of heat and power and as feedstock for the production of chemicals and liquid fuels (e.g., Khodakov et al., 2007; Bremaud et al., 2005; PNNL and NREL, 2004). Therefore, gasification-based biorefinery is recognised as one of the potential platforms in an integrated biorefinery. The resulting syngas is a multifunctional intermediate for the production various value-added products as well as electricity and heat (Demirbas, 2009).

In order to optimize the production of syngas for use in an integrated biorefinery, a systematic technique is needed. In this work, automated targeting (Ng, 2010) is further extended to multiple-cascade automated targeting to determine different critical operating parameters of biomass gasification (e.g. gasification temperature, type of biomass, etc.). Performances of gasification process, such as, biomass conversion, syngas composition, energy consumption, are normally reported for specific gasification operating parameters in the literature. Thus, the performances are often available only for discrete parameters, instead of continuously. In the absence of detailed gasification and chemical synthesis model, which normally involves non-linear programming (NLP) and high computational efforts, the proposed multiple-cascade automated targeting approach can be used to determine the optimum allocation of raw materials, intermediates and final products prior to detail design using discrete performance data. In addition, the proposed approach in a linear programming (LP) model which can be solved without computational difficulties.

In the previous work by Ng (2010), carbon content and flowrate of biomass are taken as quality and quantity measurement respectively, for the synthesis of an integrated biorefinery based on analogies with water integration (i.e., direct reuse and recycle (Ng et al., 2009a), interception (Ng et al., 2009b) and property integration (Ng et al., 2009c), total resource conservation network (Ng et al., 2010)). The most important benefit of automated targeting is that this technique is able to provide useful insights for system design which may not be possible with alternative formulations; specifically with the automated targeting formulation, the "golden rule" of pinch analysis can be applied (Ng, 2010).

The previous work (Ng, 2010) is restricted to handle single process constraint (i.e., carbon content) and is thus limited in applicability. In order to optimize the overall performance of an integrated biorefinery, multiple key process parameters (i.e., heat input of biomass gasifier, syngas specification for downstream synthesis process, gasification temperature, etc.) need to be taken into consideration for optimal product allocation and technology selection. For example, in a thermal-conversion process (i.e., gasification), operating temperature is directly linked to heat of formation of the raw material and heat input. Therefore, this parameter is crucial in determining the biomass conversion and syngas specification. Thus, heat of formation of the biomass stream, gasification agents and syngas are taken as extensive quality to measure the amount of heat input required for the gasification process. As mentioned previously, syngas specification, especially the $H_2$/CO ratio, is crucial for the downstream synthesis process. Thus, $H_2$/CO ratio is selected as the quality measure for downstream process. In order to synthesize an optimal gasification-based biorefinery, various process specifications (e.g., heat of formation, syngas composition, etc.) need to be accounted for simultaneously. A generic multiple-cascade approach technique (MCAT) is developed in this work.

## 2. Problem statement

The problem of synthesizing a gasification-based integrated biorefinery may be formally stated as follows:

A set of biomass sources $i$, SRB$i$ can be converted to syngas $p$ (SRS$p$). Each source, SRB$i$ has a given flowrate of $F_{SRBi}$ and is characterized based on the extensive property of the stream. It is crucial to select the right critical process parameters for each stream to determine the optimal integrated biorefinery design. For example, as temperature and heat input is directly linked to the heat of formation the streams, to determine the optimum gasification temperature and amount of additional heat input required for thermal-conversion processes such as gasification or pyrolysis, the difference of the heat of formation of the inlet (i.e., biomass, gasification agents) and outlet streams of syngas at gasification temperature are to be used as the quality measurement. On the other hand, a set of gasifier sinks $j$, SKG$j$ which represents the