CHEMICAL ENGINEERING RESEARCH AND DESIGN XXX (2014) XXX–XXX

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Heuristic framework for the debottlenecking of a palm oil-based integrated biorefinery

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ABSTRACT

This paper presents a heuristic framework that can be used for the debottlenecking of a palm oil-based integrated biorefinery with multiple processes and products. In current industrial practice, any individual unit within these systems is generally designed for a required size. Besides, it also takes into account of an additional margin for safety to meet the requirement of the baseline state of the process. In case there is a variation in the quality of the supplied feedstock or an increase for product demand, it becomes necessary to identify the bottleneck process unit in order to handle the new variation and meet all requirements. In response, the system has to be debottlenecked by altering important operating parameters from the baseline state that limits the change. This stage entails formulating and solving a detailed model for this particular process. In this paper, frameworks are presented to aid decision makers to first identify a bottleneck and subsequently debottleneck the process. The frameworks are essentially a guide for design and safety engineers for decision making at conceptual design stage. A design stage palm oil-based integrated biorefinery case study is solved to demonstrate the proposed approach.

Keywords: Biorefinery; Continuous process; Debottlenecking framework; Input–output model; Palm Oil; Heuristic framework

1. Introduction

It is common for the production industry to undergo a steady increase in product demand with the growing technology and/or business development. This growth imposes a great challenge to design engineers and researchers, as this entails increased production. The increase in product demand can be accomplished by means of building a new production plant, or by debottlenecking an existing facility (Schneider, 1997) or even by debottlenecking a process plant at the design stage. In most cases, the latter option is most preferred. Generally, debottlenecking is a classic approach of achieving a desired plant performance that a unit is presumed incapable of with its current configuration (Schneider, 1997). The

Abbreviations: BCA, benefit–cost analysis; BCR, benefit–cost ratio; CBA, cost–benefit analysis; CDM, clean development mechanism; CPO, crude palm oil; EFB, empty fruit bunches; FFB, fresh fruit bunches; HAZID, hazid identification; HAZOP, hazard operability; HP (steam), high pressure steam; IIM, inoperability input–output model; LP, linear programming; LP (steam), low pressure steam; MILP, mixed integer linear programming; MINLP, mixed integer non-linear programming; MP (steam), mid pressure steam; PKC, palm kernel cake; PKO, palm kernel oil; PKS, palm kernel shell; POME, palm oil mill effluent; PPF, palm press fiber; QRA, quantitative risk assessment.

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Received 5 September 2013; Received in revised form 7 February 2014; Accepted 19 February 2014

http://dx.doi.org/10.1016/j.cherd.2014.02.024

Nomenclature

Indices
i stream index ($i = 1, 2, \ldots, I$)
j process unit index ($j = 1, 2, \ldots, J$)

Parameters
a_{ij} input and output matrix/flowrate of stream i to or from process unit j
C_j^{Cap} annualised capital cost of process unit j at the baseline state
C_j^{Fixed} fixed cost of process unit j
C_i^{Stream} unit cost of stream i
x_j^L lower limit of operating capacity of process unit j
x_j^U upper limit of operating capacity of process unit j
y_i^L lower limit of stream y flowrate
y_i^U upper limit of stream y flowrate

Variables
$C^{Equipment}$ total capital cost of equipments
x_j operating capacity of process unit j
y_i net output of stream i from process unit j

four goals behind the idea of debottlenecking are feedstock quality variation which is supply-oriented, and throughput increases, alterations of yields and efficiencies, and equipment specifications modifications which are process-oriented. Debottlenecking of an existing facility, essentially may continue throughout its lifetime as long as there is an increase in demand.

The problem of identifying and relieving the process bottleneck is another significant topic of research. The importance of increased productivity of a process plant has earned attention in many research works. The literature contains effective methods for identifying bottlenecks and debottlenecking process plants of various backgrounds. Harsh et al. (1989) presented a work that identifies the process bottlenecks with flowsheet optimisation strategy. It was done prior to applying a mixed integer non-linear programming (MINLP) model to retrofit an ammonia process. Diaz et al. (1995) used an MINLP model to determine the optimal configuration and operating conditions of an ethane extraction plant by introducing minor plant structural modifications. On the other hand, Voudouris (1996) developed a large scale mixed integer linear programming (MILP) model for the fine chemical industry. The model helped to identify production bottlenecks and subsequently debottleneck the supply chain in the case of schedule and throughput enhancement. Later, Litzen and Bravo (1999) proposed the “stair-step chart” to visualise the cost–benefit ratio (BCR) of each step progressively toward the debottlenecking goal. In the work of Litzen and Bravo (1999), the analysis emphasised on the interactions among process units, instead of individual units.

On the other hand, Ahmad and Polley (1990) ventured into the attempt of debottlenecking heat exchanger networks (HEN) with the use of *pinch analysis*. This method predicts the least requirement of energy and capital where HEN retrofit is done for increased throughput. Another attempt of HEN debottlenecking by considering realisation of pressure drop optimisation procedure was also performed (Panjeshahi and Tahouni, 2008). The optimisation procedure optimised the additional area and the operating costs involved in the HEN, and was validated against a crude oil pre-heat train subjected to a 20% throughput increase. Alshekhli et al. (2010) used a computer-aided process simulation tool to model and debottleneck an industrial cocoa manufacturing process. The work was intended to increase the cocoa production rate and determine an economically viable production scheme. Other works that also used process simulations for debottlenecking of batch processes include Koulouris et al. (2001). It presented a systematic simulation-based methodology for identifying bottlenecks in a synthetic pharmaceutical batch process as well as a strategy for eliminating them. Meanwhile, Tan et al. (2006) also presented a debottlenecking strategy for batch process in pharmaceutical industry via process simulation. Most recently, Tan et al. (2012) developed a methodology for the identification of bottlenecks in continuous process plants that can be described by a system of linear equations. This algebraic approach is based on the concept of inoperability or inoperability input–output model (IIM). IIM was proposed by Haimes and Jiang (2001) to analyse the failure of interdependent infrastructure systems suffering from disruptive events. As an extension, Kasivisvanathan et al. (2013) adapted this concept of inoperability to determine the optimal operational adjustments when disruptions occur in multi-functional energy systems, such as polygeneration plants and integrated biorefineries. Morales-Rodriguez et al. (2012) on a different league presented the development and application of a systematic model-based framework for bioprocess optimisation involving lignocellulosic ethanol production.

This paper presents heuristic frameworks for identifying bottlenecks in a palm oil-based integrated biorefinery. The frameworks are essentially a guide for design and safety engineers for decision making at conceptual design stage. An integrated biorefinery is defined as a processing facility that integrates biomass conversion processes to produce biofuels, power, and biochemicals from biomass with minimum waste generation (Demirbas, 2009; Fernando et al., 2006). A palm oil-based integrated biorefinery is thus defined as a processing facility that converts various types of palm-based biomass into higher value added products (Kasivisvanathan et al., 2012). These biomasses that are extracted from a palm oil mill include empty fruit bunches (EFBs), palm press fiber (PPF), palm kernel cake (PKC), palm kernel shell (PKS) and palm oil mill effluent (POME). They are sent to the biorefinery network integrated to the mill in order to produce biofuels, biochemicals and other bio-based food. According to Ng and Ng (2013a,b), palm oil-based biorefinery can then be integrated with palm oil mill, combined heat and power plant as well as palm oil refinery to form an Integrated Palm Oil Processing Complex (POPC) which maximise the economic performance of the palm oil industry. Later, Ng et al. (2013) further analysed the interactions of multiple owners of those processing facilities via industrial symbiosis concept. A detail review of the applications of Process System Engineering in palm-based biomass processing industry is presented by Ng and Ng (2013b).

Essentially, the debottlenecking strategy in this paper is presented to meet requirements of the variation in supply and production demand. In the presented case study, the palm oil-based integrated biorefinery is first described by a set of linear equations with scale-invariant material and energy balances. The process bottleneck is then identified via the algebraic approach proposed by Tan et al. (2012). Next, the heuristic