ARTICLE IN PRESS
CJChE-00777; No of Pages 15
Chinese Journal of Chemical Engineering xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Chinese Journal of Chemical Engineering
journal homepage: www.elsevier.com/locate/CJChE

Rule-based scheduling of multi-stage multi-product batch plants with parallel units☆

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ARTICLE INFO

Article history:
Received 28 September 2016
Received in revised form 25 December 2016
Accepted 21 March 2017
Available online xxxx

Keywords:
Line-up competition algorithm
Order assignment rule
Multi-stage multi-product
Parallel unit
Scheduling optimization

ABSTRACT

A novel rule-based model for multi-stage multi-product scheduling problem (MMSP) in batch plants with parallel units is proposed. The scheduling problem is decomposed into two sub-problems of order assignment and order sequencing. Firstly, hierarchical scheduling strategy is presented for solving the former sub-problem, where the multi-stage multi-product batch process is divided into multiple sequentially connected single process stages, and then the production of orders are arranged in each single stage by using forward order assignment strategy and backward order assignment strategy respectively according to the feature of scheduling objective. Line-up competition algorithm (LCA) is presented to find out optimal order sequence and order assignment rule, which can minimize total flow time or maximize total weighted process time. Computational results show that the proposed approach can obtain better solutions than those of the literature for all scheduling problems with more than 10 orders. Moreover, with the problem size increasing, the solutions obtained by the proposed approach are improved remarkably. The proposed approach has the potential to solve large size MMSP.

1. Introduction

In batch chemical industry many products are processed through several sequentially connected stages. In order to improve the efficiency of production, non-identical parallel processing units are used in each stage. In such plants, the scheduling of plant operations is a routine activity. However, because of the many alternate ways in which orders can be assigned to various units and produced in different sequences, the task of optimal scheduling is formidable. Hence, the multi-stage multi-product scheduling problem (MMSP) in batch plant has received great attention from both academia and industry. In the past decades, many studies on MMSP have been reported in the literature [1–7]. The main solution methods is to establish mixed-integer linear programming (MILP) model first, including objective function and a set of equality and inequality constraints, then solve the model using a modeling software.

Pinto and Grossmann [8] presented a continuous-time mixed-integer linear programming (MILP) model with continuous time representation for MMSP, which relied on the use of parallel time axes for units and tasks. Later, they proposed an alternative model in which the pre-ordering of orders was imposed explicitly by applying a representation of the time slots for the units. This resulted in a significant reduction in the computational time [9].

Hui and Gupta [10,11] established a MILP model for MMSP using three-dimensional 0–1 variables instead of tetra-index 0–1 variables to represent the sequence-dependent relationship between order and equipment. The main advantage of this model compared to the other previously proposed formulations was the significant reduction in model size and consequently shortening the solution time.

Gupta and Karimi [12] presented a continuous-time MILP formulation without using time slots for short-term scheduling of such plants. The formulation allowed both sequence-dependent and unit-dependent setup times and common operational considerations such as order/unit release times. They developed novel constraints for assignment of consecutive orders on a single unit and evaluated them thoroughly to identify the best constraints. Case study results showed the superiority of the proposed formulations.

Castro and Grossmann [13] presented a multiple-time-grid, continuous-time MILP model for MMSP. The formulation could handle both release time and due dates with different time-based objective functions efficiently, such as the minimization of total cost, total earliness, or makespan. Afterwards, Castro, Grossmann and Novais [14] presented another two kinds of continuous time MILP model based on multiple-time-grid to solve MMSP with sequence-dependent changeover time constraints.

Xue and Yuan [15] put forward MILP model with pre-ordering approach to solve MMSP. The pre-ordering approach could identify the infeasible assignments through which the number of binary variables was significantly reduced. Illustrative examples showed that the size of the proposed model was small, thus significantly shortening the solution time in comparison with the existing models in literature.

The above mentioned methods took the same way for solving MMSP. First, a group of binary variables were introduced to indicate the order allocation and the unit selection. Then, the MILP models for MMSP were built using discrete or continuous time representation

☆ Supported by the National Natural Science Foundation of China (No. 21376185)
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http://dx.doi.org/10.1016/j.cjche.2017.03.014
1004-9541/

Please cite this article as: B. Shi, *et al.*, Rule-based scheduling of multi-stage multi-product batch plants with parallel units, *Chin. J. Chem. Eng.* (2017), http://dx.doi.org/10.1016/j.cjche.2017.03.014

approach. Finally, some traditional deterministic optimization algorithms or commercial computing software were employed to solve to the models [16]. Because of the complexity of MMSP, MILP models established by traditional methods were large-scale and their generality were poor, which made it difficult to deal with complex constraints and only feasible for small size problem. When the problem size increases linearly, the computational time of MILP will increase exponentially. It is difficult for MILP to solve large-size MMSPs. Although some researchers claimed that their MILP models were suitable for large-size problems, the solutions to large-size problems were far from the optimum, even if the algorithm ran for very long time [16]. Therefore, it is urgent to explore reasonable scheduling model and seek more effective approach for solving large-size MMSP.

Different from the traditional MILP models of MMSP, He and Hui [16] presented a heuristic approach based genetic algorithm (GA) for MMSP. In their method, an order sequence was encoded into the chromosome of the GA. Through the evolutionary mechanism of GA, a group of random chromosomes was evolved to achieve the optimal or near-optimal solution.

In this paper, a novel heuristic rule based model for MMSP with parallel unit is presented. The multi-stage multi-product batch production process is then divided into multiple sequentially connected single process stages by using hierarchical scheduling strategies combined with the concepts of "virtual release time" and "virtual due date". According to the features of the proposed model, line-up competition algorithm (LCA) is introduced to solve the MMSP model. The performance of the proposed method is illustrated by solving two typical complex illustrative MMSP examples.

The rest of this paper is organized as follows. Section 2 details mathematical model of MMSP with parallel units, and presents hierarchical scheduling method; Section 3 introduces computational procedures of LCA for MMSP. In Section 4, problems from the literature are solved to illustrate the performance of the proposed approach. Finally, the conclusions are given in Section 5.

2. Model Development

2.1. Problem definition

In this paper, the scheduling problem of multi-stage multi-product batch plants with parallel units is considered. In MMSP, a set of production orders is to be processed. Each order, involving a single product, requires a certain number of processing stages (as shown in Fig. 1). The features of this process are as follows:

(1) Each order has a predetermined release time and due date;
(2) Each order involves a single product requiring a single processing batch;
(3) Each order requires multiple successive processing stages, and can only be processed once in each stage.
(4) Each order can only be processed in a subset of the given units in each stage. It means that there may be forbidden units for each order. The process time of order is unit-dependent.
(5) Some units have finite unit release times. Hence, they are not available from the beginning of the time horizon of interest.
(6) A unit processes only one order at a time. When one order changes over to another order, time for unit cleaning and preparing is required. The changeover times are sequence-dependent or both sequence- and unit-dependent;
(7) Because of flavor and/or color incompatibilities, some order sequences are forbidden at any equipment item.
(8) Each unit belongs to one production stage, at the same time it can only handle one order.

Given all the above features, the scheduling problem to be tackled involves determining (1) the allocation of orders to units in each stage, (2) sequencing orders in each unit, and (3) timing each order so that all scheduling constraints are taken into account and, at the same time, some measures of the customer satisfaction and/or the plant performance are optimized.

The following assumptions are used to derive the scheduling formulation for MMSP:

(1) All the model parameters are deterministic.
(2) Materials of each order are constant throughout the process, no material loss.
(3) Once a batch of materials was produced, it cannot be interrupted during the process.
(4) No resource constraints except unit are considered.
(5) There is unlimited intermediate storage between two stages.

2.2. Scheduling objectives

Two typical time-based scheduling objectives, total flow time and total weighted process time, are chosen to be optimized [8,16].

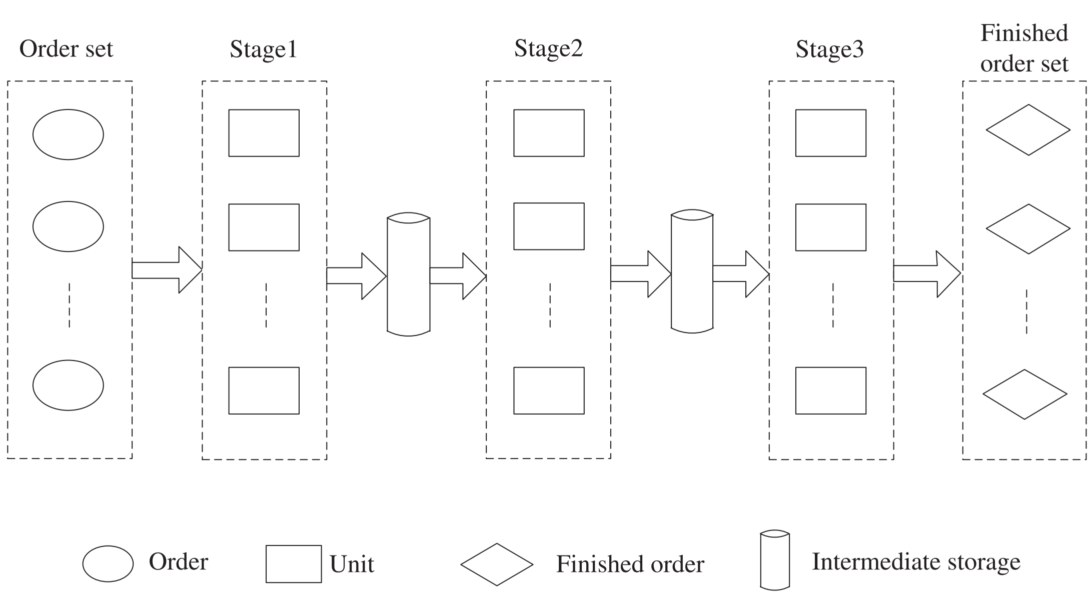

Fig. 1. Schematic of a multistage batch plant with parallel units.