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Optimal scheduling of single stage batch plants with direct heat integration

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ABSTRACT

This paper addresses the multi-objective optimization problem arising in the operation of heat integrated batch plants, where makespan and utility consumption are the two conflicting objectives. A new continuous-time MILP formulation with general precedence variables is proposed to simultaneously handle decisions related to timing, product sequencing, heat exchanger matches (selected from a two-stage superstructure) and their heat loads. It features a complex set of timing constraints to synchronize heating and cooling tasks, derived from Generalized Disjunctive Programming. Through the solution of an industrial case study from a vegetable oil refinery, we show that major savings in utilities can be achieved while generating the set of Pareto optimal solutions through the ε-constraint method.

1. Introduction

Energy efficiency is one of the easiest and most cost effective ways to combat climate change. Improving energy productivity by increasing energy efficiency is one of the objectives of the strategic plan of the United States Department of Energy (U.S. Department of Energy, 2014) that includes new capabilities to realize significant savings in the nation's industry. The European Union Framework Programme for Research and Innovation (Horizon 2020) also features a call (European Commission, 2014) that aims at organizational innovation to increase energy efficiency in industry, where savings of at least 13% are expected. In particular, activities should consider total-site energy management schemes and system optimization methodologies to identify saving potentials.

Process integration is the system-oriented approach for the efficient use of energy and includes pinch analysis (Linnhoff et al., 1982) as well as a variety of mathematical programming models (Biegler et al., 1997). The main concept is that by exchanging heat between a hot (at a higher temperature) and cold process stream, energy requirement for external utilities (e.g. steam, cooling water) is reduced twice, which in turn lowers the consumption of fossil (or renewables) fuels and electricity that are needed for their production. Process integration started with the optimal design and retrofit of industrial processes of the continuous type and has been extended to the design and operation of batch plants. Since the topic of the current paper, energy recovery in batch processes, has been the subject of a recent review paper (Fernández et al., 2012), the remainder of this section will focus on references that are closer to the approach being proposed.

While determining minimum utility consumption for a continuous plant can easily be accomplished through simple graphical methods like composite curves, heat cascades or linear programming models, the same cannot be said for batch plants. If the scheduling and heat integration decisions are decoupled, the complete schedule can be divided into a few time intervals with constant number of streams, and pinch analysis can be applied to each interval leading to the total utility consumption (Kemp and MacDonald, 1987). However, it was soon realized that rescheduling could lead to further savings (Kemp and Deakin, 1989), thus highlighting the importance of addressing the simultaneous scheduling and heat-integrated problem. This is a considerable more challenging problem that demands math-programming models.

There are two forms of heat integration in batch plants (Fernández et al., 2012). In direct heat integration, process streams can only exchange energy if they co-exist in time (at least partially).

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Nomenclature

Sets/indices

C/c	cold streams
H/h	hot streams
I/i	products
j	type of interaction between a hot and a cold stream (e.g. start-start, start-end)
K/k	subtasks of production recipe
K_i	subtasks of the recipe of product i
M/m	equipment units
M_i	predetermined unit for the production of product i
PS/ps	process streams (either cold or hot)
$PS_{i,k}$	single stream linked to product i subtask k

Parameters

$bm_{h,c}$	tightest big-M parameter for temperature driving force constraints between h and c
cp_{ps}	heat capacity of process stream ps (J/K)
hz	time horizon (upper bound on makespan) (h)
$p_{i,k}$	processing time for product i of subtask k (h)
$q_{h,c}$	maximum energy that can be exchanged between streams h and c (J)
$ramp_{ps}^{\min}$	minimum temperature-change rates for stream ps (K/h)
$ramp_{ps}^{\max}$	maximum temperature-change rates for stream ps (K/h)
t_{ps}^{in}	supply temperature of process stream ps (K)
t_{ps}^{out}	target temperature of process stream ps (K)
$\overline{ut}$	upper bound on utility consumption from epsilon-constraint method (J)
δ	width of subintervals in epsilon-constraint method (h)
ε	parameter of epsilon-constraint method for generating Pareto set (h)
$\underline{\varepsilon}/\overline{\varepsilon}$	lower/upper bound on ε (h)
Δt	minimum approach temperature (K)

Variables

$E_{i,k}$	ending time for product i of subtask k (h)
MK	makespan (h)
Q_h^{CUs}	energy removed by cooling utility during first cooling stage of hot stream h (J)
Q_h^{CUe}	energy removed by cooling utility during second cooling stage of hot stream h (J)
Q_c^{HUs}	energy supplied by hot utility during first heating stage of cold stream c (J)
Q_c^{HUe}	energy supplied by hot utility during second heating stage of cold stream c (J)
$Q_{h,c}^j$	energy exchanged between streams h and c during interaction of type j (J)
$S_{i,k}$	starting time for product i of subtask k (h)
T_{ps}^*	intermediate temperature in two-stage heating/cooling of stream ps (K)
Tm_{ps}	intermediate time in two-stage heating/cooling of stream ps (h)
Ts_{ps}	starting time of two-stage heating/cooling of stream ps (h)
Te_{ps}	ending time of two-stage heating/cooling of stream ps (h)
UT	total energy exchanged with hot and cold utilities (J)
$X_{i,i'}$	binary variable indicating if product i is produced before product i'
$Y_{h,c}^j$	binary variable indicating if the interaction between streams h and c is of type j

In indirect heat integration, a heat transfer medium is needed to gather the energy from the hot stream, which is then stored until the cold stream becomes available. While it requires auxiliary equipment, it provides additional operational flexibility and can thus lead to higher utility savings.

Papageorgiou et al. (1994) calculated the potential benefits of both direct and indirect modes with a discrete-time State-Task Network formulation. The incorporation of direct heat integration can be handled simply by defining heat integration tasks for each pair of streams in the process representation, resulting in a mixed-integer linear problem (MILP). Indirect heat integration requires a far more complex mixed-integer nonlinear model due to the need to consider rigorous mass and energy balances for the heat transfer medium. The most important assumption highlighted by the authors was the fixed operating characteristics of heat-integrated operations, with given heat loads for the heat transfer medium in the different hourly segments of the full duration of the task.

Also dealing with a multipurpose batch plant, Vaklieva-Bancheva et al. (1996) proposed a continuous-time formulation for the direct heat exchange mode. Assuming a maximum number of non-redundant campaigns, with each campaign featuring a subset of products not sharing equipment units, it is possible to determine a priori the total load of each potential match involving heat integration. The optimal campaigns and matches are selected through binary variables, limited to the constraint that during a campaign, each product is integrated with not more than one other product. If a match is indeed selected, it is assumed that the starting times of interacting tasks are the same, which has the advantage of automatically determining the relative timing of all stages for the two products involved (due to the zero-wait operating policy), besides avoiding the need to consider intermediate temperatures explicitly. The authors note that direct heat exchange may delay production to the extent that product demands are not met but no analysis is provided on the tradeoff between production time and total utility consumption.

Through the solution of a multistage batch plant with three products, eight equipment units and two hot and two cold process streams, Adonyi et al. (2003) showed that utility consumption with direct heat integration can be reduced considerably by loosening the upper bound on the makespan. Their S-graph approach for direct heat integration is also limited to at most one heat exchanger unit for each hot/cold stream.

Halim and Srinivasan (2009) addressed the bi-objective optimization problem involving total utility consumption and makespan for a multipurpose batch plant with direct heat integration. In their two-step optimization approach, the first step is concerned with generating the minimum makespan schedule by solving a MILP problem, which is followed by an integer-cut based stochastic search that generates alternate optimal solutions. In the second step, the time horizon is split into different time intervals and minimum utility targets are calculated for each interval of every generated schedule. After 1000 iterations, three sets of solutions with very similar makespans were obtained for the well-known Kondili et al. (1993) problem but no tradeoff was observed since the lowest makespan also corresponded to the lowest utility consumption. Seid and Majozi (2014) have found that such was in fact a dominated solution, reporting a schedule with improvements in both objective functions. Once more there was no