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Scheduling of displacement batch digesters using discrete time formulation

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ABSTRACT

This paper provides mathematical programming based optimization model and computational results for short-term scheduling of displacement batch digesters in a pulp industry. The scheduling problem involves development of an optimal solution that yields the best sequence of operations in each of the parallel batch digesters sharing common resources. The constraints are imposed on meeting the demand of pulp of different qualities within a specified time horizon. The problem comprises of both fixed-time and variable time durations of the tasks, different storage policies, zero-wait and finite wait times, and handling of shared resources. The scheduling problem is formulated using a state-task-network (STN) representation of production recipes, based on discrete time representation resulting in a mixed-integer linear programming (MILP) problem which is solved using GAMS software. The basic framework is adapted from the discrete-time model of Kondili et al. (Comput. Chem. Eng., 1993, 17, 211–227). Different case studies involving parallel digesters in multiple production lines are considered to demonstrate the effectiveness of the proposed formulation using two different objective functions.
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Keywords: Optimization; Scheduling; Discrete-time representation; State-task-network representation; Displacement batch digesters; Pulp industry

1. Introduction

This paper focuses on the problem of developing a mathematical model for optimal operation of displacement batch digesters in a pulp industry. Scheduling is required because there are constraints of time and availability of resources for doing various tasks involved during batch digester operation. Scheduling is targeted to optimize the batch digester operation by taking into account the production requirements and available resources. Typical objectives of importance are maximization of the production within a given time horizon or maximization of the heating and cooking time while achieving targeted production within a given time horizon. The second objective implicitly ensures reduction in operating costs, as longer heating and cooking times lead to lower steam consumption.

Typically, wood pulping process involves production of pulp of different qualities in a digester house having multiple production lines. Each production line comprises of several batch digesters operating in parallel for meeting the overall pulp demand in a specified time horizon. Each production line has limited resources such as chip filling stations, impregnation liquor pumps, steam, and blow down tank, which are shared among all the parallel digesters in that line for various stages of the batch digester operation. Recently, displacement batch digesters (DBD) have evolved as an energy efficient alternative to the conventional batch digesters (CBD) for Kraft pulping. This is achieved by storing the hot used liquor from the previous batches in the storage tanks and subsequently using the stored liquor for the next batches, thus, leading to a significant energy recovery.

There is extensive literature available on scheduling of batch plants in general. Several mathematical models have been proposed in the literature based on different process representations: state-task-networks (STN), resource-task-networks (RTN), and recipe diagrams, among others. These representations are popularly used for representing production systems with recipes, time dependent operation,

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Nomenclature

Indices

i	tasks
j, d	units (digesters here)
t, t'	discrete intervals
s	states
r	resources
l	production line

Sets

I	set of tasks
HC	set of heating and cooking tasks
J	set of units (digesters)
T	set of discrete intervals
I_j	set of tasks i suitable in unit j
I_j^p	set of tasks that produce digester j
I_j^c	set of tasks that consume digester j
J_i	set of units j suitable for task i
I_j	set of tasks i suitable for unit j
S	set of states
P_s	subset of states for raw materials
ZW	subset for zero-wait states
FW	subset for finite-wait states
P	subset of pulp states
I_s^p	set of tasks that produce state s
I_s^c	set of tasks that consume state s
I_{st}	set of tasks that consume steam
R	set of resources
I_r	set of tasks that utilize resource r

Parameters

TT	total number of discrete intervals
NT_{ij}	number of intervals over which task i occurs in unit j
$NT0_{ij}$	number of intervals for the continuing task i of unit j at the initial time
α_{ij}	fixed processing time of task i in unit j
ρ_{is}	proportion of tasks i consuming (negative) and producing (positive) state s
D_s	demand of pulp states
$E0_d$	initial excess resource available for digester d
ST_s^{max}	maximum storage capacity for finite storage states
ST_s^i	initial amount of state s available
C_{ij}^{min}	minimum capacity of task i in unit i
C_{ij}^{max}	maximum capacity of task i in unit j
F^{max}	upper bound on amount of flow transfer between HBL Tank 2 and IL tank
C	coefficient of flow transfer F for steam leveling
C_{2ij}	coefficient that corresponds to steam consumption for task i in unit j at time t
S^{max}	upper bound on steam availability for steam leveling constraint

Binary variables

w_{ijt}	whether task i occurs in unit j at interval t

Continuous variables

b_{ijt}	amount of material undertaking task i in unit j at interval t
st_{st}	excess (not consumed) amount of state s at the beginning of interval t
$st0_s$	initial amount of state s required
e_{jt}	excess resource available for unit j at interval t
f_t	amount of flow transfer between HBL Tank 2 and IL tank
y_{ijt}	whether task i occurs in unit j at time interval t

and shared resources; and can be used for any type of problem these systems may face, e.g. design, scheduling, planning, storage or equipment sizing, optimization of operation, retrofit, etc. There are numerous models proposed in the literature for scheduling based on different time representations. Based on the time representation used different models can be broadly classified as discrete-time and continuous time based models. Extensive reviews were written by Floudas and Lin (2004), Mendez et al. (2006), Shaik et al. (2006), and Maravelias (2012), who presented comparisons of different models and discussed associated challenges.

In the literature, there is not much work done related to scheduling of pulp digesters, and the relevant work is concerned with only conventional batch digesters. Hvala et al. (1993) addressed online scheduling of nine conventional batch digesters operating in two parallel production lines under common resource limitations. They proposed a solution method based on a heuristic algorithm combining neighborhood search technique and linear programming. Later, Castro et al. (2002) developed a discrete-time resource-task-network (RTN) based formulation for scheduling of a resource constrained four batch conventional digester system leading to a mixed-integer linear programming (MILP) model. For estimating the durations of heating tasks, they used a separate process model – a distributed heterogeneous dynamic model in *gPROMS*. They concluded that the bottleneck was in the steam availability and an increase in the total available steam is significant for improving the productivity. Castro et al. (2003) developed RTN-based discrete and continuous time models for periodic scheduling of conventional batch digesters. The discrete time MILP model was solved for different cycle times in an iterative fashion to determine the optimal cycle time. While their continuous-time formulation resulted in a mixed-integer nonlinear program (MINLP) which they found it difficult to solve.

To the best of our knowledge, short-term scheduling of displacement batch digesters has not been attempted in the literature. With this motivation, in this work, we develop a mathematical model for short-term scheduling of parallel displacement batch digesters attached to multiple production lines with resource constraints. The proposed model is based on a state-task-network (STN) representation using discrete-time formulation. We consider an adaptation of the discrete-time model of Kondili et al. (1993) and Shah et al. (1993) and develop additional constraints to suit the specific problem of scheduling of displacement batch digesters with shared resources and different storage and wait policies. Computational results involving several case studies are presented to demonstrate the effectiveness of the proposed model. The discrete-time formulation has been chosen for the ease in handling of shared resources for this complex scheduling problem. Currently, we are working on developing a continuous-time model as well.

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