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Computational methods for the simultaneous strategic planning of supply chains and batch chemical manufacturing sites

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ABSTRACT

In this work we present efficient solution strategies for the task of designing supply chains with the explicit consideration of the detailed plant performance of the embedded facilities. Taking as a basis a mixed-integer linear programming (MILP) model introduced in a previous work, we propose three solution strategies that exploit the underlying mathematical structure: A bi-level algorithm, a Lagrangean decomposition method, and a hybrid approach that combines features from both of these two methods. Numerical results show that the bi-level method outperforms the others, leading to significant CPU savings when compared to the full space MILP.

1. Introduction

The concept of supply chain management (SCM), which appeared in the early 1990s, has recently raised a lot of interest since the opportunity of an integrated management of the supply chain (SC) can lead to significant economic benefits. In the context of Process Systems Engineering (PSE), the optimal integration of supply, manufacturing and distribution activities is the main goal of the emerging area known as enterprise-wide optimization (EWO), which as opposed to SCM, places more emphasis on the manufacturing stage (Grossmann, 2005). In the recent past, there have been many contributions in the area of SCM. Excellent reviews on the topic, with emphasis on supply chain design and planning using mathematical programming tools, can be found in the works by Melo, Nickel, and Saldanha-da-Gama (2009), Papageorgiou (2009) and Grossmann (2012).

1.1. *Integration of decision levels in SCM*

From a functional viewpoint, decisions made in SCM have been traditionally divided in three basic levels according to their temporal and spatial scale: strategic, tactical and operational. Several authors have recognized the importance of integrating decision levels in SCM as an effective manner to increase the overall profit (Goetschalckx, Vidal, & Dogan, 2002; Grossmann, 2004; McDonald & Reklaitis, 2004; Papageorgiou, 2009; Shah, 2005; Varma, Rekalitis, Blau, & Pekny, 2007), but very few contributions have been made in this field.

Particularly, the SC design and planning, SC planning and scheduling, and SC redesign and planning were traditionally treated as isolated areas (see Goetschalckx et al., 2002; Maravelias & Sung, 2009; Rungtusanatham & Forza, 2005). However, in the recent past, attempts have been made to deal with them in a simultaneous fashion. Following this approach, Lee, Lee, and Reklaitis (2000) studied the capacity expansion problem of multisite batch plants. Sundaramoorthy and Karimi (2004) presented an approach for new product introduction and planning in pharmaceutical supply chains. Guillén, Badell, Espuña, and Puigjaner (2006) integrated planning and scheduling decisions of chemical SCs taking into account financial management issues. The integration of financial considerations into SCM was also addressed by Longinidis and Georgiadis (2013) and Susarla and Karimi (2012). Amaro and Barbosa-Póvoa (2008) presented a modelling approach for the sequential planning and scheduling of SCs, while Cóccola, Zamarripa, Mendez, and Espuña (2013) addressed the integration of production and distribution tasks in multi-echelon supply chains.

As for the integration of spatial decisions in SCM, to the best of our knowledge, only a few papers have dealt with the integrated design of SCs along with the involved plants. The design of multi-product plants can be posed as the problem of selecting the processing units and their sizes so as to minimize a selected design

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Nomenclature

Sets

I	set of products
J_l	set of stages of batch plant l
K	set of customer zones
L	set of production plants
M	set of warehouses
R	Set of raw materials
STF_{jl}	set of discrete sizes for units of stage j of plant l
SV_{jl}	set of discrete sizes for units of stage j of plant l

Indices

d	number of in phase units
g	discrete size for storage tank
G_{jl}	number of available discrete sizes for a tank of stage j of plant l
i	product
j	Stage
k	customer zone
l	Plant
m	Warehouse
n	number of out of phase units
p	discrete size for batch unit
P_{jl}	number of available discrete sizes for a unit of stage j of plant l

Parameters

C_{ann}	capital charge factor
Cd_{im}	warehouse maintenance cost coefficient
$Cdep_m$	warehouse installation cost coefficient
Cpl_l	plant installation cost coefficient
$Craw_{sr}$	raw material cost coefficient
$Cprod_{il}$	production cost coefficient
Ctd_{imk}	transportation cost
Ctp_{ilm}	transportation cost
$Ctraw_{srl}$	transportation cost
fp_{ril}	raw material conversion factor
H_l	time horizon of plant l
NB_{ijl}^{UP}	maximum number of batches of product i
NP_{jl}^{UP}	maximum number of in phase unit for stage j of plant l
NT_{jl}^{UP}	maximum number of out of phase unit for stage j of plant l
Q_{il}^{LO}	lower bound for product i in plant l
Q_{il}^{UP}	upper bound for product i in plant l
Q_m^{UP}	maximum warehouse capacity
Q_{sr}^{UP}	upper bound for raw material r at site s
SF_{ijl}	size factor of product i in stage j of plant l
ST_{ijl}	size factor of product i in tank of stage j of plant l
t_{ijl}	processing times for each product i in stage j of plant l
VF_{jpl}	discrete size for batch units in stage j of plant l
VTF_{jlg}	discrete size for storage tank in stage j of plant l
α_{jl}	cost coefficient for units of stage j of plant l
$\tilde{\alpha}_{jl}$	cost coefficient for tank of stage j of plant l
β_{jl}	cost exponent for units of stage j of plant l
$\tilde{\beta}_{jl}$	cost exponent for tank of stage j of plant l
ϕ	maximum ratio allowed between the number of batches of consecutive stages

Binary variables

ex_l	binary variable for plant allocation
v_{jpl}	binary variable that denotes if the units of stage j have size p
vt_{jpl}	binary variable that denotes if the units of stage j have size p
x_{jln}	binary variable for the number of out of phase parallel units of stage j of plant l
xx_{jld}	binary variable for the number of in phase parallel units of stage j of plant l
y_m	binary variable for warehouse allocation
z_{il}	binary variable for product selection in plant l

Continuous variables

e_{ijlpd}	variable that takes value Q_{il} if $v_{jlp} = 1$ and $xx_{jld} = 1$
f_{ijlg}	variable that takes value Q_{il} if $vt_{jlg} = 1$ and $xx_{jld} = 1$
Nb_{ijl}	number of batches of product i in stage j of plant l
NP_{jl}	number of units in phase in stage j of plant l
NT_{jl}	number of units out of phase in stage j of plant l
w_{ijln}	variable that represents the bilinear term $Nb_{ijl}\, x_{jln}$
Q_{il}	amount of product i in plant l
Q_{ilm}	amount of product i transported from plant l to warehouse m
Q_{imk}	amount of product i transported from warehouse m to customer zone k
Q_{sril}	amount of raw material r transported from site s to plant l for producing product i
T_{il}	total time for producing product i in plant l
V_j	continuous variable that denotes the size of a batch unit in stage j
λ_{ijgl}	variable that represents the bilinear term $vt_{jlg}\, Nb_{ijl}$
ρ_{jlpnd}	variable that represents the term $v_{jlp}\, x_{jln}\, xx_{jld}$

objective, while satisfying the minimum production requirements over a defined time of planning. The design of batch processes has been an active area of research in the PSE community over the last decades (see the review by Barbosa-Póvoa, 2007 for further details and references). In contrast, the incorporation of batch plant design into SCM has received little attention.

Corsano, Montagna, Iribarren, and Aguirre (2007) presented a detailed non linear programming (NLP) model for the design of a multisite plant complex, considering the integration between plants simultaneously with their optimal operation and production planning. Corsano, Vecchietti, and Montagna (2011) presented an MINLP optimization model for a sustainable design and performance analysis of sugar/ethanol SCs. A detailed model for ethanol plant design was embedded in the SC model in order to obtain the plant and SC designs simultaneously. In a more general work, Corsano and Montagna (2011) presented an MILP model for the simultaneous optimization of SCs and their batch plants, showing that the simultaneous optimization outperforms hierarchical approaches.

1.2. Solution approaches in SCM

Unfortunately, the integration of decisions leads to large-scale MILPs that are hard to solve, and whose complexity increases with the number of production plants, batch stages and/or final products. Therefore, it becomes evident that the integration of decision levels poses a major computational challenge.

The preferred modelling tool in SCM has been MILP. The motivation for this choice is that these formulations tend to be represented at a high level, and hence apply fairly simple representations of