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Multiperiod production planning and design of batch plants under uncertainty

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ABSTRACT

A two-stage stochastic multiperiod LGDP (linear generalized disjunctive programming) model was developed to address the integrated design and production planning of multiproduct batch plants. Both problems are encompassed considering uncertainty in product demands represented by a set of scenarios. The design variables are modeled as here-and-now decisions which are made before the demand realization, while the production planning variables are delayed in a wait-and-see mode to optimize in the face of uncertainty. Specifically, the proposed model determines the structure of the batch plant (duplication of units in series and in parallel) and the unit sizes, together with the production planning decisions in each time period within each scenario. The model also allows the incorporation of new equipment items at different periods. The objective is to maximize the expected net present value of the benefit. To assess the advantages of the proposed formulation, an extraction process that produces oleoresins is solved.

1. Introduction

Batch processes have been widely studied throughout the last years due to their particular suitability for the production of large number of low-volume, high-value products in the same facility (Barbosa-Póvoa, 2007). Usually, at the stage of conceptual design of a batch plant, there are parameters, either external or internal to the process, which are subject to considerable uncertainty. These market and technical parameters include, for instance, product demands, raw materials availability, prices of chemicals, reaction constants, efficiencies, etc.

This work is focused on multiproduct batch plants where several products are produced following the same sequence of processing stages. A special feature of these facilities is their ability to meet production requirements and maximize profits given uncertainties in the market demands for the products.

In dealing with optimization under uncertainty, three research philosophies have been employed over the last years: stochastic programming, fuzzy programming and stochastic dynamic programming (for a short overview see Sahinidis, 2004). Most of the existing approaches that address the effect of uncertainty into batch process optimization have applied stochastic programming (Acevedo & Pistikopoulos, 1998; Aguilar-Lasserre, Bautista Bautista, Ponsich, & González Huerta, 2009; Cao and Yuan, 2002; Cui & Engell, 2010; Ierapetritou and Pistikopoulos, 1996; Liu & Sahinidis, 1996; Maravelias & Grossmann, 2001; Petkov & Maranas, 1997; Subrahmanyam, Pekny, & Reklaitis, 1994; Wu & Ierapetritou, 2007).

Stochastic programming deals with optimization problems whose uncertain parameters are modeled either by continuous probability distributions or by a finite number of scenarios. The approach using scenario analysis has been considerably exploited in the literature and has proven to provide reliable and practical results for optimization under uncertainty (Alonso-Ayuso, Escudero, Garín, Ortuño, & Pérez, 2005; Escudero, Kamesam, King, & Wets, 1993; Gupta & Maranas, 2003; Karuppiah, Martín, & Grossmann, 2010; Liu & Sahinidis, 1996; Shah and Pantelides, 1992; Subrahmanyam et al., 1994). In this paper, the uncertainty in product demands is tackled by the scenario approach.

In general, the two-stage stochastic programming strategy has been considered an effective and widely used method for addressing the optimization problems under uncertainty. In this approach, decision variables are explicitly classified according to whether they are implemented before or after a random event occurs. First-stage (here-and-now) decisions must be made before the uncertain parameters reveal themselves while second-stage (wait-and-see) decisions, also called recourse actions, are made after the outcome of the random events is observed. Thus, through recourse actions, stochastic models consider corrective measures that can be taken after the realization of some uncertain parameters. The two most common objective functions in the literature are the expected cost/profit of the problem.

In the area of batch processing, there are significant contributions on design and planning under uncertainty. Approaches tackling the production planning problem include Liu and Sahinidis

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Nomenclature

Indices

g	added units in parallel
h	units in series
i	products
k	discrete sizes for the units
m	units in parallel
p	operations
s	scenarios
t, τ	time periods

Deterministic parameters

BM	big-M constants
co_{it}	operating cost coefficient of product i at time period t
cp_{it}	cost coefficient for late delivery of product i in time period t
d^U_{its}	upper bound of demand of product i in time period t for scenario s
d^L_{its}	lower bound of demand of product i in time period t for scenario s
F_{it}	conversion of raw material to produce i at time period t
G_p	set of units in parallel that can be added in operation p
H	time horizon
H_t	net available production time for all products in time period t
H_p	set of possible configurations of units in series in operation p
H^U_p	the maximum number of units in series that can be allocated in operation p
M^U_p	maximum number of units in parallel operating out of phase in operation p
np_{it}	sales price for product i in time period t
NT	maximum number of time periods
SF_{ipt}	size factor of product i in operation p in time period t
SV_p	set of available discrete sizes for the batch units in operation p
p_s	probability of scenario s
pt_{iph}	processing time of product i in operation p with h units in series in period t
r_p	number of discrete sizes available for operation p
wp_{it}	waste disposal cost coefficient per product i in time period t
wr_{it}	waste disposal cost coefficient per raw material i in time period t
α_p	cost coefficient for a batch unit in operation p
β_p	cost exponent for a batch unit in operation p
γ_{pt}	cost coefficient for a batch unit in operation p at time period t
ε_{it}	inventory cost coefficient of raw material i in time period t
κ_{it}	purchasing price for the raw material of product i in time period t
υ_{pk}	standard volume of size k for batch unit in operation p
σ_{it}	inventory cost coefficient of product i in time period t
ζ_i	time periods during which raw materials have to be used
χ_i	time periods during which products have to be used

Boolean variables (first-stage decision variables)

Z_{ph}	true if configuration h is selected in unit operation p
W_{phk}	true if the unit size k is selected in operation p with configuration h
Y_{phmt}	true if there are m units in parallel out-of-phase in operation p with configuration h in time period t
X_{pgt}	true if g units in parallel are added in operation p in time period t

Deterministic variables (first-stage decision variables)

CE_{pt}	investment cost in operation p in time period t
CO_p	batch unit cost in operation p
N_{pt}	number of set of units in parallel in operation p in time period t

Stochastic recourse variables (second-stage decision variables)

C_{its}	amount of raw material for producing i purchased in time period t under scenario s
IM_{its}	inventory of raw material i at the end of a time period t under scenario s
IP_{its}	inventory of final product i at the end of a time period t under scenario s
n_{its}	number of batches of product i in time period t under scenario s
PW_{its}	product i wasted at time period t due to the limited product lifetime under scenario s
q_{its}	amount of product i to be produced in time period t under scenario s
QS_{its}	amount of product i sold at the end of time period t under scenario s
RM_{its}	raw material inventory for product i in time period t under scenario s
RW_{its}	raw material i wasted in time period t due to the limited product lifetime under scenario s
T_{its}	total time for producing product i in time period t under scenario s
ϑ_{its}	late delivery for product i in time period t under scenario s

(1996) who presented a two-stage model for the process planning and process capacity expansion with random variables that assume values from both discrete and continuous probability. Petkov and Maranas (1997) extended the multiperiod planning and scheduling model for multiproduct plants introduced by Birewar and Grossmann (1990) including uncertain product demands. Wu and Ierapetritou (2007) proposed a multi-stage stochastic programming formulation for the simultaneous solution of production planning and scheduling problems using a rolling horizon strategy.

With regard to the batch plant design under uncertainty, Shah and Pantelides (1992) presented a stochastic formulation for the design with uncertain product requirements considering different scenarios. Subrahmanyam et al. (1994) addressed the design and scheduling of batch process through a multiperiod model. The problem is split into two stages: in the first, the design is obtained without considering scheduling constraints, while, in the second stage, a detailed scheduling model is solved. Cao and Yuan (2002) addressed the problem of the optimal design of batch plants with uncertainty in product demands considering different operating modes of parallel units for different products. Alonso-Ayuso et al. (2005) proposed an approach for the product selection and plant sizing problems under uncertainty. Aguilar-Lasserre et al. (2009) developed a multi-objective optimization problem for the design of batch plants with uncertain market demands for products.