Improved exact and meta-heuristic methods for minimizing makespan of large-size SMSP

Yaohua He\textsuperscript{a}, Yingzong Liang\textsuperscript{b}, Zuming Liu\textsuperscript{a}, Chi-Wai Hui\textsuperscript{b,⁎}

\textsuperscript{a} Department of Chemical & Biomolecular Engineering, National University of Singapore, 117585, Singapore
\textsuperscript{b} Department of Chemical & Biomolecular Engineering, Hong Kong University of Science and Technology, Hong Kong

A R T I C L E   I N F O

Keywords:
Unrelated parallel machine scheduling
Mixed integer programming
Heuristic
Simulation-based optimization

A B S T R A C T

The single-stage multi-product scheduling problem (SMSP) in a batch plant with unrelated parallel units has been solved by both exact and meta-heuristic methods. Although new ideas have been put forward continually, large-size instances are still challenging due to the NP-hardness of the problem. This paper extends the fastest mixed integer linear programming (MILP) model so far for SMSP with sequence-dependent changeovers to general cases where unit/order release times need to be considered. Improved versions of the line-up competition algorithm (LUCA) are also proposed. Computational tests with representative examples indicate that the improved versions are more effective in solving large-size SMSP.

1. Introduction

The single-stage multi-product scheduling problem (SMSP) in a batch plant with unrelated parallel units is an important sequential process scheduling issue (Floudas and Lin, 2004). A SMSP requires only one single stage to process a product (or an order), and there are parallel processing units for selection. In the studied SMSP, all batches of the same order are assumed to be processed consecutively by one unit. SMSP has been widely studied by a number of researchers. The solution methods can be classified into the four categories: mixed integer linear programming (MILP), constraint programming (CP), heuristics (using scheduling rules in practice) and meta-heuristics (a term widely used in computing intelligence). MILP and CP are called exact methods which can prove optimality, but are intractable in solving large-size problems. Meta-heuristics are usually called stochastic methods in mathematical and chemical communities, and are effective in solving large-size problems but cannot prove optimality.

A continuous-time MILP model for SMSP was proposed Cerda et al. (1997). Tri-index decision variables as well as the concept of predecessor and successor were used to describe the order assignment to various production units while considering sequence-dependent changeover constraints. To deal with large-size problems, heuristics, such as preordering, were applied to reduce the number of feasible predecessors for each order. On the basis of the notion of time slots, two models were proposed by Karimi and Medonald (1997) for parallel semi-continuous processes considering sequence-dependent setup times, orders, and their corresponding due dates in order to minimize the inventory. The major advantage of this formulation is that it can incorporate fixed time events such as due dates while using continuous-time representation.

Hui and Gupta (2001) presented a general MILP model for SMSP. The model applied three sets of bi-index decision variables to handle order sequence-dependent constraints. The main advantage of this formulation is the significant reduction in the number of binary variables, consequently shortening the solution time. The authors claimed their method suitable for handling large-size industrial problems, though the tested instances were only up to 20-order.

Chen et al. (2002) developed an MILP model for SMSP using the continuous-time representation and the concept of time slot. The allocation of orders and units to time slots were represented by two sets of binary variables. Their MILP model not only involved fewer binary variables than any other models based on the notation of time slot (Pinto and Grossmann, 1998), but also was able to deal with different objective functions.

An important advance was introduced by Sundaramoorthy and Karimi (2005) in a MILP model without big-M constraints. Higher efficiency is achieved compared with other methods in maximizing profit and minimizing makespan.

A new RTN-based continuous-time MILP model for SMSP was presented by Castro and Grossmann (2006). The model was based on the general formulation by Castro et al. (2004), but with one obvious difference: a different time grid was used for each unit instead of a single time grid for all events taking place. In their model, release times and due dates are calculated explicitly. The new formulation out-
performed other continuous-time MILP models and standalone CP models (Jain and Grossmann, 2001), and was similar to the hybrid MILP/CP method by Maravelias and Grossmann (2004) on a set of examples where the objective was total cost minimization, or total earliness minimization. However, this model did not consider changes between jobs. Hence, Castro et al. (2006) presented two new multiple-time-grid continuous-time formulations for MMSP and SMSP, CT4I and CT3I, where the processing units were subject to sequence-dependent changeovers, product orders were subject to both release times and due dates, and the objective was the minimization of total cost, total earliness or makespan.

For makespan minimization, the multiple-time-grid, continuous-time formulation by Castro and Grossmann (2006) is not the best efficient exact method. The CP method and the discrete-time formulation were found to be the best exact methods (Castro and Grossmann, 2005), though these two methods suffered from the weakness of considering integer data and a rapid performance decrease with increasing problem complexity.

Inspired by the ideas of subtour elimination (Miller et al., 1960) and tight lower bound for the makespan (Erdrik-Dogan and Grossmann, 2007), Liang and Hui (2016) came up with the fastest exact method. The CP method and the discrete-time formulation were found to be the best exact methods (Castro and Grossmann, 2005), though these two methods suffered from the weakness of considering integer data and a rapid performance decrease with increasing problem complexity.

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With respect to meta-heuristic methods for SMSP, He and Hui (2007a) first developed a genetic algorithm (GA) combining heuristic rules for large-size SMSP with forbidden changeovers and processes (CP constraints). The CP constraints can be easily handled in the MILP model by fixing relevant decision variables with zeros, which enable the solver to reach the optimum faster and to achieve better solutions because the constraints cut search branches. However, the existence of CP constraints was once the reason or excuse for rejection of heuristic methods. The penalty method used to handle the CP constraints allowed the proposed GA to effectively solve the large-size SMSP. He and Hui (2008) further applied the rule-based GA to other examples, including an example generated randomly with up to 200 orders to be processed by 16 units and benchmarks from the literature (Castro and Grossmann, 2006; Castro et al., 2006), and the performance of the rules summarized in He and Hui (2007b) were tested.

Considering the problem-dependent performance of the heuristic rules used in the algorithms, He and Hui (2006) presented the idea to let the algorithm automatically select the appropriate rules for problems investigated. Based on the impact factor analysis to the heuristic rules, He and Hui (2007b) systematically summarized seven rules for the objective of makespan related minimization. Meanwhile, they developed the automatic rule combination (ARC) method for SMSP.

Based on our previous work, Shi et al. (2012) presented the line-up competition algorithm (LUCA) to obtain optimal order sequence and unit-selection rule for SMSP. The objective was to minimize makespan, total tardiness or total cost. In addition to the rules for minimizing makespan and total tardiness adopted from He and Hui (2006, 2008), four rules for minimizing total cost were presented. LUCA obtained better solutions for some instances than our previous work (He and Hui, 2006, 2007a, 2007b, 2008).

However, LUCA does not outperform the previously proposed meta-heuristic methods if both solution speed and quality are taken into account. In fact, LUCA is a genetic algorithm that dismisses the crossover operation and only uses the mutation operation for evolution. LUCA searches in a larger solution space during each iteration and runs more iterations for better solutions. What is more, LUCA itself can be further improved in two aspects at least, the way to update new generation and the mutation process. In this paper, we first come up with the improvements on LUCA, subsequently conduct a comprehensive comparative study under the condition of the same hardware and software, which implies that the comparison does make sense.

2. Problem description and an Adapted MILP model

2.1. Problem description

In a single-stage multi-product plant, a number of unrelated processing units (M) are available to process a number of customers' orders (N). Each unit u can be ready for use at time uru, which is defined as unit release time. Each order i can be ready for processing by a unit at time ori, which is defined as order release time. An order can be processed by a unit through one stage, i.e., once one order is processed by one unit, the processing cannot be interrupted until the job is completed. At the completion time (Ci), the order is ready to be delivered to the customer. An order can be processed by some, if not all, units in the plant, but the processing time pui is unit-dependent. For a unit to process two consecutive orders i and j, a changeover time orij is required, and it is sequence-dependent. Some changeovers may be forbidden. Because of the unit-dependent processing times, sequence-dependent changeover times and possibly different order/unit release times, the assignment of N orders to M units with shortest completion time (minimizing makespan Cmax=max{C1, C2, ..., CN}) is an interesting combinatorial optimization problem, which challenges the researchers to propose various scheduling algorithms, including exact and heuristic methods. The single-stage multi-product scheduling problem (SMSP) with unrelated parallel units can be classified into unrelated parallel machine scheduling (Pinedo, 1995).

Example 1, i.e., Example 1 in He and Hui (2008), or Example 2 in Shi et al. (2012), is used to illustrate the algorithms in this article. Table 1 presents the problem data of the 10-order/4-unit instance of Example 1.

<table>
<thead>
<tr>
<th>orj</th>
<th>Processing times (pui)</th>
<th>Changeover times (orij)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>u1</td>
<td>u2</td>
</tr>
<tr>
<td>11</td>
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</tr>
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<td>12</td>
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</tr>
<tr>
<td>16</td>
<td>0</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>110</td>
<td>0</td>
<td>7.80</td>
</tr>
</tbody>
</table>

orj = order release time; uru = unit release time.
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