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Overview of Industrial Batch Process Scheduling

Máté Hegyháti, Ferenc Friedler*
Department of Compurer Science and Systems Technology, University of Pannonia
Egyetem u. 10, Veszprém, 8200 Hungary
friedler@dcs.uni-pannon.hu

The operation of a production facility has a major effect on the efficiency; therefore it is of upmost importance to find the best possible schedule. Due to the high practical expediency, the topic of batch process scheduling has gained growing interest in the last two decades and many approaches have been published to solve a wide variety of scheduling problems. In the present work first the different type of batch scheduling problems are overviewed, then the advantages and disadvantages of the available methods for batch process scheduling are summarized.

1. Problem Definition

Batch production plants provide a wide range of scheduling problems that can be categorized based on many parameters. Méndez et. al. (2006) has given a detailed roadmap for classifying batch scheduling problems. Here, only the three major aspects are highlighted.

A batch process is usually described by a recipe that gives an ordering of tasks to produce the desired product. In the most general case, this connection of tasks is described by a network, however, in many case studies and literature examples the tasks have a sequential ordering. Even for sequential processes, two subclasses of recipes have to be distinguished: in multiproduct processes each of the products has the same sequential production, whereas in the multipurpose case each product is produced by different sequence of the same production steps.

The intermediate storage policy is another important parameter for batch scheduling problems that can strongly affects both the problem's complexity and the optimal solution. If the materials can be stored in any amount without any limitation, it is called Unlimited Intermediate Storage (UIS) policy. On the contrary, if the storage vessels have finite capacity, it is denoted as Finite Intermediate Storage (FIS) or Common Intermediate Storage (CIS) policy, depending on whether the intermediate materials has dedicated or common storage units. In case of the absence of storage equipments, Non-intermediate Storage (NIS) policy is assumed, where the intermediates can be stored only in the processing units until they are transferred to a different unit for further production. The most strict storage policy is called Zero Wait (ZW), when no storage is allowed for the intermediates, not even in the processing units. It is also common in the industry for a process to have different storage policies for different intermediates that is called Mixed Intermediate Storage (MIS) policy.

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Finally, the goal of the optimization has to be mentioned. The two most common objectives in batch process scheduling are the minimization of the overall processing time, called makespan; and the maximization of the profit or throughput for a given time horizon. In practice, other aspects can be considered as constraints or objectives, e.g., wastewater generation (Gouws and Majozi, 2009) or heat recovery (Adonyi et. al., 2003).
Furthermore, the degree of uncertainty (Li and Ierapetritou, 2008), sequence dependent setup times (Kopanos et. al., 2009), etc., can influence the problem complexity.

2. Mathematical Approaches

Over the last two decades, lot of approaches has been developed to solve batch scheduling problems that can be classified also in many different ways. One obvious aspect is the applied mathematical model during the optimization. Most of the published approaches formulate the problem as a mixed integer linear programming (MILP) or mixed integer non-linear programming (MINLP) model (Floudas and Lin, 2004). On the other hand, some methodologies use special graphs as the mathematical models, like the S-graph (Sanmartí et. al., 2002) or timed automata (Panek et. al., 2008).

2.1 MILP and MINLP based approaches

For the mathematical programming techniques, the crucial point is the definition of the binary variables, that mostly determines the efficiency, size, and applicability of the proposed model. Among the published mathematical programming approaches two main classes of formulations can be distinguished: time point and precedence based models. Recipe representation is also a common aspect to classify MILP based models. The first general network representation was the State-Task Network (STN), where circles represent the states and rectangles represent the tasks (Kondili et. al., 1993). Pantelides (1993) has presented the Resource-Task Network (RTN), where circles represent not only states, but any type of resources, including processing units as well. Later on, Majozi and Zhu (2001) have introduced the State-Sequence network (SSN) for multipurpose processes, where the network is a directed graph, which vertices are the so-called effective states of the process. Figure 1 shows the flowsheet and STN, RTN, SSN representation of the same process.

2.1.1 Time point based formulations

In case of time point or time interval based models the time horizon is discretized by a predefined number of time points or time slots. The typical binary variable is $y(i,j,n)$, which denotes whether task i is performed in unit j at event point n, thus the number of binary variables strongly depends on the number of time points. However, there is no known approach to determine the sufficient number of time points for the globally optimal solution, thus an iterative approach is usually used, which may result in suboptimal schedules (Castro et. al., 2001). On the contrary, these models can address general network based scheduling problems with batch sizing, due dates, material balances and various storage policies.

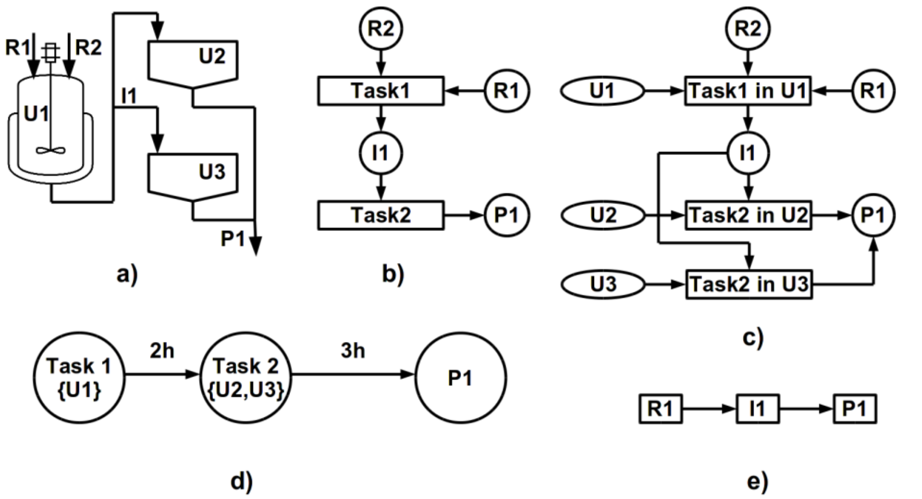

Figure 1: Representations of a process: a) flowsheet b) STN c) RTN d) S-graph e) SSN.

The earliest models discretized the time horizon into a certain number of even time intervals (Kondili et. al., 1993). These models are called discrete-time models, which provide relatively simple constraints, but need a large number of time points to achieve solution with reasonable quality. To reduce the number of binary variables, continuous-time approaches were developed for both sequential (Pinto and Grossmann, 1995) and network based (Zhang and Sargent, 1996) scheduling problems, where the discretization of the time horizon is not equidistant, a new continuous variable is assigned to the exact timing of each global time point. In the sequel, unit-specific continuous-time models were presented (Ierapetritou and Floudas, 1998), where the exact time of the same time point can vary among different equipment units, which further reduces the necessary number of time points. Figure 2 illustrates the required number of time points in the case of different time discretization techniques.

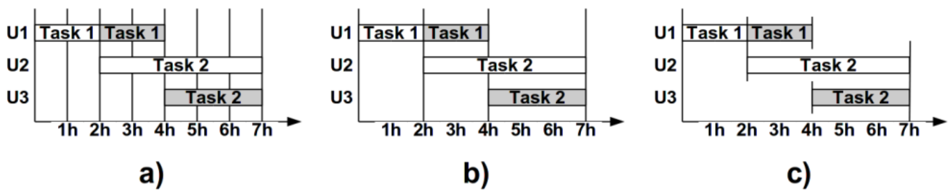

Figure 2: Different time point based formulations: a) discrete b) global continuous c) unit specific continuous.

2.1.2 Precedence based formulations

Precedence based MILP formulations can be categorized to general precedence (Méndez *et.* al., 2001); immediate precedence (Méndez et. al., 2000); unit-specific immediate precedence (Cerdá et. al., 1997) models based on the exact definition of the binary variables. These binary variables denotes whether batch *i* is preceded by batch i′ immediately or indirectly in a certain unit or all of the units. This type of approaches do not require to discretize the time horizon, i.e., there is no need to define the number of time points a priori. On the other hand, the size of this models is sensitive to the number of batches, and resource limitations are difficult to implement (Kopanos *et. al.*, 2010). Due to the definition of binary variables, the branch-and-bound algorithm solving the model has similar search space to the graph based approaches described in the next section.

2. Graph Based Models

Graph representation fits more to the combinatorial nature of scheduling problems, than mathematical programming formulations, therefore, graph based methods can effectively exploit the specific nature of the problem. Since these approaches are a new direction in batch process scheduling, the introduced frameworks has not yet been extended to address all specific classes of industrial problems. Due to their strict mathematical model generation, they never provide infeasible solutions, which problem may arise with MILP based models (Hegyháti et. al., 2009).

2.1 S-graph framework

The S-graph framework was originally developed to solve makespan minimization problems with NIS policy (Sanmartí et. al., 2002). The mathematical model for the optimization is a directed graph, in which the nodes represent the tasks and products of the process. The ordering of tasks in time is expressed by two set of arcs: recipe-arcs and schedule-arcs. The former ones are included in the so-called recipe graph (see Figure 1), which features as the input of the branch-and-bound based optimization algorithm. The schedule-arcs are inserted into the graph based on the scheduling decisions that has been made through the optimization. The result is the schedule-graph, that uniquely defines the optimal schedule. The framework has been extended to throughput maximization problems by Majozi and Friedler (2006). The most important advantage of the S-graph framework is, that its rigorous mathematical foundation ensures the globally optimal solution of the problem, and never generates infeasible or suboptimal solutions. The problem specific model and algorithms usually results in less computational needs, but as the other side of the same coin, it requires deep insight and programming skills to extend the framework to undiscovered class of scheduling problems.

2.2 Timed-automata based models

Timed automata has been presented by Alur and Dill (1994) as the generalization of the ω-automata to accept infinite timed words over an alphabet. The automata is extended with a set of clocks, that can be reset by the transitions, or be a basis for state invariants or transition conditions. Although automata is usually used for analytical purposes, it has been shown, that it is suitable for optimization through reachability analysis (Fehnker, 1999). The extension with pricing parameters (Alur et. al., 2001) resulted in priced time automata, where the aim is to find a path from the starting state to the target state with optimal cost. Based on this model, Panek et. al. (2008) formulated batch scheduling problems. The advantage of this approach is an automatic generation of the problem model by parallel composition, whilst batch-sizing, intermediate storage is still a challenging task to be solved with this approach.

3. Concluding Remarks

The large number of methods appeared for scheduling of batch processes differ in many aspects, and can solve a various classes of industrial problems. Most of the methods consider MILP formulation that can address a wide range of scheduling problems. Graph-based methods, that avoid modeling issues arising for MILP formulations, are introduced to special class of batch scheduling problems with the guarantee of global optimality and promising computational needs. MILP based approaches tend to reduce the model size, and provide more efficient formalizations, whilst graph theoretical approaches are being extended to wider range of scheduling problems.

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