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Production Scheduling of a Large-Scale Industrial Continuous Plant: Short-Term and Medium-Term Scheduling

Munawar A. Shaik,[a] Christodoulos A. Floudas,[a] Josef Kallrath,[b] Hans-Joachim Pitz[b]

[a]*Department of Chemical Engineering, Princeton University, Princeton, NJ 08544, USA, floudas@titan.princeton.edu*
[b]*BASF Aktiengesellschaft, Scientific Computing,GVC/S – B009,D-67056, Ludwigshafen, Germany, josef.kallrath@web.de*

Abstract

In this work, we describe short-term and medium-term scheduling for a large-scale industrial continuous plant. For medium-range scheduling, two sub-problems are solved using a rolling horizon based decomposition scheme. An upper-level model is used to find the optimal number of products, and length of the time horizon to be considered for solving the lower level short-term scheduling problem. At the lower level, we proposed an improved model for short-term scheduling of continuous processes using unit-specific event-based continuous-time representation. The proposed formulation is demonstrated on an industrial large-scale polymer compounding plant comprising several processing and storage units operating in a continuous-mode for producing hundreds of different products over one month time horizon.

Keywords

Short-term scheduling, medium-term scheduling, continuous-time, event based, continuous process, storage, state-task-network.

1. Introduction

The short-term and medium-term scheduling problem of continuous plants has drawn less consideration in the literature compared to that of batch plants, although continuous units are prevalent in the chemical process industries. In medium-range scheduling relatively longer time horizons of several weeks are considered, while short-term scheduling deals with shorter time horizons of the order of several hours to days. The medium-term scheduling problem is more difficult to solve, and hence, it invariably involves some kind of decomposition schemes in practice [1-2], especially for large-scale industrial problems [3-4].

In this work, we present short-term and medium-term scheduling for a large-scale industrial continuous plant. For medium-range scheduling, a rolling horizon based decomposition scheme [2-3] is used and two sub-problems are solved. At the upper-level, a variation of the model proposed in [2-3] is used to find the optimal number of products, and length of the time horizon to be considered for solving the short-term scheduling problem at the lower level. At the lower level, we propose an extension of the model in [5] for short-term scheduling of continuous processes using unit-specific event-based continuous-time representation [2-12]. A comparative study of different continuous-time models for short-term scheduling of batch plants can be found in [7]. Earlier, Ierapetritou and Floudas [6] had proposed an approximation of the storage task timings for handling different storage requirements for short-term scheduling of continuous plants. Shaik and Floudas [5] extended the model in [6] in order to precisely handle the different storage requirements. The formulation in [5] is based on the state-task-network representation resulting in a mixed-integer linear programming (MILP) model that accurately accounts for various storage requirements such as dedicated, flexible, finite, unlimited and no intermediate storage policies. The formulation allows for unit-dependent variable processing rates, sequence-dependent changeovers and with/without the option of bypassing of storage requirements. In this work, we extend the formulation in [5] to adapt to the requirements of an industrial large-scale polymer compounding plant comprising several processing and storage units operating in a continuous-mode for producing hundreds of different products over one month time horizon.

In the next section, the problem statement for medium-term scheduling of an industrial continuous plant is described. The proposed methodology along with the results for the industrial problem considered is presented in Section 3, followed by conclusions in Section 4.

2. Problem Statement

The medium-term scheduling problem can be defined as follows: Given the production recipe of the plant in terms of task sequences, suitable units and their capacities, the processing rates and cleanup times, storage policy for the intermediates, the time horizon, demands and due dates of different products that can be produced; the aim in medium-term scheduling is to determine the optimal sequencing of tasks in each unit, the amounts to be produced, the start times and processing times of each task, in order to satisfy the market requirements while maximizing/minimizing some objective function. The medium-term scheduling problem is similar to the short-term scheduling problem except that the time horizon considered is relatively longer thus resulting in a large-scale MILP model which is more difficult to solve using the currently available computational resources. Hence, we use a rolling horizon based decomposition scheme [2-3] to enable solving this problem in reasonable computational time.

The industrial problem considered comprises of 10 parallel extruders in two different buildings (5 extruders in each building) and about 85 units. The basic operations are continuous feed transfer, feed silo storage, polymer extrusion, product silo storage, and final product filling. The plant produces about 100 products that belong to 65 different grades over one month time horizon. The feed and product silos have finite storage requirements. The plant additionally has several special restrictions such as limitation on the usage of number of parallel filling units, restriction on product lifting on weekends, time-dependent limitation on raw material availability, and restrictions on changeover timings, which are handled efficiently using the proposed formulation described in the next section.

3. Proposed approach

In this work we use a variation of the decomposition scheme in [2-3] for solving the overall medium-term scheduling problem as described below.

3.1. Methodology

The overall framework for solving the medium-term scheduling problem consists of two sub-level problems to be solved iteratively in a rolling horizon approach. At the upper level the objective is to determine the length of the sub horizon, and the total number of products and their demands to be included at the lower level short-term scheduling problem. The lower level short-term scheduling problem is then solved for each of these sub-horizons in a rolling horizon manner until the demands of all products are met. Before solving each sub-horizon, preprocessing of data is done to ensure there is sufficient demand of products from all critial units through product demand aggregation.

3.1.1. *Upper-level decomposition model*

To enable solution of the overall medium-term scheduling problem in reasonable computational time, we must consider trade-off between quality of solutions and required computational resources. This is accomplished through the upper level decomposition model used to find the number of products and their demands to be included in the sub-horizon for short-term scheduling, by using the model complexity limit, which imposes restriction on the size of the lower level scheduling problem in terms of the number of binary variables that can be handled to find a good feasible solution in reasonable computational time. The proposed model for the upper level is a variation of the model used in [2-3]. It distinguishes products which are make-to-order (MTO) and make-to-stock (MTS). The MTO products that have demands in the current sub-horizon are always selected. When a product is selected in the current sub-horizon, the proposed model allows partial selection of its demand to effectively match the computational complexity limit. Similarly, for articles that are filled through trucks the complete demand due in the given sub-horizon is always selected. Additionally, the upper level model itself has provision for imposing a minimum utilization of all critical units (for instance extruders in the industrial problem considered), while selecting products to be included in the current sub-horizon.

3.1.2. *Lower-level short-term scheduling model*

Given the length of the sub-horizon, the products selected and their demands from the upper level decomposition model, the lower level short-term scheduling model seeks to find the optimal sequencing, the amounts to be produced, the start and finish times of different tasks in each unit. Compared to the earlier model in [6], the model in [5] presents improved sequencing and rigorous storage constraints using unit-specific event-based continuous-time representation. In this work, we extended the short-term scheduling model for continuous plants in [5], to adapt to the specific requirements of the industrial problem considered. In the industrial case study considered, there are additional restrictions such as: (i) no product filling by trucks in the weekends because of higher costs, (ii) no changeovers are allowed between 4 to 7 am/pm (during shift change) in the extruders because of manpower limitations, (iii) changeover from phosphorous products to non-phosphorous products in the extruders can only occur between 7:30 am to 1:30 pm of the day shift due to safety requirements, (iv) minimum lot size restriction for some extrusion tasks, to be modeled as a soft constraint, and (v) some units have higher priority for utilization compared to other units. To handle the restrictions on changeover timings in the proposed model, changeovers in the extruders are treated as separate tasks, and the start and end times of the changeover tasks are accordingly restricted at such event points, which are estimated to be proportional to the fraction of total length of short-term horizon available. The objective function considered is minimization of several penalty terms: for underproduction, overproduction, late production, early production, penalty for violation of minimum lot-size in extruders, penalties for minimizing the idle time on critical units, and penalties on total number of binary variables, subject to maximization of total production. There is higher penalty for underproduction and tardiness of MTO products and truck filled products compared to MTS articles.

3.2. Case study

The proposed framework is applied to the industrial polymer compounding plant discussed earlier. Additionally, some preprocessing steps are carried out before solving the upper and lower level models. To handle the truck ban restriction on weekends, all the truck filling products that have demands on weekends are moved earlier to the weekdays, and higher penalties are imposed for underproduction of these products on weekdays. No product aggregation is done for truck filled articles to minimize the wait time of trucks. To ensure efficient utilization of all extruders in each sub-horizon, the MTS products are aggregated and moved to earlier days. There are demands for about 100 products over one month time horizon. Not all products are suitable on every unit. In the decomposition model, we consider 60 sub-horizons of each 12 h. Using a model complexity limit of 1000 binary variables, and 8 event points, we iteratively solve the upper level and lower level models in a rolling horizon approach.

3.3. Results & discussions

In the upper level model, we used a maximum limit of one sub-horizon to be selected. In each sub-horizon, for the products and demands selected by the upper level, the proposed lower level scheduling model is solved for about 15 to 20 min CPU time. The computations are performed on 3.2 GHz, Pentium 4 machine with 1 GB RAM using GAMS (distribution 21.7) and CPLEX 9.0.2. The total demand of all products (4381.2 tons) for the one month (720 h) is met within 54 sub-horizons of each 12 h. There is no underproduction of any product. The overall computational time for solving all the 54 sub-horizons is about 24 h. We have an overall overproduction of about 400 tons and the maximum finish time among all units is about 644 h, which is much before the end of the overall time horizon (720 h). All the extruders are efficiently utilized with minimal idle times. Additionally, in each of the extruders we have some free time available indicating additional production capacity. The overall free time available in the ten extruders is: 410, 407, 225, 180, 156, 390, 410, 181, 132, and 210 hours, respectively. All the MTO demands are met on time. No truck articles are delivered on weekends. No changeovers take place in the extruders during shift change timings. All changeovers from phosphorous products to non-phosphorous products occur during the specified timings of the day shift. The model runs smoothly without interruption for all the sub-horizons.

4. Conclusions

In this paper, we present short-term and medium-term scheduling of a large-scale industrial continuous plant. To enable solving the overall medium-term scheduling problem in reasonable computational time, we use a variation of the rolling horizon based decomposition scheme used in [2-3]. At the upper level, the proposed model is flexible and can include partial demands, while selecting products to be included at the the lower level scheduling problem based on the computational complexity limit. In the lower level scheduling model, we proposed a novel mathematical model for short-term scheduling, which is an extension of the models in [5-6], to adapt to the requirements of an industrial case study. The proposed framework is demonstrated on an industrial continuous polymer compounding plant resulting in efficient utilization of the critical units (extruders).

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