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On production planning and scheduling in food processing industry: Modelling non-triangular setups and product decay

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ABSTRACT

Production planning and scheduling in food processing industry (FPI) requires taking specific characteristics into account. First of all, setups are usually sequence-dependent and may include the so-called non-triangular setup conditions. Secondly, planning problems in FPI must take product decay into consideration. We present an MILP model that handles these characteristics. We study its behaviour and complexity and show that optimal production schedules become significantly different when non-triangular setups and product decay are taken into account. Numerical results are provided for medium size instances, including a comparison with a standard MP-based heuristic.

1. Introduction

Adequate and efficient production planning and scheduling is one of the most challenging problems for present-days enterprises. Lot-sizing and scheduling in Food Processing Industry (FPI) is usually more complex than in other continuous and discrete processing environments. First of all, planners have to deal with decline in quality of products, related quality requirements and safety regulations of products, market driven standards regarding shelf life, and variability of demand and prices. Secondly, the diversity of products in FPI increased considerably in the past decades and global competition on the food market has forced manufacturers to participate in an on-going trend towards increased variety (e.g. ingredients and flavours, customised packaging, prints and/or labels) of (new) products. Soman et al. [54] state that the majority of research contributions do not address specific characteristics of food processing, e.g. high capacity utilisation, sequence-dependent setups and limited shelf life due to product decay.

In general practice, lot-sizing and scheduling problems are solved separately in successive hierarchical phases [12,17,40,54,56]. First optimal lot-sizes for given product families are determined and afterwards production schedules are generated. The generated schedules on the shop floor often fail to realise production targets, because changeover losses are not correctly accounted for on a higher planning level. As a consequence, the planning process has to be redone (with or without over-time) and/or frequent rescheduling takes place in daily practice [40]. Currently, there exists a general consensus regarding a closer integration of lot-sizing and scheduling decisions, see Meyr [44], Gupta and Magnusson [33], Jans and Degraeve [36], Almada-Lobo et al. [2], Clark et al. [13], and Menezes et al. [43]. Guimarães et al. [31] survey the main modelling approaches and present a classification framework for integrated lot-sizing and scheduling models. Some recent real-life applications of simultaneous lot-sizing and scheduling can be found for instance in [24,7,9]. In spite of the increasing attention for simultaneous lot-sizing and scheduling in literature, surprisingly little research has been done to include specific aspects of food industry (e.g. product decay) into traditional lot-sizing and scheduling models.

Planning (i.e. lot-sizing) models differ from scheduling models in a number of ways. Kreipl and Pinedo [40] give an extensive overview of practical issues for planning and scheduling processes. In a special issue on lot-sizing and scheduling, Clark et al. [13] confirm the need for more realistic and practical variants of models for simultaneous lot-sizing and scheduling. Features such as (i) non-triangular setups, (ii) perishability, and (iii) delivery time windows are labelled by the authors as hot topics and open research opportunities. The research question of this paper is how to include the first two characteristics in models for simultaneous lot-sizing and scheduling.

(1) *Sequence-dependent setups and non-triangular setups.* There is a complicating issue with respect to sequence-dependent

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setup costs and times, commonly referred to as the assumption of the triangular setup conditions [13,14,2,33]. Menezes et al. [43] confirm that non-triangular setups may occur in FPI due to contamination between production lots. Clark et al. [14] mention that contamination is a particularly concern for FPI. The authors refer for instance to the severe (i.e. lethal) impact of copper in concentrates for sheep due to an ineffective sequencing of production lots. Due to processing conditions of different product variants (e.g. several heating and/or cooling levels) and other product specific requirements (e.g. flavours, addition of specific additives, the danger of contamination between subsequent production runs), changeover costs and times between two subsequent products i and j may become substantially less by processing another product k between i and j. As a consequence, applying models that assume triangular setup conditions may generate non-consistent solutions from a scheduling point of view.

(2) *Product decay*. In many FPI cases, the quality or value of perishable food products deteriorates rapidly after production. Considering product decay in lot-sizing enforces smaller production quantities. Consequently, individual products are produced at higher frequency. This increases the difficulty of sequencing.

This paper investigates implementing the characteristics into models for simultaneous lot-sizing and scheduling under tight capacity constraints. We present an MILP model that includes the identified characteristics. Moreover, the approach offers a natural starting point for integrating delivery time windows in lot-sizing and scheduling models as mentioned by Clark et al. [13]. Small scale examples demonstrate that optimal production schedules become significantly different when including non-triangular setups and product decay. Two model formulations are presented and compared with a known approach from literature.

The remainder of the paper is organised as follows. Section 2 embeds the model in existing approaches from literature. Section 3 presents two MILP models for the problem under consideration. Section 4 provides small scale numerical examples to demonstrate the impact of non-triangular setups and product decay. Moreover, the complexity of the model is studied. Section 5 provides numerical results for medium size instances, including a comparison with a straightforward MP-based heuristic. Concluding remarks and suggestions for further research are given in Section 6.

2. Embedding in the literature

Models for lot-sizing and scheduling can be classified according to the segmentation of the planning horizon. From a modelling point of view, it is convenient to distinguish two general classes of models [19], i.e. small bucket (SB) and big (or large) bucket (BB) modelling approaches. In SB models, the planning horizon is divided into a finite number of small time periods such that in each period either at most two products can be produced, or there will be no production at all. Conversely, in BB approaches the planning horizon is divided into longer periods, usually of equal length. In each period, multiple products may be produced. As a consequence, SB models are usually associated with short term planning horizons and BB models with medium term planning horizons.

2.1. Small bucket approaches

A typical example of SB approaches is the Discrete Lot-sizing and Scheduling Problem (DLSP). The basic DLSP includes (sequence-independent) setup costs and setup carry-over at zero setup time [25]. Inclusion of setup carry-over implies that setup states of a machine are carried over between period boundaries. Porkka et al. [49] compare models with and without setup carry-overs. They show that substantial savings in costs and production time can be achieved by fundamentally different production plans enforced by carry-overs. Comparable results are found by Sox and Gao [57]. However, in the basic DLSP, setup states are not preserved over idle time. Sequence-dependent setup costs and times are neither considered in the DLSP. Many extensions of the (basic) DLSP have been described in literature. We refer to Drexl and Kimms [17] and Salomon et al. [52] for a broader view on variants of the DLSP.

Fleischmann [26] analyses the multi-item single machine DLSP with sequence-dependent setup costs. An artificial product is introduced to represent idleness of the machine. Salomon et al. [53] continue the latter study and reformulate a DLSP that captures sequence-dependent setup times (DLSPSD). The triangular setup conditions are assumed to hold. However, machine idleness is represented by an artificial product. Jordan and Drexl [37] present a comparable model in which idleness is indicated by an artificial product too. It should be mentioned that if idleness is represented by an artificial product, the changeover matrix must fulfil very strict conditions to cope with sequence-dependent setup times. Otherwise the setup state of the machine is not correctly carried over across the boundaries of idleness. A recent approach is due to Guimarães et al. [31]. The authors propose a classification framework to survey and classify the main modelling approaches for the integration of sequencing decisions in discrete time lot-sizing and scheduling models.

Wolsey [62] extended the work of Constantino [15] for problems with sequence-independent setups for small bucket formulations with sequence-dependent setup times and costs. Idleness is not represented by an artificial product. However, the triangular setup conditions are assumed to hold. We will refer to Wolsey's model as the general small bucket model (GSB).

2.2. Big bucket approaches

In contrast to small bucket models, the planning horizon of a big bucket (BB) model is usually divided into longer periods of equal length. Time intervals in a BB model may represent a time slot of one week (or more) in practice [17]. In each period, multiple products can be manufactured. Releasing the “all-or-nothing” production principle of (most) SB models implies that a BB model includes the possibility to determine continuous lot-sizes.

The Capacitated Lot-Sizing Problem (CLSP) is a typical example of a big bucket model. It is closely related to the (small bucket) DLSP. Decision variables, parameters and objective function are comparable in both problems [17]. However, the CLSP does not include sequence-dependent setup costs and times. As a consequence, setup carry-over between period boundaries is not included either. Suerie and Stadtler [59] use the simple plant location problem to obtain a tight new model formulation for setup carry-over in the CLSP with sequence-independent setup costs and times.

Sox and Gao [57] introduce the Generalised Capacitated Lot-sizing Problem (GCLP). The GCLP uses less binary variables for including setup carry-over in the CLSP with sequence-independent setup costs and no setup times. Sequence-independent setup times may be included; probably at the expense of additional computational effort. The authors also apply the network reformulation approach as proposed by Eppen and Martin [19] and compare the behaviour of a set of models. The results demonstrate that incorporating setup carry-over has a significant effect on both costs and lot-sizes.

We observe a tendency in simultaneous lot-sizing and scheduling to incorporate characteristics of small bucket models into