

On the Optimization of Production Scheduling in Industrial Food Processing Facilities

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Abstract

This work presents the development and application of an efficient solution strategy for the optimal production scheduling of a real-life food industry. In particular, the case of a canned fish production facility for a large-scale Spanish industry is considered. Main goal is to develop an optimized weekly schedule, in order to minimize the total production makespan. The proposed solution strategy constitutes the basis to develop an efficient and robust approach for this complex scheduling problem. A general precedence Mixed-Integer Linear Programming (MILP) model is utilized for all scheduling-related decisions (unit allocation, timing and sequencing). To solve the scheduling problem in a computational time accepted by the industry, a two-step decomposition algorithm is employed. Salient characteristics of the canned fish industry are aptly modelled, while valid industry-specific heuristics are incorporated. The suggested solution strategy is successfully applied to a real study case, corresponding to the most demanding week of the plant under study.

Keywords: production scheduling, food industry, MILP, decomposition

1. Introduction

Market trends and competitiveness has steered food industry towards large production volumes, complex alternative recipes and an increasing product portfolio, making production scheduling a challenge. The current industrial practice imposes scheduling-related decisions to be mainly derived by managers and operators, hence the overall plant performance is subject to their experience. Computer-aided scheduling tools can significantly improve these decisions by proper consideration of all involved parameters and therefore significantly enhance production scheduling (Harjunkoski, 2016). As a result, productivity is improved, while customers remain satisfied and profits increase. Acknowledging the importance of optimized production scheduling, the scientific community has widely studied the topic over the last 30 years, introducing numerous scheduling models (Méndez et al., 2006). However, most of these works consider small-

scale study cases. This is mainly attributed to the fact that production scheduling is an NP-hard problem, therefore large complex instances can become intractable. The scientific community has widely recognised the lack of applications to real industrial cases (Harjunkski et al., 2014). Recently some attempts have been made to close the existing gap between theory and industrial practice. In (Kopanos et al., 2010), the authors studied a real-life yoghurt production facility using a novel mixed discrete and continuous MILP model. Furthermore, Baumann and Trautmann, (2014) proposed a hybrid MILP method for make-and-pack processes using a decomposition strategy and a critical-path improvement algorithm. Moreover, Aguirre et al., (2017) combined a novel MILP model that incorporates TSP (Travelling Salesman Problem) constraints, with a rolling horizon algorithm. In this work a solution strategy is proposed that deals with scheduling problems of large-scale industrial food production facilities. In particular, an MILP model is proposed to optimize the production schedule, while a two-step decomposition algorithm is utilized to solve the problem in an acceptable computational time.

2. Problem statement

In this work, the canned fish production in a real-life industrial facility is examined. Specifically, the production process of Frinsa del Noroeste S.A., located in Ribeira, Spain, is investigated using real process data. The plant is capable of producing more than 400 codes, and it is one of the largest canned fish industries in Europe. The facility comprises of multiple stages, including both batch and continuous processes (Fig. 1). The raw materials arrive in the facility in the form of frozen fish blocks, and as such they need to be unfrozen in the thawing chambers. Then, the blocks are chopped in the appropriate size and filled in the cans alongside with all other ingredients (brine, olive oil etc.) required by the recipe. In the next stage, the sealed cans are sterilized in order to ensure the microbiological quality of the final products. Finally, the cans are packaged in their final form (6-pack, 12-pack, boxes etc.) and are stored in the warehouse, to be later distributed in the market.

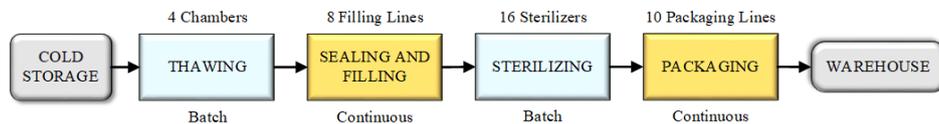


Figure 1: Facility layout

The plant under consideration can be identified as a multiproduct, multistage facility with both batch (thawing, sterilizing) and continuous (sealing and filling, packaging) processes each utilizing multiple parallel units. Additionally, the large production demand and high production flexibility increases significantly the plant's complexity. The thawing stage is oversized compared to the processing capacity of all other stages, therefore it is a valid assumption to omit it from this study. Unfortunately, no clear bottlenecks exist, and as such all other processing stages need to be modelled. The short-term scheduling horizon of interest is 5 days, whereas all units are available 24 hours per day. Sequence-dependent changeovers are considered. All design and operating constraints of the facility, such as a limited waiting time between stages to ensure microbiological integrity, are taken into account. The objective is to minimize the total production makespan, while ensuring demand satisfaction.

3. Mathematical framework

The key scheduling decisions to be made are related to: a) the number of product batches required to satisfy the incoming orders, b) the allocation of product batches to units in every processing stage, c) when will the process of each batch in every stage start and finish and d) in what relative sequence. A typical industrial practice in most food industries, imposes the operation of the intermediate batch processes in their maximum capacity. Utilizing the batch stage to its fullest, leads to reduction of changeovers between products and a general increase in the plant's productivity. Thus, the number of batches of each product required to satisfy the demand is calculated a priori, based on the given demand, the inventory levels and the capacity of the sterilization chambers.

3.1. MILP model

The suggested MILP model is based on the general precedence framework. Due to lack of space, only a brief description of the model is presented:

$$\sum_{j \in (SJ_{s,j} \cap PJ_{p,j})} \bar{Y}_{p,b,s,j,n} = 1 \quad \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, n \in I_n^{\text{in}} \quad (1)$$

$$L_{p,b,s,n} + \sum_{j \in (SJ_{s,j} \cap PJ_{p,j})} (fs_{p,b,j,n}^{\text{time}} \cdot \bar{Y}_{p,b,s,j,n}) = C_{p,b,s,n} \quad \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, n \in I_n^{\text{in}} : s = 1 \quad (2)$$

$$C_{p,b,s,n} + W_{p,b,s,n} = L_{p,b,s+1,n} \quad \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, n \in I_n^{\text{in}} : s < 3 \quad (3)$$

$$L_{p',b',s,n} \geq C_{p,b,s,n} + ch_{p,p',j}^{\text{time}} - M \cdot (1 - X_{p,p',n}) - M \cdot (2 - \bar{Y}_{p,b,s,j,n} - \bar{Y}_{p',b',s,j,n}) \\ \forall p \in I_p^{\text{in}}, p' \in I_{p'}^{\text{in}}, b \in PB_{p,b,n}, b' \in PB_{p',b',n}, j \in (PPJ_{p,p',j} \cap SJ_{s,j}), n \in I_n^{\text{in}} : p < p', s \neq 2 \quad (4)$$

$$L_{p',b',s,n} > C_{p,b,s,n} - M * (1 - \bar{X}_{p,b,p',b',n}) - M * (2 - \bar{Y}_{p,b,s,j,n} - \bar{Y}_{p',b',s,j,n}), \\ \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, p' \in I_{p'}^{\text{in}}, b' \in PB_{p',b',n}, j \in (PPJ_{p,p',j} \cap S_{s,j}), n \in I_n^{\text{in}} : p < p', s = 2 \quad (5)$$

$$C_{p,b,s+1,n} - L_{p,b,s,n} \leq Q_p \quad \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, n \in I_n^{\text{in}} : s = 1 \quad (6)$$

$$C_{p,b,s,n} \leq 24 \quad \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, n \in I_n^{\text{in}} : s = 3 \quad (7)$$

$$C_{p,b,s,n}^{\text{max}} \geq C_{p,b,s,n} \quad \forall p \in I_p^{\text{in}}, b \in PB_{p,b,n}, n \in I_n^{\text{in}} : s = 3 \quad (8)$$

Constraints (1) guarantee that all product batches p,b to be scheduled on day n will be processed by exactly one unit j in every stage s , using the binary allocation variable $\bar{Y}_{p,b,j,n}$. Constraints (2) impose the timing constraints in the sealing and filling stage. More specifically, they state that the completion of the sealing and filling task for every product batch to be scheduled in every day $C_{p,b,s,n}$ is equal to the starting time of the task $L_{p,b,s,n}$ plus the required processing time $fs_{p,b,j,n}^{\text{time}}$. Similar constraints are used for the sterilization and packing stages. To synchronize the stages, constraints (3) are employed. The continuous variable $W_{p,b,s,n}$ defines the waiting time between each stage. The sequencing

constraints between product batches in every stage are portrayed in constraints (4) and (5). Two general precedence variables are introduced, $X_{p,p',n}$ and $\bar{X}_{p,b,p',b',n}$, alongside a big-M parameter. The first precedence variable defines the sequencing of product batches in the continuous stages (sealing and filling and packing), while the latter in the batch stage (sterilization). Notice, that the batch sets b, b' are not used in the first precedence variable, since a single campaign policy is followed in the continuous stages. This way the binary variables are significantly decreased, thus the computational complexity of the problem is reduced. In particular, constraints (4) state that if a product p is processed prior to p' on day n ($X_{p,p',n} = 1$) and both product batches are processed in the same unit j ($\bar{Y}_{p,b,j,n} = \bar{Y}_{p',b',j,n} = 1$), then the starting time of p', b' must be greater than the completion time of p, b plus any required changeover $ch_{p,p',j}^{time}$. Similarly, constraints (5) impose the sequencing constraints in the sterilization stage. Constraints (6) enforce the waiting time between the sealing and filling stage and the sterilization stage to be less than a specific limit Q_p . This limit ensures the microbiological integrity of the final product. To ensure that the daily scheduling horizon is not violated, constraints (7) are used. The objective of the model is the minimization of the total production makespan C_{max} and is expressed by constraints (8).

3.2. Decomposition algorithm

The complexity of the examined plant is such that an exact method cannot solve the scheduling problem in reasonable time. Therefore, a two-step decomposition algorithm is employed to split the initial problem into several tractable subproblems. First, the weekly scheduling problem is decomposed in a temporal manner into 5 daily scheduling subproblems. Then, an order-based decomposition is utilized to solve the daily scheduling problem for a specific number of products in each iteration. Fig. 2. illustrates the flowchart of the proposed solution strategy. At first the batching subproblem is solved to translate the product orders into batches. Afterwards, the number of orders to be scheduled in each iteration are set. Then, the MILP is solved for the specified subproblem area (day and number of products) and only the binary variables (unit allocation, sequencing) are fixed. When all orders are scheduled for a given day, all variables are fixed, and the algorithm continues to the next day. Finally, when all days are considered, the complete schedule is generated.

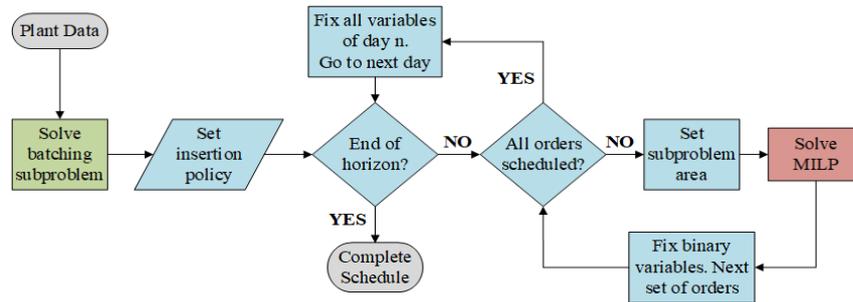


Figure 2: Solution strategy

4. Results

An industrial study case using real data from the Frinsa production plant is presented. In total 136 final products are to be scheduled, corresponding to a real weekly demand from a period with the most intensive production. To solve this complex case, the proposed solution strategy is utilized. In each iteration the daily schedule for half of the product-orders was chosen to be optimized. The MILP model was implemented in GAMS 25.1 and solved using CPLEX 12.0. Optimality is reached for all iterations of the suggested solution strategy. Figure 3 illustrates the complete schedule generated for all units of every processing stage. Each color corresponds to a batch or lot of a product-code.

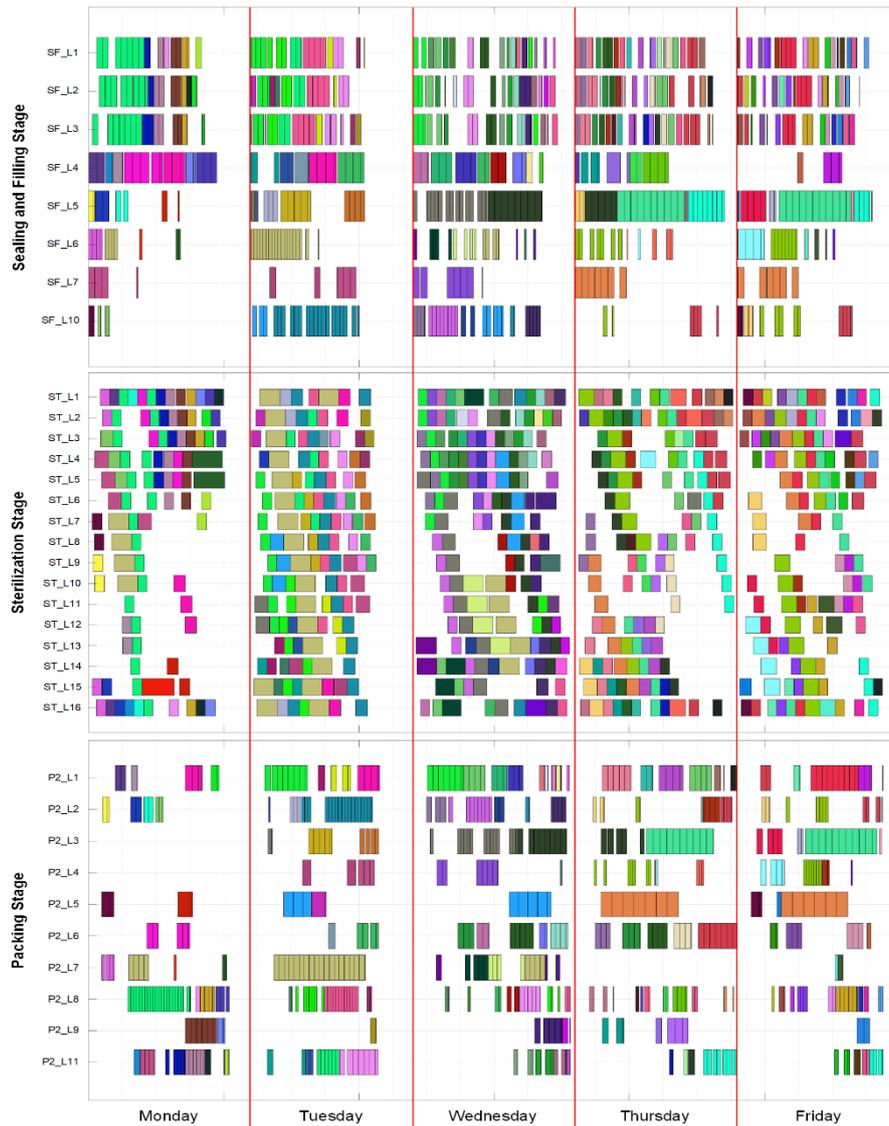


Figure 3: Gantt chart of units of all processing stages

Compared to the real weekly schedule proposed by Frinsa, the optimized schedule of the proposed strategy illustrates interesting results. To satisfy the given demand, the manually derived schedule by Frinsa, requires the addition of a shift on Sunday evening, while the optimized schedule satisfy all orders within 5 days. Moreover, the total CPU time for the solution of the problem is approximately 1 hour and it is acceptable by the company.

5. Conclusions

This work presents the optimization-based production scheduling of a large-scale real-life food industry. More specifically, all major processing stages of a canned fish production facility have been optimally scheduled. The industrial problem under consideration illustrates significant complexity, due to the mixed batch and continuous stages, each having numerous shared resources, the large number of final products and the various operational, design and quality constraints. This make-and-pack structure (one or multiple batch or continuous processes followed by a packing stage) is typically met in most food and consumer packaged goods industries, hence, the presented solution strategy can be easily implemented in other industrial problems. It has been shown that the suggested solution strategy can optimally schedule even the most demanding weeks of the examined industry in acceptable time, leading to reduction of overtime production. The proposed strategy can be the core for a computer-aided scheduling tool that can facilitate the decision-making process for the production scheduling of food industries. Current work focuses on the introduction of cost related objectives, as well as, the incorporation of uncertainty in product demands.

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