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The role of energy consumption in batch process scheduling

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Abstract

Makespan minimization or throughput maximization, the most common objectives in batch process scheduling are related to economical aspects; energy consumption or sustainability are not directly taken into account (Mendez *et al.*, 2006; Hegyhati and Friedler, 2010). Some of the published methods consider utility cost (Adonyi *et al.*, 2003) or wastewater minimization (Halim and Srinivasan, 2010) during the optimization in addition to economical aspects, nevertheless, the overall energy requirements of a process have never been taken into account.

In the present work, a scheduling method is proposed that also considers the energy demands of transfer of liquid materials. In the available mathematical models, transfer of intermediate materials has impact only on the overall processing time, and does not express the energy consumption of the transfer. Transfer time of intermediate materials is usually regarded as a fixed value, however, there is an energy - time tradeoff for pumping of intermediate, raw, or product materials. The energy cost of transfer depends on the height difference between the source and destination, the cross-section area of the pipe, viscosity of the material, and the available time. The proposed method integrates pumping strategies into the general scheduling problem to tackle the transfer energy demands. Although this energy is much smaller in magnitude compared to the usual heat energy requirements, still, it is worth investing effort in its reduction, since it is in the form of electrical energy.

Keywords: batch, scheduling, transfer energy, optimization

1. Introduction and problem definition

The S-graph framework was introduced by Sanmarti *et al.* (2002) for makespan minimization with non-intermediate storage (NIS) policy, and has been extended later to other storage policies and objective functions. The concepts proposed for the integration of energy consumption of liquid material transfers can be applied for all of the storage policies and objective functions formerly addressed by the S-graph framework. This paper covers the minimization of energy requirements for material transfer with respect to predefined time horizon and batch sizes considering NIS operational policy. To facilitate understanding, a brief introduction is given about the S-graph framework.

The mathematical model of the framework is a directed graph, called S-graph, in which a vertex is assigned to each task and to the events of removing each final product from the unit in which it was produced. The task precedence of the recipe is represented by so-called recipe-arcs. The weight of each arc expresses the processing times. The vertices and the recipe-arcs together form the S-graph for the recipe; it is the input of the combinatorial optimization algorithm. A simple S-graph representing a recipe is given in Figure 1, where three products, (*p1,p2,* and *p3*) are produced in thre units (*j1,j2,* and *j3*).

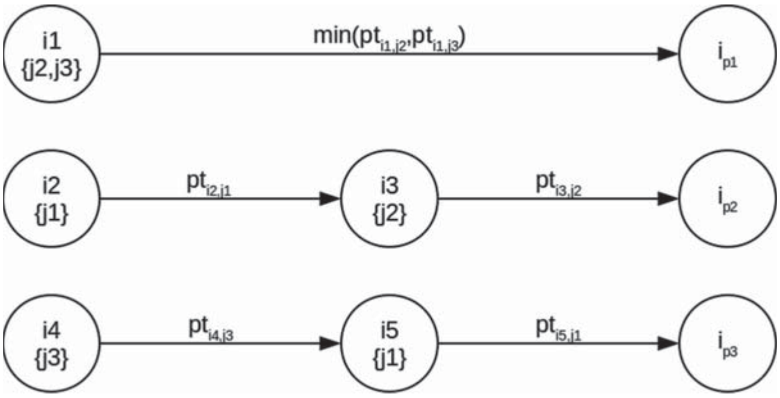

Figure 1: S-graph representing a recipe for a multipurpose batch process with three products

The first product is produced by a single step, *i1*, that can be performed in either unit *j2* or *j3*. The other two products are produced through two consecutive steps (*i2,i3* and *i4,i5,* respectively), each with only one applicable unit.

During the optimization process, the graph is extended with zero-weighted arcs, called schedule-arcs, that represent the sequencing of tasks assigned to the same unit. The resultant S-graph defines a schedule. Note, that this graph can unambiguously be transformed to any common schedule representations, e.g., to Gantt-chart.

In order to model the material transfers independently in the S-graph framework, special vertices are introduced for each material, as illustrated in Figure 2 for intermediates and products. Filling of raw materials is considered similarly by adding additional task nodes to the beginning of each recipe and special vertices for the raw materials.

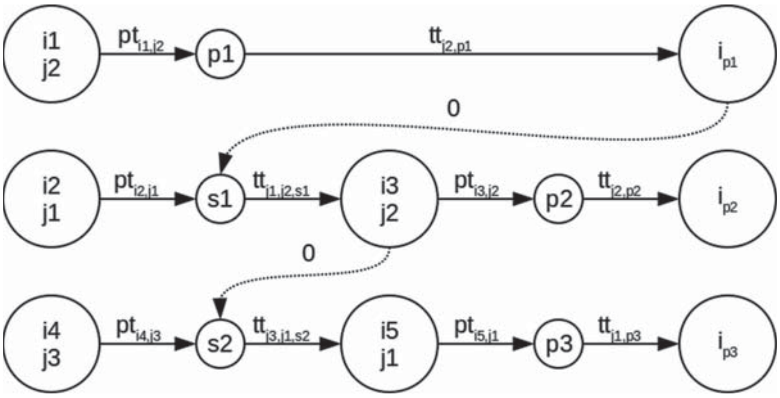

Figure 2: Material transfer representation on the S-graph

The problem considered in this paper is specified by the time horizon, recipe, batch sizes, required number of batches for each product, piping between units, and the vertical position of units.

Two different scenarios are addressed:

(i) Each pump has a single operating mode, i.e., for a material transfer the transfer time and energy requirement is a fixed value

(ii) For each transfer, several operating modes are available for the corresponding pump, where changing the operating mode alters the time and energy demand of the transfer

2. Minimizing energy of material transfers with fixed operating modes

Let parameters $tt_{j,j',s}$ and $tec_{j,j',s}$ denote the transfer time and energy cost for transferring material s from unit j to unit j'. These parameters are a priori given based on the fixed vertical position of the units, the material properties, and the fixed operating mode of the corresponding pump. Note that virtual units are introduced for feeding the raw materials and removing the products, thus their transfer costs can also be described by the aforementioned parameters.

To address this type of problems, the original S-graph based branch-and-bound algorithm presented by Sanmarti *et. al.* (2002) has to be modified at two points:

- the longest path algorithm providing the overall production time is to be applied for feasibility test;
- the bounding function is defined as the sum of $tec_{j,j',s}$, $min_j(tec_{j,j',s})$, $\min_{j'}(tec_{j,j',s})$, or $\min_{j,j'}(tec_{j,j',s})$ for all the materials depending on the allocation decisions that has already been made. It gives a lower bound for the overall energy consumption.

In a current implementation (Smidla and Heckl, 2010), both of these functions are evaluated in constant time. Thus, these modifications do not increase the complexity of the original algorithm.

3. Minimizing energy of material transfer with different operating modes

In addition to the previously mentioned potentials, each pump has several operating modes to choose from. Let $n_{jj'}$ denote the number of operating modes for the pump on pipes between units j and j'. For each operating mode k ($1 \leq k \leq n_{jj'}$), let $tt_{kjj's}$ and $tec_{kjj's}$ denote the time and energy demand for transporting material s from unit j to unit j'.

At a partially scheduled subproblem in the original branch-and-bound algorithm, the following steps are to be executed:

Step 1: For each material transfer the highest possible source and lowest possible destination is selected if this decision has not yet been made.

Step 2: Each material transfer is considered initially with the fastest, thus the most energy consuming operating mode.

Step 3: If the longest path violates the constraint on the time horizon, the subproblem is infeasible therefore, it is pruned from the branch-and-bound tree. Otherwise, continue with Step 4.

Step 4: If there is no material transfer, where energy consumption can be reduced by changing the operating mode of the corresponding pump without increasing the longest path over the time horizon, continue with Step 6, otherwise continue with Step 5.

Step 5: Select a material transfer that satisfies the above mentioned criteria, apply the energy saving change on the operating mode for the corresponding pump and continue with Step 4.

Step 6: The energy consumption of the current graph provides a valid upper bound for the subproblem.

At Step 4, several strategies can be considered for selecting material transfers. The described algorithm is fast to evaluate, however, the provided bound is not tight if there is a path in the graph which contains at least two transfer nodes. In order to get the minimal transfer energy cost for a scheduled graph at the leaf of the branch-and-bound tree, a generalized knapsack problem is to be solved.

4. Illustrative example

The proposed methodology is illustrated on a simple multiproduct batch process. The flowsheet of the process with the layout information, piping and processing times is given in Figure 3. The product is produced through two consecutive steps, each having two applicable equipment units. The energy and time demands for the transfer of the intermediate material for different operating modes are given in Table 1.

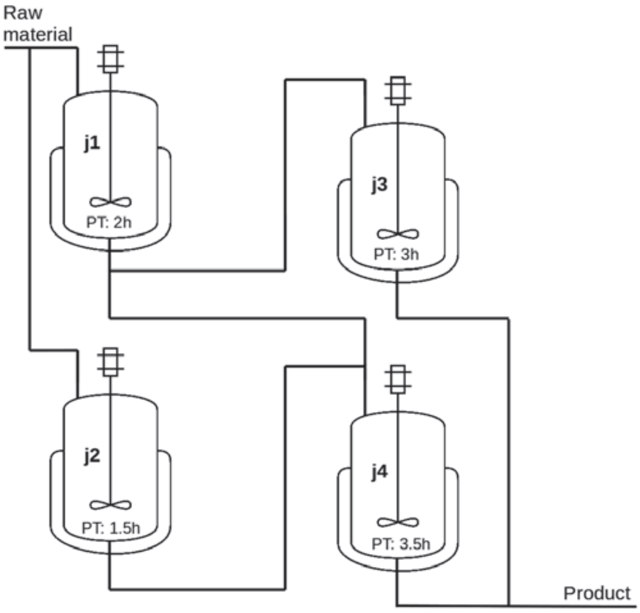

Figure 3: Flowsheet of illustrative example

Table 1: Material transfer parameters

Source unit	Destination unit	Operating mode	Transfer time	Energy consumption
j1	j3	Fast	15 min	10 kJ
		Slow	30 min	7 kJ
j1	j4	Fast	5 min	5 kJ
		Slow	15 min	2 kJ
		Off	30 min	0 kJ
j2	j4	Fast	30 min	10 kJ
		Slow	15 min	7 kJ

The objective is to minimize the energy required for the transfer of the intermediate material while producing 4 batches of the product within a 9 h time horizon. The optimal schedule with 34 kJ of energy consumption is shown in Figure 4 and 5.

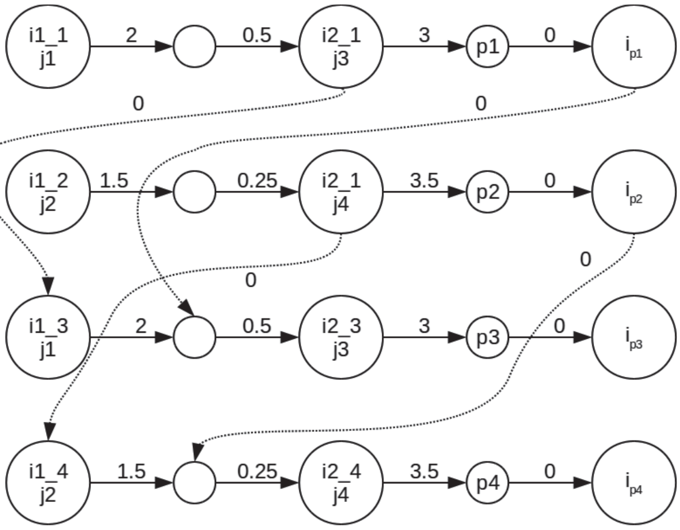

Figure 4: S-graph of the optimal solution for the illustrative example

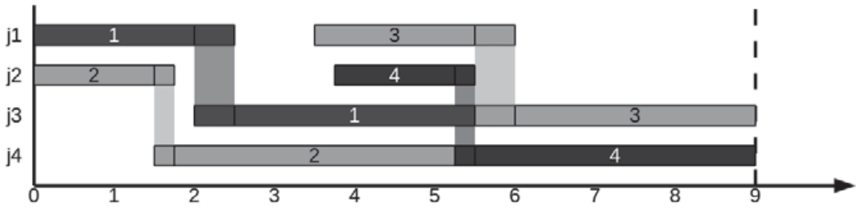

Figure 5: Gantt-chart of optimal solution for the illustrative example

5. Concluding remarks

The formerly developed S-graph framework has been extended to address the energy demands of liquid material transfers in batch process scheduling. The electrical energy used for transferring liquid materials is minimized with fixed batch sizes and time horizon. The proposed method can be integrated with other extensions of the S-graph framework, e.g., Adonyi *et. al.* (2003), to consider both transfer and heat energy demands.

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