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Research Paper

An improved model for Heat Integration of intermittent process streams in multipurpose batch plants

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HIGHLIGHTS

- A mathematical model for simultaneous scheduling and Heat Integration is presented.
- The model maximises heat recovery from process streams during material transfer.
- Allowing streams to exchange heat after storage provides additional flexibility.
- Heat Integration results in increased production and reduced utility requirements.
- The impact of the number of heat exchangers on heat recovery has been evaluated.

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ABSTRACT

This paper presents a mathematical technique for simultaneous Heat Integration (HI) and process scheduling in multipurpose batch plants. Taking advantage of the intermittent continuous behaviour of process streams during transfer between processing units, as determined by the production recipe, the presented formulation aims to maximise the coincidence of availability of hot and cold stream pairs with feasible temperature driving forces for heat recovery, whilst taking into consideration process scheduling constraints. Distinct from similar contributions in the published literature, time is treated as one of the key optimisation variables instead of a predefined parameter, in which case the production schedule is allowed to change. HI during stream transfer has the added benefit of shortened processing time, which invariably improves the throughput, as more batches are likely to be processed within a given time horizon, compared to conventional heating and cooling *in situ*. Application of the proposed model to a case study shows improvements of up to 50% in utility cost savings and more than two-thirds in product revenue. In addition, further analysis reveals that the use of only three additional heat exchangers can achieve a more than 80% improvement in profit.

1. Introduction

A batch process is, by definition, any process as a consequence of discrete tasks following a predefined sequence from raw materials to final products [1]. The prescribed sequence is known as a *recipe*. Batch processes have attracted industrial and academic interest because of their inherent flexibility and adaptability to changes in product specifications and operating conditions. Such processes are perfectly suited to the production of low volume, high value-added products (e.g. pharmaceuticals and agrochemicals), and can be used to produce a variety of products from the same plant by sharing equipment. In most instances, equipment sharing is a result of similar recipes.

The trend towards batch processing calls for the development of effective techniques for production planning and scheduling. Much research has been conducted on developing mathematical models to improve batch plant efficiency [2], with recent advances in computer technology allowing large and more complex problems to be handled by using optimisation techniques. Common objectives of batch process scheduling include makespan minimisation for known product demands, and profit maximisation within a given time horizon [3]. Among the various slot-, event- and precedence-based models in the published literature, the formulation presented by Seid and Majozi [4] appears to be promising with relatively good computational performance in terms of optimality and solution time. The mixed integer linear programming (MILP)

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Nomenclature

Indices and sets

$j \in J$ processing units
$j \in J_{in}^{c}$ processing units to have cooling for input materials
$j \in J_{out}^{c}$ processing units to have cooling for output materials
$j \in J_{s}^{c}$ processing units consuming state s
$j \in J_{in}^{h}$ processing units to have heating for input materials
$j \in J_{out}^{h}$ processing units to have heating for output materials
$j \in J_{s}^{p}$ processing units producing state s
$j \in J_{in}^{*}$ processing units to have heating or cooling for input materials
$j \in J_{out}^{*}$ processing units to have heating or cooling for output materials
$p \in P$ time points
$s \in S$ states
$s \in S_{j}^{c}$ states consumed in unit j
$s \in S^{int}$ intermediate states
$s \in S^{prod}$ product states
$s \in S^{raw}$ raw material states
$s_{in,j} \in S_{in,j}$ inlet streams
$s_{in,j} \in S_{in,j}^{eff}$ effective states representing tasks
$s_{out,j} \in S_{out,j}$ outlet streams
$s_* \in S_* = S_*^h \cup S_*^c$ process streams for HI
$s_*^c \in S_*^c$ cold streams
$s_*^h \in S_*^h$ hot streams

Parameters

CCU cold utility cost
$Cp(s)$ specific heat capacity of state s
$Cp_{in}(s_{in,j})$ specific heat capacity of the input material to the task
$Cp_{out}(s_{in,j})$ specific heat capacity of the output material from the task
Cp^{cw} specific heat capacity of cooling water
CHU hot utility cost
H time horizon of interest
$\dot{M}^{cw}$ constant cooling water flow rate through the jacket
$\dot{M}^{st}$ constant steam flow rate through the jacket
$Q_0(s)$ initial amount of state s in the storage
Q^U upper bound for heat loads
Q_s^U maximum storage capacity for state s
$T_{op}(s_{in,j})$ operating temperature for the task
$T_{stor}(s)$ storage temperature of product state s
T_{in}^{cw} inlet temperature of cooling water
T_{out}^{cw} outlet temperature of cooling water
T_{sat}^{st} saturated steam temperature
$Ts_0(s)$ initial temperature of state s in the storage
tt material transfer time
V_j^L minimum capacity of unit j
V_j^U maximum capacity of unit j
ΔT_{min} minimum temperature difference
Γ a large enough positive value
λ^{st} steam latent heat
$\rho_s^c(s_{in,j})$ fraction of state s in the input material consumed by the task
$\rho_s^p(s_{in,j})$ fraction of state s in the output material produced by the task
$\tau(s_{in,j})$ constant duration of the task

Variables

$ms_{in}(s,j,p)$ amount of state s sent to storage from unit j at time point p
$ms_{out}(s,j,p)$ amount of state s sent from storage to unit j at time point p
$mt(s,j,j',p)$ amount of state s sent from unit j to unit j' at time point p
$m_u(s_{in,j},p)$ amount of material used for the task at time point p
$q_{CU}(s_*^h,p)$ heat exchanged between the hot stream and the cold utility at time point p
$q_{ex}(s_*^h,s_*^c,p)$ heat exchanged between the hot and cold streams at time point p
$q_{HU}(s_*^c,p)$ heat exchanged between the hot utility and the cold stream at time point p
$q_{in}^c(s_{in,j},p)$ amount of cooling for the input material at time point p
$q_{out}^c(s_{in,j},p)$ amount of cooling for the output material at time point p
$q_{in}^h(s_{in,j},p)$ amount of heating for the input material at time point p
$q_{out}^h(s_{in,j},p)$ amount of heating for the output material at time point p
$qs(s,p)$ amount of state s stored at time point p
$T_f(s_*,p)$ final temperature of the process stream at time point p
$T_i(s_*,p)$ initial temperature of the process stream at time point p
$T_{in}(s_{in,j},p)$ temperature of the input material at time point p
$T_{out}(s_{in,j},p)$ temperature of the output material at time point p
$t_p(s_{in,j},p)$ end time of the task at time point p
$t_u(s_{in,j},p)$ start time of the task at time point p
$tr_{in}(s_{in,j},p)$ time required for heating or cooling for the input material at time point p
$tr_{out}(s_{in,j},p)$ time required for heating or cooling for the output material at time point p
$tm_{in}(s,p)$ time at which state s is sent to storage at time point p
$tm_{out}(s,p)$ time at which state s is sent from storage at time point p
$Ts_{out}(s,p)$ outlet temperature of state s from storage at time point p
$w_{in}(s,j,p)$ binary variable indicating if state s is sent to storage from unit j at time point p
$w_{out}(s,j,p)$ binary variable indicating if state s is sent from storage to unit j at time point p
$x(s_*^h,s_*^c,p)$ binary variable indicating if there is a heat exchange between the hot and cold streams at time point p
$x_{CU}(s_*^h,p)$ binary variable indicating if the hot stream uses the cold utility
$x_{HU}(s_*^c,p)$ binary variable indicating if the cold stream uses the hot utility
$y(s_{in,j},p)$ binary variable indicating if the task is active at time point p
$y_{CU}(s_*^h)$ binary variable indicating if there is a cooler for the hot stream
$y_{ex}(s_*^h,s_*^c)$ binary variable indicating if there is a heat exchanger for the hot and cold streams
$y_{HU}(s_*^c)$ binary variable indicating if there is a heater for the cold stream
$y_{in}^c(s_{in,j},p)$ binary variable indicating if there is cooling for the input material at time point p
$y_{out}^c(s_{in,j},p)$ binary variable indicating if there is cooling for the output material at time point p
$y_{in(s_{in,j},p)}^h$ binary variable indicating if there is heating for the input material at time point p
$y_{out}^h(s_{in,j},p)$ binary variable indicating if there is heating for the output material at time point p
$z(j,j',p)$ binary variable indicating if there is material sent from unit j to unit j' at time point p