Computers and Chemical Engineering 77 (2015) 59–73

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Multi-bucket optimization for integrated planning and scheduling in the perishable dairy supply chain

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ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form 24 March 2015
Accepted 26 March 2015
Available online 3 April 2015

Keywords:
Integrated planning and scheduling
Mixed integer linear programming
Constraint programming
Hybrid approach
Perishability
Dairy supply chain

ABSTRACT

This paper considers a dairy industry problem on integrated planning and scheduling of set yoghurt production. A mixed integer linear programming formulation is introduced to integrate tactical and operational decisions and a heuristic approach is proposed to decompose time buckets of the decisions. The decomposition heuristic improves computational efficiency by solving big bucket planning and small bucket scheduling problems. Further, mixed integer linear programming and constraint programming methodologies are combined with the algorithm to show their complementary strengths. Numerical studies using illustrative data with high demand granularity (*i.e.*, a large number of small-sized customer orders) demonstrate that the proposed decomposition heuristic has consistent results minimizing the total cost (*i.e.*, on average 8.75% gap with the best lower bound value found by MILP) and, the developed hybrid approach is capable of solving real sized instances within a reasonable amount of time (*i.e.*, on average 92% faster than MILP in CPU time).

1. Introduction

The yoghurt production is a semi-continuous process and subject to individual characteristics. Yoghurt is a notably perishable product within the category of dairy industry (Lütke Entrup et al., 2005). The perishability highly restricts its storage duration and delivery conditions. It has a wide variety of retail cup sizes or labels, contents and special ingredients with numerous flavoured and coloured types. When it comes to producing large numbers of products from a few initial product recipes, product dependent cleaning, sterilizing, re-tuning issues of pipes and mixing units arise to avoid contamination (Montagna et al., 1998). Especially, long sequence-dependent setup times and high costs are considerable at the filling and packaging stages of the yoghourt production and, they cause a noticeable reduction of available production times and increase the costs. Hence, planning and scheduling of the yoghurt production require specific models to support decision making.

Mixed integer linear programming (MILP) models provide mathematical frameworks to represent specific characteristics of problems and to get optimal solutions. The MILP is an extensively accepted tool in the dairy industry for well-defined problems (*e.g.*, Banaszewska et al., 2012; Kopanos et al., 2011a, 2012a). Bilgen and Çelebi (2013) present a MILP model addressing the production scheduling and distribution planning problem in a yoghurt production line of multi-product dairy plants. They consider the yoghurt production with perishability and sequence-dependency issues by focusing on the packaging stage operating with parallel units sharing common resources. Sel and Bilgen (2014a) state that integrated multi-echelon, multi-period planning and scheduling models accounting for multi-stage semi-continuous yoghurt production particularities are found to be of practical use in the field. Accordingly, the contribution of this study is aligned with the gap pointed out by Sel and Bilgen (2014a) presenting a literature review and discussion on quantitative models for supply chain management within dairy industry.

In this paper, we consider a production and distribution problem for a two-stage semi-continuous set type yoghurt production which is also comparable to other dairy production processes (*e.g.*, cheese, butter and ice cream). The production side fundamentally corresponds to packaging and fermentation/incubation operations. The distribution side considers the storage of products and the delivery to distribution centres (DCs). The scope of the considered problem is illustrated in Fig. 1. For the problem, we introduce a multi-echelon, multi-period integrated MILP model with shelf life consideration. Our integrated MILP model is an extension of the formulation previously proposed by Bilgen and Çelebi (2013). The model is extended by considering timing and capacity constraints with respect to the incubation operation of set type yoghurt.

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http://dx.doi.org/10.1016/j.compchemeng.2015.03.020
0098-1354/

Nomenclature

For the mathematical description of the models the following notation is introduced: Indices and sets:

$i \in Is$ days ($IS = \{1, \ldots, I\}$)
$d \in Ds$ demand days ($DS = \{1, \ldots, D\}$)
$j, k, t \in P^{S1}$ products ($P^{S0} = \{0, \ldots, P\}$, $P^{S1} = \{1, \ldots, P\}$)
$l \in Ls$ lines ($LS = \{1, \ldots, L\}$)
$a \in As$ distribution centres ($AS = \{1, \ldots, A\}$)

Monetary parameters of MILP models
$Loss_j$ cost of the decrease on the shelf life of product j (€/l per day)
$VarCost_j$ variable production cost of product j (€/l)
$StrgCost_j$ inventory cost of product j (€/l per day)
$SetupCost_{jk}$ changeover cost from product j to k (€)
$LineCost_j$ operating cost of line l (€ per day)
$PwCost_j$ waste cost of product j during packaging (€/min)
$IncCost$ operating cost of incubation room (€)
$OverTCost$ overtime cost (€/min)
$TransCost_a$ transportation cost from plant to DC a (€)
$UnmDCost_j$ unmet demand cost of product j (€)

Technical parameters of MILP models
$ShelfLife_j$ shelf life of product j (day)
$CrRate_j$ minimum shelf life requirement of customer for product j (% of shelf life)
$IncTime_j$ incubation time of product j (min)
$Demand_{jda}$ demand of DC a for product j on demand day d (l)
$QContTime$ quality control time (day)
$MchSpeed_j$ machine speed for product j (l per min)
$StCapacity$ storage capacity of the plant (min)
$IncCapacity$ incubation capacity of the plant (min)
$MinLot_j$ minimum production lots of product j (l)
$MaxLot_j$ maximum production lots of product j (l)
$SetupTime_{j \in P^{S0} k}$ changeover time from product j to k (min)
$MaxTime_i$ maximum available time on day i (min)
$RTime_i$ regular working time on day i (min)
$Capacity_i$ production capacity on day I (min)
γ_j factor for converting product quantity to storage unit, *e.g.*, pallet
M scalar chosen to be huge number

Technical parameters of CP model
$IncDuration_j$ Incubation duration of job j (min)
Tj the type associated with each interval variable in the sequence, a non-negative integer
$Setup$ setup time defined as triple (hour) $Setup = \{<j, k, st> | j, k \text{ in } J^S : j \neq k : st \text{ in } ST^S\}$
STS set of setup times

Decision variables of integrated model and planning submodel – MILP
x_{ijld} quantity of product j produced on line l on day i for demand day d (l)
y_{jda} quantity of product j produced for DC a for demand day d (l)
$UnmD_{jda}$ unmet demand of product j for DC a on demand day d (l)
inv_{ij} inventory of product j at the end of day i (l)
$overtime_i$ overtime on day i (min)
PT_{ij} production time of product j on day i (min)
$FT_{ij \in P^{S0} l}$ finishing time of product j on line l on day i (min)
$CmaxLine_{il}$ maximum completion time of line l on day i (min)
$CmaxProduct_{ij \in P^{S0}}$ maximum completion time of product j on day (i) (min)
$IncNb_{ij \in P^{S0}}$ number of incubation for product j on day (i)
$binsetup_{ij \in P^{S0} k \in P^{S0} l}$ changeover from product j to k on line l on day i (binary)
$IncSequence_{ij \in P^{S0} k \in P^{S0}}$ incubation sequence of product j preceding product k in day i (binary)
bin_{ijl} production of product $j$on line $l$on day i (binary)

Decision variables of scheduling sub-model – MILP
x_{jld} quantity of product j produced on line l for demand day d (l)
PT_j production time of product j (min)
$FT_{j \in P^{S0} l}$ finishing time of product j on line l (min)
$CmaxLine_l$ maximum completion time of line l (min)
$CmaxProduct_{j \in P^{S0}}$ maximum completion time of product j (min)
$IncNb_{j \in P^{S0}}$ number of incubation for product j
$binsetup_{j \in P^{S0} k \in P^{S0} l}$ changeover from product j to k on line l (binary)
$IncSequence_{j \in P^{S0} k \in P^{S0}}$ incubation sequence of product j preceding product k (binary)

Decision variables of scheduling submodel – CP
$Task_j$ activities corresponding with each of job j, interval variable
$OptTask_{jl}$ operational activities which has optional size of $Duration_j$, interval variable
$OptTask_{jl}$ optional activities correspond with each of job j operated on line l
$Duration_j$ size of the $OptTask_{jl}$
Inc_j incubation activities which has size of $IncTime_j$, interval variable
Inc_j incubation activities correspond with each of job j
$Schedule_j$ variable represents a total order over a set of $OptTask_{jl}$, sequence variable
$Schedule_j$ T_j integer type is used

The scheduling constraints corresponding to both packaging and incubation operations are reformulated efficiently inspired by the generic MILP model of parallel machine scheduling with sequence dependent setup times, which is studied by Guinet (1993) as a vehicle routing formulation.

MILP software may be not powerful enough to handle the computational effort of integrated models of real sized problems. A production schedule typically comprises 500–1500 operations and complex technological constraints such as parallel processing units, sequence-dependent changeovers (Baumann and Trautmann, 2014). The inadequacy of MILP is the usage of various big M constraints and an enormous number of binary variables for making scheduling decisions. In this case, a decomposition heuristic which divides the model into different planning and scheduling time buckets can reduce the complexity caused by the scheduling decisions.

Constraint programming (CP) has been developed as a useful modelling and solution paradigm overcoming the computational limitations for many scheduling cases such as staff, train, assembly line, batch plant and flexible manufacturing system scheduling (Novas and Henning, 2014). The CP models provide more convenient analyses for real cases by requiring less computational efforts. However, they search values of decision variables in a certain domain and the optimum cannot be guaranteed for planning problems which have large domains of continuous variables