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Multi-level production planning in a petrochemical industry using elitist Teaching–Learning-Based-Optimization

Rajasekhar Kadambur, Prakash Kotecha *

Department of Chemical Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039, Assam, India

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ABSTRACT

The complex nature of the petrochemical industries necessitates an efficient decision on a large number of factors so as to optimally operate a plant. Production planning is an integral part of the petrochemical industry and requires the optimal selection of processes, production levels and products to maximize its profit. Previously an MILP formulation has been proposed for guiding the petrochemical industry development in Saudi Arabia (Alfares & Al-Amer, 2002). In this article, we state the limitations of this formulation and propose an alternate elitist TLBO algorithm based strategy to overcome them. The benefits of this strategy include the determination of better production plans that lead to higher profits and have been demonstrated on the eight case studies in the literature. The proposed strategy is generic and can be applied to determine production plans of multiple levels in various industries.

1. Introduction

A petrochemical industry processes feedstock such as crude oil and natural gas to produce primary petrochemicals such as methanol, ethylene, propylene, benzene, toluene, xylene, etc. These primary petrochemicals are transformed into petrochemical intermediates and derivatives such as acetic acid, vinyl chloride, styrene and adipic acid which are subsequently converted into products such as paper, plastic products and fibers that are essentially used to manufacture everyday consumer products. These petrochemical products are produced using a series of complex networks on a very large scale and hence their production is highly capital intensive (Yoon et al., 2008). The petrochemical industries have a huge impact on the economy of a nation as their products act as raw materials of other industries of the manufacturing sector. A large number of petrochemical industries from the Middle Eastern countries (Al-Amer, Al-fares, & Rahman, 1998; Al-Sharrah, Alatiqi, & Elkamel, 2003; Alfares & Al-Amer, 2002) have started to use their natural resources to export petrochemical products to benefit their economy. To harness the maximum benefit, a number of optimization models have been built for specific countries including the development of a model for the Norwegian petrochemical industry (Mikkelsen & Rudd, 1981; Stokke, Ralston, Boyce, & Wilson, 1990), the development of Mixed Integer Linear Programming (MILP) models for Mexican petrochemical industry (Jiménez & Rudd, 1987; Toledo, Aranda, & Mareschal, 2010), the development of MILP models to identify the synergy in mergers and acquisitions in the Korean petrochemical industry (Yoon, Park, Lee, Verderame, & Floudas, 2008, 2009; Yoon et al., 2008) and MILP model for maximizing profit which aids in guiding petrochemical industries in Saudi Arabia (Alfares & Al-Amer, 2002). The petrochemical sector is estimated to be worth over $600 billion globally (Al-Faresi, 2011) and is extremely competitive.

Some of the previous research work which have focussed on various factors of the petrochemical industry include the integration of refineries and petrochemical plants (Al-Qahtani, Elkamel, & Ponnambalam, 2008), capacity expansion (Bok, Lee, & Park, 1998), efficient spatial organization of petrochemical plants (Liu, Jin, Liu, Ding, & Xu, 2013), efficient job scheduling (Lee, Ryu, Lee, & Lee, 2009), optimal supply chain management (Lababidi, Ahmed, Alatiqi, & Al-Enzi, 2003), efficient production planning (Alfares & Al-Amer, 2002) and synergistic mergers and acquisitions (Yoon et al., 2008). In order to address the complex challenges in a petrochemical plant, various objectives have been used in the optimization of the petrochemical industry that include minimizing the total cost (Rudd, 1975), minimizing the raw material requirement (Stadtherr & Rudd, 1976), minimizing the harmful environmental impacts (Al-Sharrah, Alatiqi, Elkamel, & Alper, 2001), maximizing the annual profit (Jiménez, Rudd, & Meyer, 1982), and maximizing the thermodynamic availability (Sophos, Rotstein, & Stephanopoulos, 1980a). Most of the research work focuses on the petrochemical industry from a single objective and deterministic optimization perspective. Few works that have

* Corresponding author. Tel.: +91 361 258 2277; fax: +91 361 258 2291.
E-mail address: pkotecha@iitg.ernet.in (P. Kotecha).

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considered multi-objective optimization in the context of petrochemical industries include maximization of thermodynamic availability change, minimization of lost work, minimization of feedstock consumption (Sophos, Rotstein, & Stephanopoulos, 1980b) and selection of environmentally friendly processes (Al-Sharrah et al., 2001) while some of the recent works have accounted the uncertainties in operating these plants (Al-Qahtani & Elkamel, 2008; Lababidi et al., 2003). However, to the best of our knowledge, evolutionary algorithms have found only limited applications in the production planning of petrochemical industries. In this work, we propose the use of an evolutionary elitist TLBO based strategy to determine the optimal production planning that overcomes many of the limitations of the MILP model in literature (Alfares & Al-Amer, 2002).

Teaching Learning Based Optimization algorithm (TLBO) is a recently proposed population based Artificial Intelligence technique for solving non-linear constrained optimization problems (Rao, Savsani, & Vakharia, 2011, 2012). It is inspired from the teaching learning environment in the class wherein a student learns from the teacher as well as from the classmates by peer interaction. The elitist version of this algorithm is known as elitist TLBO (Rao & Patel, 2012) and it ensures that the value of the objective function progresses monotonically. The performance of the TLBO algorithm has been critically studied (Waghmare, 2013; Črepinšek, Liu, & Mernik, 2012) and it has been used to solve a number of optimization problems arising in various fields such as design of planar steel frames to obtain minimum weight frames subject to strength and displacement requirements (Toğan, 2012), minimization of total operating time of over-current relays (Singh, Panigrahi, & Abhyankar, 2013), minimization of error in terms of distance between the model cloud and data cloud in 3D affine registration (Jani, Savsani, & Pandya, 2013), minimization of power loss and energy cost by optimal placement of capacitors in radial distribution systems (Sultana & Roy, 2014) and minimum weight design of truss structures in terms of stress and joint displacement of structure (Degertekin & Hayalioglu, 2013).

In this article, we review the MILP formulation for the production planning problem in literature and demonstrate its limitations. Subsequently, we propose an elitist TLBO based optimization strategy which overcomes the limitations of the MILP formulation in the literature. The benefits of proposed strategy are demonstrated on all the eight case studies that have been reported in literature (Alfares & Al-Amer, 2002). To the best of our knowledge, elitist TLBO has not been applied to constrained problems of this size (>100 variables and >100 constraints) in literature and hence this work also establishes the performance of elitist TLBO on large problems. The article is structured as follows: In the following section, we provide the problem description and follow it up with a critical review of the MILP formulation. Subsequently, we review the elitist TLBO algorithm and propose a strategy based on this for two scenarios which assist in determining efficient production plans. Subsequently, the utility of the proposed strategy is demonstrated using the case studies from the literature (Alfares & Al-Amer, 2002). We conclude the article by outlining the developments in this article and discussing possible future work.

2. Problem description: production planning in petrochemical industries

A petrochemical industry can produce products from a wide range of processes and raw materials. For example, propylene oxide has been reported to be produced from Arco and Shell process (with styrene product), Texaco and Arco process (with T butanol byproduct), and Chlorohydrin and Cell liquor neutralization process (Alfares & Al-Amer, 2002). Each process require different quantities of raw materials to produce a unit quantity of a product and each process can be operated at three different capacity levels viz. low, medium and high production level. Production and investment cost of each level varies non-linearly with the production levels and impacts the profitability of the plant. In addition, some of the resources such as raw materials and financial investment are available in limited quantities and hence the optimal production plan is to be designed within these limitations. Ideally, the industry would prefer to produce the most profitable product but this may be limited by a number of factors including the demand in the market. Under this scenario, the petrochemical industry needs to determine (i) the type and amount of products that have to be produced, (ii) the processes to be selected for production, and (iii) the production level to be employed to produce a particular product from a particular process, so that the production plan is globally optimal and yields maximum profit. This is a combinatorial optimization problem and it has been previously modeled as a Mixed Integer Linear Programming (MILP) wherein the production and investment cost of production level varies non-linearly and is modeled as a piece-wise linear function as shown in Fig. 1. We will briefly review the model to demonstrate its limitations. The MILP model is as follows

$$\textit{Maximize} \quad \text{Profit} = \sum_{j=1}^{J} E_j X_j - \left(C_{lj} L_j + C_{mj} M_j + C_{hj} H_j\right) \tag{1}$$

$$\textit{subject to}: \quad X_j = l_j L_j + m_j M_j + h_j H_j \tag{2}$$

$$L_j \leqslant Y_j \tag{3}$$

$$H_j \leqslant 1 - Y_j \tag{4}$$

$$L_j + M_j + H_j = Z_j \tag{5}$$

$$X_j \leqslant N Z_j, \quad N \text{ is a large number (as in the big} - \text{M method)} \tag{6}$$

$$\sum_{j=1}^{J} V_{lj} L_j + V_{mj} M_j + V_{hj} H_j \leqslant B \tag{7}$$

$$\sum_{j=1}^{J} b_{jt} X_j \leqslant R_t, \quad t = 1, \ldots, T \tag{8}$$

$$\sum_{j \in S_i} X_j \leqslant D_i, \quad i = 1, \ldots, I \tag{9}$$

$$X_j, L_j, M_j, H_j \geqslant 0; \quad Y_j, Z_j = 0 \text{ or } 1; \tag{10}$$

$$\sum_{j \in S_i} Z_j \leqslant 1, \quad i = 1, \ldots, I \tag{11}$$

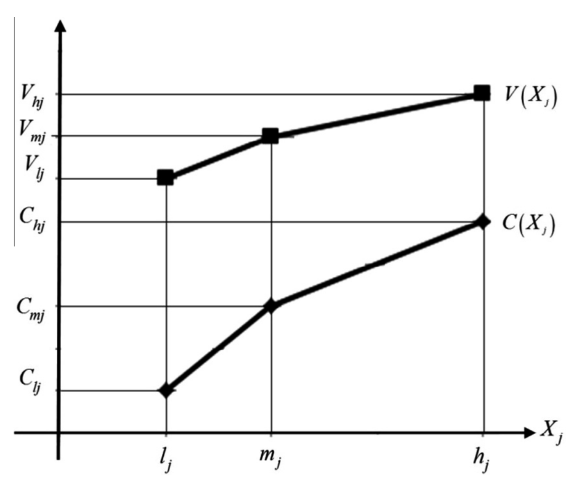

Fig. 1. Production cost and investment cost as a function of production level capacity.