Computers & Industrial Engineering 100 (2016) 133–143

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Optimal production planning in a petrochemical industry using multiple levels

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ARTICLE INFO

Article history:
Received 14 February 2015
Received in revised form 27 June 2016
Accepted 14 August 2016
Available online 17 August 2016

Keywords:
Production planning
Petrochemical industry
Combinatorial optimization

ABSTRACT

An optimal production plan is crucial for the competitiveness of a petrochemical industry. In this article, we review a previously modelled formulation for guiding petrochemical industries in Saudi Arabia (Alfares & Al-Amer, 2002) and discuss its limitations. We propose a mathematical formulation that enables the determination of better production plans yielding higher profits by overcoming the limitations of the formulation in literature. In addition to yielding better production plans, the proposed formulation is easier to build and expressive in nature. Moreover the proposed formulation is generic to accommodate any number of production levels. The benefits of proposed formulation are demonstrated with the help of eight case studies taken from the literature and show an improvement of up to 16.31% in profit.

1. Introduction

Petrochemical industries have become an integral part of the manufacturing sector and are estimated to be worth over $600 billion globally (Al-Faresi, 2011). The products of petrochemical industries predominantly act as raw materials for other industries of the manufacturing sector and can thus have huge ramifications on the economy of a nation. A large number of the Middle Eastern countries have started to use their ample natural resources to export petrochemical products thereby contributing positively to their economies (Al-Amer, Al-fares, & Rahman, 1998; Al-Sharrah, Alatiqi, & Elkamel, 2003; Alfares & Al-Amer, 2002).

A petrochemical industry uses series of complex networks to convert feedstock such as oil and gas to primary petrochemicals such as methanol, ethylene, propylene, benzene, toluene, xylene, etc. These primary petrochemicals are subsequently converted into petrochemical intermediates and derivatives which are ultimately transformed into products used in the market. The petrochemical industries operate at very high production levels which is achieved either through the large scale of the individual equipment or through the large scale of the entire plant (Yoon, Park, Park, et al., 2008). Modern day plants usually have an annual capacity of 1 million tons and possess a diverse portfolio.

A variety of optimization based strategies have been used for efficiently operating the petrochemical plants. These include efficient production planning (Alfares & Al-Amer, 2002), mergers and acquisitions (Yoon, Park, Park, et al., 2008), 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), and optimal supply chain management. A number of objectives such as minimization of the total cost (Rudd, 1975), minimization of the raw material requirement (Stadtherr & Rudd, 1976), minimization of harmful environmental impact (Al-Sharrah, Alatiqi, Elkamel, & Alper, 2001), maximizing the annual profit (Jiménez, Rudd, & Meyer, 1982), maximizing the thermodynamic availability (Sophos, Rotstein, & Stephanopoulos, 1980) have been used by researchers to address the challenges in the petrochemical industry. However most of the research work accommodates only a single objective and only few works have considered the simultaneous optimization of conflicting multiple objectives (Al-Sharrah et al., 2001; Sophos et al., 1980). Though much of the work is deterministic in nature, some of the recent works have also accounted for various uncertainties that exist in operating these plants (Al-Qahtani et al., 2008; Lababidi, Ahmed, Alatiqi, & Al-Enzi, 2003).

Predominantly mathematical programming techniques have been used for the solution of optimization problems occurring in the petrochemical industry and only few instances of artificial intelligence based optimization techniques are found in literature (Nilson, Persson, & Anderson, 2009). Depending on the application, Linear Programming (LP) models (Escobar-Toledo, 2001; Stadtherr

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http://dx.doi.org/10.1016/j.cie.2016.08.008
0360-8352/

Nomenclature

Parameters

- b_{jt} tons of raw material t required for producing one ton of X_j
- B total available budget ($) for investment
- c_{lj} capacity of the production level l of process j (tons of product/year)
- C_{lj}, C_{mj}, C_{hj} production cost ($/ton) of process j per ton of X_j corresponding to the capacity level l_j, m_j and h_j respectively
- D_i total annual demand of product i (ton/year)
- E_j selling price of product j ($/ton)
- I total number of products
- ICI_{lj} intercept of the investment cost line between levels c_{l+1} and c_l of process j
- ICS_{lj} slope of the investment cost line between levels c_{l+1} and c_l of process j
- J total number of processes
- l_j, m_j, h_j capacity of low, medium and high production levels of process j (tons/year) respectively
- L number of production levels of a process
- N_S process number
- N_T product number
- P_{ij} 1 if product i can be produced from process j, 0 otherwise
- PCI_{lj} intercept of the production cost line between levels c_{l+1} and c_l of process j
- PCS_{lj} slope of the production cost line between levels c_{l+1} and c_l of process j
- R_t available feedstock of raw material t (tons/year)
- S_i set of all processes producing product i
- T total number of raw materials
- V_j total investment cost ($/ton) of process j for manufacturing X_j
- V_{lj}, V_{mj}, V_{hj} investment cost ($/ton) of process j for manufacturing X_j corresponding to the capacity levels l_j, m_j and h_j respectively

Continuous decision variables

- C_j total production cost ($/ton) of process j for producing X_j
- IC_{lj} investment cost ($/ton) of process j for manufacturing x_{lj}
- L_j, M_j, H_j portions using production levels l_j, m_j and h_j respectively
- PC_{lj} production cost ($/ton) of process j for manufacturing x_{lj}
- x_{lj} amount of product produced ($\times 10^3$ tons/year) from the capacity level between c_l and c_{l+1} of process j
- X_j amount of product produced ($\times 10^3$ tons/year) from process j
- Z'_j 1 if $X_j > 0$ or 0 if $X_j = 0$
- z_{lj} 1 if $x_{lj} > 0$ or 0 if $x_{lj} = 0$

Binary decision variables

- Y_j 1 if $X_j \leqslant m_j$ or 0 if $X_j > m_j$
- Z_j 1 if $X_j > 0$ or 0 if $X_j = 0$

& Rudd, 1978), Mixed Integer Linear Programming (MILP) models (Alfares, 2007; Jiménez et al., 1982; Schulz, Diaz, & Bandoni, 2003), Non Linear Programming (NLP) models (Corsano, Montagna, Iribarren, & Aguirre, 2006; Kralj & Glavič, 2007), and Mixed Integer Non Linear Programming (MINLP) models (Al-Qahtani et al., 2008; Kraemer, Kossack, & Marquardt, 2007) regularly occur in the design of petrochemical plants. Some of the works that are specifically focussed on the petrochemical industries of a particular country include the use of a LP model to maximize profit for the Norwegian petrochemical industry (Mikkelsen & Rudd, 1981; Stokke, Ralston, Boyce, & Wilson, 1990), the use of a MILP model to minimize the operating cost for the Mexican petrochemical industry (Jiménez & Rudd, 1987; Toledo, Aranda, & Mareschal, 2010), the development of transformed MILP models for identifying the synergy in the Korean petrochemical industry (Yoon, Park, Lee, et al., 2008; Yoon, Park, Lee, Verderame, & Floudas, 2009; Yoon, Park, Park, et al., 2008) and the development of a MILP formulation for guiding the development of petrochemical industry in Saudi Arabia (Alfares & Al-Amer, 2002). Thus it can be seen that optimization has been widely used in the efficient planning and operation of petrochemical industries.

In this article, we critically review the MILP formulation in literature (Alfares & Al-Amer, 2002) for the production planning and propose an alternate multi-level LP formulation. The proposed formulation overcomes the drawbacks of the formulations in literature which artificially restricts the production levels and leads to lower profits and suboptimal utilization of resources. The proposed formulations not only aid in the discovery of better solutions but also require lower computational effort. The benefits of proposed formulation are demonstrated on cases studies from the literature.

The article is structured as follows: In the next section, we provide the problem description and follow it up with a review of the MILP formulation available in the literature (Alfares & Al-Amer, 2002) and detail its limitations. Subsequently, we propose a multi-level formulation that overcomes these limitations and lead to production plans with higher profit. The utility of the proposed formulations is subsequently demonstrated on case studies from the literature. We finally conclude by summarizing the developments in this article and discussing potential future work in this direction.

2. Problem definition: production planning in petrochemical industries

A wide range of processes are available for producing a particular product in a petrochemical industry as shown in Tables 1–4. For example, methanol can be produced from Lurgi process, ICI process copper catalyst and ICI LCM process (Alfares & Al-Amer, 2002). Each process may require different amounts of raw materials and can be operated at different production capacity levels viz. low, medium and high production level. Due to the inherent nature of the process and the dynamics of production, the production cost and the investment cost of each level varies with the level of production as shown in Tables 1–4.

Fig. 1 shows the variation of the production cost (denoted by C_{lj}, C_{mj} and C_{hj}) and investment cost (denoted by V_{lj}, V_{mj} and V_{hj}) with respect to the three production levels l_j, m_j and h_j of a process. In addition to profitability, the production of a product is governed by factors such as the demand of the products in the market, the amount of raw materials available for the production of a particular product and the monetary resources available for the investment. In order to obtain maximum profit, the petrochemical industry needs to determine the optimal production plan by deciding the product portfolio and the production processes along with their operational levels for producing the products. This leads to a combinatorial optimization problem involving both continuous variables occurring in the form of production quantities and discrete variables occurring in the selection of production process and their operating levels.

This production planning problem has been previously modelled as a Mixed Integer Linear Programming (MILP) wherein the