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Scheduling a single machine with concurrent jobs for the frozen food industry

Pachara Chatavithee [a], Kullapapruk Piewthongngam [b,*], Supachai Pathumnakul [a]

[a] Supply Chain and Logistics System Research Unit, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002, Thailand

[b] Esaan Center for Business and Economic Research, Faculty of Management Science, Khon Kaen University, Khon Kaen, Thailand

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ABSTRACT

This study examines the air blast freezing process of the frozen food industry, which processes multiple products with variable processing rates. The analysis depicts a new, single machine-scheduling problem in which the machine can process multiple jobs concurrently, within its capacity. The machine processes independent jobs arriving at various times while incurring interruption costs when allowing the jobs to enter or leave the machine. A mixed integer linear programming (MILP) model and a heuristic algorithm are developed for scheduling, the objectives of which are to minimize the costs associated with machine activities including that of waiting to load, waiting to unload and interruption time. The heuristic algorithm demonstrates the high potential of the computational time savings by obtaining the solution within one-fifth of the mathematical model computational time.

1. Introduction

Batching machine scheduling problems have been scrupulously studied for a number of decades (i.e., Webster & Baker (1995), Potts & Kovalyov (2000); Brucker (2007), Liu, Ng, & Cheng (2010), Cheng, Cai, Yang, & Hu (2014), Suppiah & Omar (2014)). Typically, a batch processing model is the joint processing of a group of jobs. With this type of processing, no interruption is allowed during the process and no other jobs can be introduced into the machine until the processing of the batch is complete. Hence, jobs in the batch share start and departure times (Webster & Baker, 1995). These types of scenarios are often found in a heat-treatment or a burn-in operation, such as in an oven with a finite capacity (Webster & Baker, 1995).

Despite its broad applications in many industries, batch processing may not be suitable in others. In an attempt to make processing model applicable in a particular industry, Tang and Zhao (2008) developed a dynamic programming model that minimizing makespan and total completion time for steel production. Their model aims to address a semi-continuous batch scheduling problem with a single machine (heating furnace) that processes multiple jobs simultaneously. Another non-batch processing model was developed by Wang and Tang (2011). Their mathematical model and particle swarm optimization algorithm addresses a single machine which capable of processing multiple job simultaneously. Jobs enter and leave the machine continuously one by one, though the model requires all jobs to be ready for processing at time zero.

Significantly distinct from past research, our study considers the single machine (i.e., the air blast freezing machine) that can process multiple jobs (i.e., the product trolleys) concurrently. There is no mechanism for all jobs to be processed at time zero. Each job has a distinct ready time, which is the completion time of job at the previous workstation. Furthermore, the processing times of each job are not identical. The cost of machine interruption is considered. The studied problem is specific to the frozen food industry with a single machine—the Air blast freezers. Air blasting is a commonly used method of freezing food; it is economical, hygienic and relatively non-corrosive to equipment. Air blast freezers are designed to supply cool air over the food product with a uniform air velocity throughout the freezer (Dempsey & Bansal, 2012). In a blast room freezer, the products are stacked on pallets or trolleys and manually loaded into the freezer (as shown in Fig. 1). Because the pallets or trolleys are manually loaded into the freezer, the low freezing rate products are removed from the freezer earlier than those products with a higher freezing rate. The number of trolleys determines the capacity of the blast room, so these machines can process or freeze a number of jobs simultaneously. More detailed characteristics of the Air blast freezing frozen food case are as follows:

* Corresponding author. Tel.: +66 43 202401; fax: +66 43 202402.
E-mail addresses: chatavithee@gmail.com (P. Chatavithee), pkullap@kku.ac.th (K. Piewthongngam), supa_pat@kku.ac.th (S. Pathumnakul).

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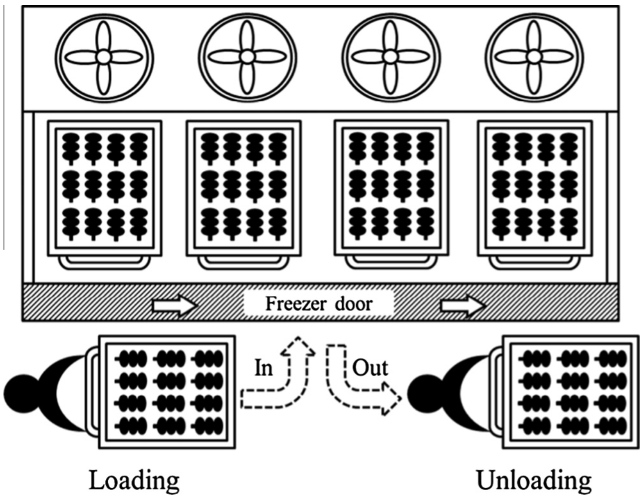

Fig. 1. Air blast freezing machine.

- As food manufacturing produces multiple products with their own unique characteristics, packaging material and geometry, the products require different freezing rates (Dempsey & Bansal, 2012). The frozen food is a case of multiple products that have varying processing times.
- The interruption costs of freezing are mainly from the cost of energy consumption (Liu, Chang, & Lin, 2004) and the food quality (Li & Sun, 2002). That is because freezing is one of the most energy consuming processes (Chourot, Macchi, Fournaison, & Guilpart, 2003). Operating the freezer efficiently often reduces the energy consumption and hence lowers the operating cost for the firm. In this sense, optimal freezing systems are often concerned with and designed for energy saving (Dempsey & Bansal, 2012). With respect to food quality, improper freezing rate and small ice crystals formation during freezing can damage food tissue, and thus, food quality (Li & Sun, 2002), efficient freezing process is therefore crucial to preserve food quality.
- The 'cost of the jobs waiting to be processed' is also introduced in our model. In our food case, the 'cost of the jobs waiting to be processed' is mainly incurred to keep food safe. A leading cause of foodborne illness is time and temperature control violation. The amount of time food spends in the temperature danger zone (41–140°F) should be reduced to lower the risk of growing food pathogens.

To conserve energy and preserve food quality due to the freezer being interrupted, it is necessary to minimize the number of freezer-door opens during production. In practice, to reduce the unnecessary interruption by the opening of the freezer doors, queued jobs may not be loaded immediately upon arrival at the freezing station, even if the machine has available capacity. Jobs can be delayed to wait for the arrival of the next job(s) to load multiple jobs simultaneously, or jobs can be loaded when the current job completes and the machine is unloaded. Similarly, it may not be necessary for jobs to be unloaded from the machine once they complete the freezing process. The job may remain in the machine until other jobs are completed and unloaded. The difficulty then becomes how to determine the suitable loading and unloading schedule needed to minimize the associated costs including the cost of the jobs waiting to be processed, the machine interruption costs (i.e., cost of freezer-door open) and the cost of jobs needing to be delayed in the machine after the process has completed.

To illustrate the characteristics of the research problem, consider an example of processing 10 jobs (i.e., product trolleys) with ready times (i.e., the times that jobs arrive at the air blast machine) and processing times as illustrated in Table 1. The machine capacity is assumed to be 3 jobs at once. Fig. 2 shows the schedule of the problem. The process is interrupted eight times, six times when new jobs are loaded and two times when jobs are unloaded from the machine, at times 105 and 125, respectively. At time 0, Job 1 and Job 2 are loaded into the machine. There is capacity availability at this time, so when Job 3 arrives at time 15, it is immediately processed. Because the processing time of Job 1 is 25 units of time, Job 4 arrives at time 20 and can be processed at the next available capacity opening, also occurring at time 25. The completion times of Job 2 and Job 3 are at time 45, which is also the time when Job 5 and Job 7 start. Though Job 5 and Job 7 start at the same time, the processing time of Job 5 is 5 units of time less than Job 6. Hence, it may be more economical to cause Jobs 5 and 6 to leave the machine at the same time as Job 7 to minimize the interruption cost. The example displays that the processing time of Job 5 is 5 units of time longer than required processing time.

2. Problem formulation

In this section, the scheduling of a set of jobs with an altered ready time is modelled, for a single machine capable of concurrently processing multiple jobs. The freezing operation by the air-blast machine in the frozen food industry is used as an example case for the model. The objective function of the model is to minimize the cost related to scheduling decisions. The problem characteristics can be summarized as follows:

(1) There are independent jobs to be processed. The arrival time and the processing time of jobs are not uniform and assumed to be deterministic.
(2) The single machine can process multiple jobs concurrently.
(3) The jobs can be loaded into the machine after they arrive, if machine capacity is available, and they can be unloaded from the machine after processing is completed. Staying in the machine longer than the required processing time is allowed.
(4) There are three major costs involved with the scheduling decisions:
   - The cost of the machine interruption when loading a job while the machine is operating on other jobs, the machine interruption cost.
   - The cost of a job waiting to be loaded to machine after arrival, the waiting to load cost.
   - The cost of job staying in the machine longer than the required processing time, called waiting to unload cost.

A mixed integer linear programming (MILP) model for the addressed problem is formulated as follows:

Table 1
Parameters of a 10-job example case.

Job	1	2	3	4	5	6	7	8	9	10
Arrival time (unit time)	0	0	15	20	30	40	45	60	60	75
Processing time (unit time)	25	45	30	30	30	45	35	20	25	20