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The influence of capacity- and time-constrained intermediate storage in two-stage food production systems

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The influence of capacity- and time-constrained intermediate storage in two-stage food production systems

Abstract

In food processing, two-stage production systems with a batch processor in the first stage and packaging lines in the second stage are common and mostly separated by capacity- and time-constrained intermediate storage. This combination of constraints is common in practice, but literature hardly pays attention to this.

In this paper, we show how various capacity and time constraints influence the performance of a specific two-stage system. We study the effects of several basic scheduling and sequencing rules in the presence of these constraints in order to learn the characteristics of systems like this.

Contrary to the common sense in operations management, the LPT rule is able to maximize the total production volume per day. Furthermore, we show that adding one tank has considerable effects. Finally, we conclude that the optimal setup frequency for batches in the first stage is dictated by the storage time constraint.

Keywords: food processing; storage tanks; capacity constraints; time constraints; simulation

1 Introduction

In the food-processing industry, production systems often consist of two stages. In general, the first stage concerns the batch processing of raw material into food products, which are packaged in the second stage.

In previous research (e.g. Van Donk, 2001), perishable goods, shared resources (such as tanks), and a divergent product structure were identified (among others) as important characteristics of food processing. These characteristics imply the presence of two types of intermediate storage limitations: capacity constraints and time constraints.

The capacity constraints are present because of a limited number of storage tanks, which often have to be shared by a multitude of products. Of course, each of these tanks also has its own capacity constraint (its maximum content). Furthermore, batches can not be stored concurrently, due to quality and traceability requirements. These constraints become even more relevant if the number of products is greater than the number of tanks, or if not all products can be stored in every tank.

The second storage limitation, time, is present due to the perishability of the intermediate food product. Unpackaged intermediate products are often more perishable than packaged products, which makes the storage time constraint in the intermediate stage of the production process more important than in other stages (raw material, final products). Within a certain time period, the product has to be packaged and transported to the customer, or else the product has to be disposed of as waste or low-quality by-product.

There are many practical situations where the two types of storage constraints are encountered. For example, in the production of dairy products, the customer often demands a certain best-before date. Thus, the possible storage time of perishable intermediates in the production process is very short. Another example is the production of flour, where intermediates have to be stored in a limited amount of

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7 silos. Due to different grains and different mixtures, the number of intermediates
8 is very large, which can result in blocking effects caused by tank unavailability.
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11 In the literature (discussed in section 2), intermediate storage is often consid-
12 ered as one single capacity constraint and the time constraint is hardly covered.
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14 This paper studies production systems with both types of constraints. We study
15 the performance of a specific two-stage system under these constraints, and use
16 several well-known (common-sense) heuristic sequencing approaches. For this
17 study, we aim to explore the impact of the intermediate storage constraints. We
18 believe a better understanding of the implications of these storage constraints is
19 necessary as a starting point for the design of solution procedures for scheduling
20 problems. We emphasize that in this paper, it is not the aim to develop a spe-
21 cific mathematical model and solve this to optimality. Instead, we consider this an
22 exploratory study using a relatively simple stylized production system (but repre-
23 senting all (real-life) complexities in terms of interactions between production ca-
24 pacities and intermediate storage). We use simulation to investigate the behaviour
25 under various capacity and time constraints on intermediate storage. We focus on
26 several performance measures such as flow time, makespan, and waste. Underly-
27 ing these measures, blocking and starvation effects play an important role. In the
28 experiments, we also study the effect of uncertainty in processing times —as this
29 is expected to influence blocking and starvation effects.
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44 The paper is organised as follows. First, we discuss previous results on two-
45 stage production systems. Then we outline the production system we study in this
46 paper and several heuristic scheduling approaches to be used in scheduling this
47 production system. Subsequently, we present the results of simulation studies,
48 which is the main contribution of this paper. Finally, the last sections will contain
49 a discussion of the results and suggestions for further research.
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2 Literature background

There is a significant amount of studies that concern two-stage production systems. These systems already offer considerable complexity, as demonstrated by Gupta (1988). Johnson (1954) was one of the first to study such a system, with one machine in each stage. More recently, most papers address systems with one machine in the first stage and multiple machines in the second stage (e.g. Gupta and Tunc, 1991; Tsubone *et al.*, 1996; Li, 1997). This type of problem is often found in process industries (Narasimhan and Panwalkar, 1984), and it resembles the typical divergent structure of production processes found in the food-processing industry (Akkerman and Van Donk, to appear).

A lot of studies, however, do not consider limited intermediate storage possibilities between the production stages. In the food-processing industries, we can distinguish capacity and time constraints on intermediate storage. Capacity constraints have been considered in several publications. In most cases, the limitation is included as an overall capacity constraint (e.g. Papadimitriou and Kanellakis, 1980; Nowicki, 1999), but several papers incorporate storage in the form of tanks (e.g. Belarbi and Hindi, 1992; Yi *et al.*, 2000). From these papers, we learn that complex scheduling problems arise, which often can only be solved heuristically. We also see that tank availability is a specific concern in such situations and a main element in the modeling. Time constraints also received some attention in previous research, but relatively few studies consider this constraint (e.g. Yang and Chern, 1995; Su, 2003). Here we see that the time constraint dominates the development of heuristics and tighter constraints require more calculation efforts. To the best of our knowledge, the specific combination of capacity and time constraints has not been addressed in the literature. Furthermore, the complexity of the scheduling problems and the inherent difficulties in developing solution methods leads us to believe a good insight in this combination of constraints is important.

In our study, the first stage concerns a batch process. In the literature, the

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7 concept of batching is used in different ways. First, due to efficiency reasons, it
8 can be convenient to process several jobs in a batch instead of processing them
9 individually (see e.g. [Potts and Kovalyov, 2000](#)). For example, setup times can
10 be involved when switching between product families. Then, the batching is the
11 result of scheduling reasons and is called family scheduling ([Webster and Baker,](#)
12 [1995](#)). The main issue in family scheduling is the trade-off between minimal setup
13 times and the order delivery time. Large batches delay the processing of orders
14 from other product families ([Potts and Kovalyov, 2000](#)). Secondly, batching can
15 also have technical reasons. In process industries, the processing stage often con-
16 cerns non-discrete products, and processing technology often implies the need for
17 batching. Then, a batch can be defined as a quantity that is planned to be pro-
18 duced in a given time period based on a formula or recipe that often is developed
19 to produce a given number of end items ([Cox and Blackstone, 2002](#)). The batch
20 sizes usually depend on the capacity of the batch processor. This is identified as
21 batch processing ([Webster and Baker, 1995](#)).

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35 In the above terminology, the kettle process in this paper is a batch processing
36 machine. However, in our case, the sequencing of kettles is another relevant issue,
37 because we assume setup times between product families. Therefore, schedul-
38 ing the kettle process in this paper includes elements from batch processing and
39 family scheduling. Furthermore, the intermediate storage time limitations we in-
40 clude also influence the coordination of the scheduling of the kettle process (see
41 also [Silver, 1989](#)). In the field of chemical engineering, we also find various ap-
42 proaches to the scheduling of batch processing operations, mostly based on mixed
43 integer linear programming (MILP) techniques (see e.g. [Kondili et al., 1993](#); [Pinto](#)
44 [and Grossmann, 1998](#)). Although these papers provide sophisticated production
45 scheduling procedures, these approaches do not provide a thorough insight in the
46 effects of constrained intermediate storage.
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3 Problem formulation

3.1 Production system

Figure 1 illustrates the production process studied in this paper. It is based on experiences in the food-processing industry, where such two-stage processing and packaging systems are very common.

[Figure 1 about here.]

Although it is a relatively simple system, it contains all basic elements that determine the complexity of two-stage food production. In this way, we think that the results of the study provide general insights into the interactions and characteristics found in two-stage systems with intermediate storage in the food-processing industry.

The first stage consists of a kettle process, where J different intermediate products are produced. The kettle content B is fixed and it requires a processing time $p_{1,j}$ to produce one kettle of intermediate product j . This processing time is subject to uncertainty, due to variation in the quality of the raw material. In the food-processing industry, the raw material usually originates from the agricultural sector. These materials often have a variable quality by nature. During the processing time, the product stays in the kettle, and can only be transported to a storage tank after processing ends.

If multiple kettles of one product are produced in one batch, no setup time is required between these kettles. However, when changing to another product, a — sequence-independent — setup period S_{up} is necessary. In this paper, a number of consecutively produced kettles of one product is referred to as a batch.

There are K storage tanks, which can each hold M finished kettles of an intermediate product. Two types of constraints are present for the intermediate storage: (i) a capacity constraint, concerning the number of tanks and their maximum content, and (ii) a storage time constraint. The capacity constraint is influenced by

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7 the fact that it is not allowed to store product from kettles in different batches in
8 one storage tank, due to traceability issues. Due to this separation of batches, it is
9 more likely that intermediate storage tanks are unavailable for a new batch.
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12 The storage time constraint is related to the customer's requirements concern-
13 ing the best-before date of a final product. To ensure a long best-before date, the
14 intermediate product that is used for an end product has to be packaged within
15 a maximum time T_{\max} . If several kettles of a product are stored in the tank, the
16 finishing time of the first kettle determines the maximum storage time.
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22 In the second stage of the production system, J packaging lines are available
23 to create various end products from each of the J intermediate products. The
24 unit processing time $p_{2,j}$ varies due to differences in packaging sizes. For small
25 packaging sizes, it takes more time to package a certain amount of product, than
26 for larger packaging sizes.
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31 Finally, for reasons of simplicity, we make the following assumptions:

- 32 • The transport times between the batch processor and the storage tanks are
33 negligible.
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- 35 • Withdrawing product from tanks for packaging can only begin after batches
36 are finished.
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- 38 • Every storage tank can be used to store every intermediate product.
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- 40 • Raw materials and packaging materials are always available.
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- 42 • Storage of finished products is not relevant, as all products are immediately
43 shipped to the customer.
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- 45 • The production system operates only on weekdays, for eight hours per day.
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53 3.2 Product flow and scheduling

54 Customer orders for the end products arrive during working days, and have to be
55 delivered the next day. The number of orders O_j for each product family j varies
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7 from day to day. All orders also have their own packaging format requirements,
8 which will be relevant in scheduling the packaging stage. At the start of each day,
9 all orders become available to the planning department. At this time, schedules
10 for the first and second stage can be created based on the orders and the current
11 intermediate storage levels. However, this is not the only moment scheduling de-
12 cisions are made. When the kettle process in the first stage has finished producing
13 the intermediates that are needed to package the set of orders for the current day,
14 it can be considered to make intermediate product for the next day. This is based
15 on whether there is time left on the day and whether intermediate storage space is
16 available.

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26 In the first stage, a cyclic scheduling approach is adopted. According to [Pinedo](#)
27 [\(2002\)](#), this is often the case in flow lines with limited intermediate storage. The
28 approach is also attractive, because it will periodically supply different intermedi-
29 ate products to the second part of the production system, providing inputs for the
30 packaging stage. The setup frequency for each intermediate product is denoted by
31 the design parameter S_f , which is equal to the amount of cycles per day.

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37 In each cycle, every product is produced once. The amount of kettles in a batch
38 depends on the amount of products requested by the customer and the usable
39 amount of product in the intermediate storage (where the usability is derived from
40 the time constraint). We use L_j to denote the amount of kettles of product j that are
41 needed on a certain day. This amount can be calculated by¹ $L_j = \lceil (O_j - U_j)/B \rceil$,
42 where B is the kettle content, U_j is the usable amount of product j which is in the
43 intermediate storage at the start of the day, and O_j the amount of products from
44 family j to be produced that day — collected on the day before. Finally, these L_j
45 kettles are divided between the production cycles. That means that the p^{th} cycle
46 for product j (called CL_{jp}) has $\lceil (L_j - \sum_{i=1}^{p-1} CL_{ji}) / (S_f - (p-1)) \rceil$ kettles.

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52 For the additional production at the end of the day, this cyclic scheduling ap-

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58 ¹The notation $\lceil x \rceil$ is defined as the smallest integer greater than or equal to the value of x , or
59 mathematically speaking: $\lceil x \rceil = \min\{y \mid y \in \mathbf{N}, y \geq x\}$.

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proach will be continued. However, the batch size (in kettles) cannot be based on customer demand, because this information is not available until the next day. Therefore, it is based on a forecast of the requested orders for the next day. On Fridays, no additional production is scheduled, because due to the storage time constraint, the product would be unusable on the next Monday. As compensation, the kettle process is started earlier on Mondays. For the remaining weekdays, production at the end of the previous day can be used and starting earlier is not necessary. In this way, the production is mostly done during the regular working hours, which can be economically attractive.

In the second stage, the intermediate product is packaged to satisfy the customer orders. Because of the varying packaging times, the packaging sequence influences the speed at which product is extracted from the tanks. In this paper, we use three different ways to sequence the production in this stage:

- FCFS rule (First Come, First Serve), where the orders are processed in the order they arrive. The main idea behind the inclusion of this rule is its usefulness as a benchmark. In many cases it is also attractive because it results in a low variance of flow time (see e.g. [Rajendran and Holthaus, 1999](#)).
- SPT rule (Shortest Processing Time), which arranges the products according to an ascending order of unit processing times. This rule is traditionally seen as the best rule in terms of flow time (see e.g. [Holthaus and Rajendran, 2002](#)), although some authors discuss its effectiveness in situations with bottlenecks (see [Bassett and Todd, 1994](#)).
- LPT rule (Longest Processing Time), which arranges the products according to a descending order of unit processing times. According to [Tsubone et al. \(1996\)](#), this rule yields good results in terms of the maximum work-in-process level, which makes it especially interesting to consider in a situation where storage is constrained (in capacity and time).

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7 The storage constraints are an important characteristic of this production sys-
8 tem. Both the production cycle in the first stage and the packaging sequence in
9 the second stage interact with these constraints. This interaction results in block-
10 ing and starvation effects. Blocking occurs when the kettle process finishes, but
11 there is no intermediate storage tank available. This means the product stays in
12 the kettle until a tank becomes available and therefore temporarily blocks further
13 production. The blocking effects are strengthened by the traceability requirements
14 mentioned before. Even a small amount of the same product as in the kettle could
15 block a storage tank. Starvation occurs when there are customer orders to pack-
16 age, but the required intermediate product is unavailable. Then, the packaging
17 line is idle until the intermediate product becomes available.

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28 If there is much blocking and starvation, it can be the case that it is not possible
29 to satisfy all customer orders within the time available.

30 31 32 33 **3.3 Illustrative example**

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35 To clarify the characteristics of the production system, figure 2 shows an example
36 of a production schedule for a system with three packaging lines, three storage
37 tanks with a content of three kettles ($J = 3, K = 3, M = 3$).

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41 [Figure 2 about here.]

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44 In this example, we present a situation where two production cycles are processed
45 in the first stage ($S_f = 2$) and the intermediate storage tanks are empty at the
46 start of the day. The storage time constraint is assumed to be nonrestrictive. The
47 impact of the capacity constraint is visible through blocking and starvation effects.
48 For each of the product families, five kettles of intermediate product are needed to
49 satisfy demand ($L_j = 5, \forall j$).

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Starvation is seen at the start of the day, and during the day after the packag-
ing of the first batches. Blocking effects can be seen in the first stage. After the
production of the first kettle in the second batch of product 3, there is no storage

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7 tank available. Only after a tank becomes available, the content of the kettle can
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9 be moved to this storage tank.

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11 This example also provides insight into the effect of production in advance. At
12 the end of the day, there is sufficient time to start with a new production cycle.
13 However, there is a reasonable chance that blocking effects will occur, due to the
14 situation that no storage tank is available. In the example, one additional batch
15 of product 1 is produced to create a starting inventory for the next day. If this
16 is possible (considering capacity and time constraints), there is a significant time
17 advantage on the next day. This advantage is that one of the packaging lines does
18 not have to wait until the batch processor finishes the first batch, which reduces
19 the amount of starvation.
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29 **3.4 Performance criteria**

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31 For the formulation of the performance criteria, we introduce several additional
32 variables. For the first stage, let $S_{1,jl}$ and $C_{1,jl}$ be the starting time and completion
33 time for the l^{th} kettle process of intermediate product j (from a total of L_j kettles).
34 For the second stage, we define $S_{2,jo}$ and $C_{2,jo}$ to be the starting time and com-
35 pletion time for the packaging of the o^{th} order an end product from family j . As
36 defined earlier, we use O_j to denote the number of orders for product j (for the
37 current day).
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45 First, we will use daily flow time, makespan, and the amount of unfinished or-
46 ders to evaluate the production systems ability to finish the requested orders. With
47 the flow time, we have a indication of the time the orders spend in the production
48 process, which (for practical considerations) translates into lead times for individ-
49 ual orders. The makespan gives us an idea on the total time needed to finish the
50 daily production. We denote these criteria by FT , MS , and UF and calculate them
51 as follows:
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$$57 \quad FT = \sum_{j=1}^J \sum_{o=1}^{O_j} C_{2,jo}, \quad (1)$$

$$MS = \max_{j,o} C_{2,j,o}, \quad (2)$$

$$UF = \sum_{j=1}^J \sum_{o=1}^{O_j} I_{j,o}^u, \quad (3)$$

where $I_{j,o}^u$ is an indicator function, defined as follows:

$$I_{j,o}^u = \begin{cases} 1, & \text{if the } o^{\text{th}} \text{ order for a product from family } j \text{ is unfinished} \\ & \text{at the end of the day} \\ 0, & \text{otherwise.} \end{cases}$$

Due to the limited storage capacity, we also measure the amount of blocking in the first stage and the amount of starvation in the second stage to evaluate the systems performance. These criteria will provide insight on the effects of the limited number of storage tanks between the two stages. In this formulation, we let $T_{1,j,l}$ denote the moment in time that the l^{th} kettle for family j is transported to an intermediate storage tank. The amount of blocking is then calculated in the following way:

$$BL = \sum_{j=1}^J \sum_{l=1}^{L_j} (T_{1,j,l} - C_{1,j,l}), \quad (4)$$

and the amount of starvation as follows:

$$ST = \sum_{j=1}^J \left(\sum_{o=2}^{O_j} (S_{2,j,o} - C_{2,j,(o-1)}) + S_{2,j,1} \right). \quad (5)$$

The other additional element in this paper is the limited waiting time of products in the intermediate storage. Therefore, it can happen that a batch of intermediate product becomes obsolete and unusable for further production. The last performance criterion we include is therefore the amount of waste. Here, SL_k and FD_k denote the storage level of product in tank k and the fill date of tank k . We measure the time constraint on intermediate storage in days, so the waste on a certain day d can be calculated as follows:

$$WA = \sum_{k=1}^K I_k^w SL_k, \quad (6)$$

where I_k^w is defined as follows:

$$I_k^w = \begin{cases} 1, & \text{if } d - FD_k > T_{\max} \\ 0, & \text{otherwise.} \end{cases}$$

4 Numerical experiments

Several experiments have been performed to analyse the performance of various configurations of the production system. The aim of these experiments is to study the influence of several intermediate storage constraints, and to study the applicability of different sequencing rules in the packaging stage.

As was mentioned in Section 3, there are several elements subject to uncertainty. In the simulation study, these are inserted as follows. The batch processing time $p_{1,j}$ is generated from a truncated normal distribution with average \bar{a} and coefficient of variance cv_a .

The customer orders for products from family j arrive during the day following a Poisson distribution with an average of λ units per day. For the second stage, the unit processing time $p_{2,j}$ is dependent on the packaging requirements of the customer and is randomly set at b_{\min} or b_{\max} , where $b_{\min} = \bar{b} - b_{\text{dev}}$ and $b_{\max} = \bar{b} + b_{\text{dev}}$. With this implementation, we are also able to study the effect of smaller and larger differences in packaging times by varying b_{dev} .

We expect that the uncertainty in the processing times has a significant impact on the performance of the production system. Variation in the moment that products are transported to the intermediate storage tanks and the moments that they are extracted from these tanks influences blocking and starvation effects and will therefore affect the systems performance.

Next to the effect of uncertainty, we will also study various configurations of the intermediate storage system. We will study capacity-constrained intermediate storage by looking at different numbers of storage tanks, as we are interested to see to what extent there is an effect on the performance criteria through increased

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7 or decreased blocking and starvation.

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9 Finally, we also look at time constraints for the intermediate storage. We expect
10 tight storage time constraints to have a big influence on the performance of the
11 sequencing heuristics and also the choice for a specific setup frequency.
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14 The parameter settings used in the initial model are listed in table 1.
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17 [Table 1 about here.]
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20 The simulation results in the following section have all been derived from 100
21 simulation runs of 10 weeks. It should be noted that, due to the storage time con-
22 straint, the products in the intermediate storage cannot be stored over the week-
23 end. This results in independence between weeks. Therefore, the run length in
24 weeks is arbitrary, as long as it is a number of full weeks.
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31 **5 Simulation results**

32 33 34 **5.1 Effects of uncertainty**

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36 To evaluate the effect of the sequencing rules used in the second stage, we will first
37 look at various differences between the processing times by varying b_{dev} . Greater
38 variation in these processing times should increase the effects of using a certain
39 sequencing rule. All other parameters have the values listed in table 1.
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44 In figure 3, the flow time and makespan are shown for various values of b_{dev}
45 and various sequencing rules. The value of b_{dev} represents the variation in pack-
46 aging times.
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51 [Figure 3 about here.]
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54 As can be seen in these figures, the amount of variation in the packaging time
55 in the second stage has significant effects on the flow time and the makespan.
56 First, using certain sequencing rules becomes more important. The result from
57 figure 3(a) can be explained by the definition of flow time (summation of finishing
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7 times). If all orders with small processing times are processed first, it is obvious
8 that a sum of completion times is smaller than if orders with long processing times
9 are processed first. However, despite the disadvantage in flow time, the makespan
10 is lower for the LPT sequencing rule (as shown in figure 3(b)). This is due to an
11 increase in the amount of starvation time; because when the second stage finishes
12 packaging relatively soon (SPT rule), it has to wait for new intermediates to con-
13 tinue. The amount of blocking time is relatively constant, due to the fact that this
14 also occurs before or during the additional production. However, this part of the
15 blocking time does not affect the packaging of customer orders.

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24 Next, the effect of uncertainty in the batch processing time is studied. With
25 more uncertainty, we expect that the chances of blocking and starvation increase,
26 which in turn could effect our main performance criteria, like flow time and make-
27 span. Therefore, in figure 4, the flow time and makespan is shown for various
28 values of sd_a , which is the standard deviation of \bar{a} .

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34 [Figure 4 about here.]

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37 More variation in the batch processing time increases the flowtime and the make-
38 span of the production system. This can be explained as follows. If the variation
39 in the batch processing time increases, we both get batches that take a longer time
40 and batches that finish faster. In the first case, makespan and flow time are nega-
41 tively influenced. In the second case, this does not necessarily have to be true. It
42 is possible that no intermediate storage capacity is available and blocking effects
43 occur. This increase in blocking is partly cancelled by a decrease in blocking effects
44 due to the longer processing times. However, these longer processing times also
45 result in an increase in starvation time. Overall, the result is an increase in flow
46 time and makespan, as was shown in figure 4.

5.2 Effect of the number of tanks

In figure 5, the flow time and makespan performance criteria are shown for different numbers of storage tanks.

[Figure 5 about here.]

With the increase of the amount of intermediate storage tanks, there is (initially) an improvement in these performance criteria. This is mostly due to a decrease in the blocking and starving time encountered. For more than six storage tanks (two for each family), not much more improvement is seen.

[Figure 6 about here.]

However, as we can see in figure 6(a), the addition of only one storage tank already results in reducing the amount of unfinished orders to almost zero. With more than six storage tanks, there is even a slight increase in the amount of unfinished orders. This is likely to be caused by an increase in waste, as is shown in figure 6(b).

5.3 Effect of the storage time constraint

The storage time constraint has a significant effect on the production systems' performance. Until now, we used a maximum storage time of one day. Here we will consider the performance for different values of T_{\max} , which we will now state in minutes. The value of T_{\max} also has an important effect on the scheduling; if the time constraint is getting tighter, it is not possible anymore to produce intermediate product for the next day.

As the storage time constraint becomes tighter, it seems logical to reduce batch sizes (increase setup frequency). In this way, smaller amounts of intermediate product are delivered to the storage tanks and can subsequently be packaged faster. Therefore, we look at different setup frequencies. Figure 7 shows the flow

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7 time and makespan for various values of T_{\max} for three different setup frequen-
8 cies. The initial setup frequency S_f in our study is 2. In the simulation, we also
9 used $S_f = 3$ and $S_f = 4$.
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12 [Figure 7 about here.]
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16 In the two figures, there is a jump at around 1000 minutes. This change is due
17 to the possibility of storing product overnight when the time constraint is above
18 1000 minutes. As we can see, being able to 'work in advance' reduces the flow
19 time and makespan significantly.
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23 Several interesting results can be seen in the figures. First, the possibility to
24 store products overnight makes the choice of setup frequency very relevant. For
25 tighter storage constraints, it is useful to increase the setup frequency from 2 to 3.
26 A higher setup frequency results in a lot of setup time and increases makespan.
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30 Secondly, the difference in flow time and makespan with and without the pos-
31 sibility to 'work in advance' is quite big. For the makespan (figure 7(b)), note that it
32 is only possible to produce the given orders in a shift of eight hours (480 minutes)
33 if the storage constraint allows to work in advance for the next day. When this is
34 not the case, extensive starving effects at the start of the day negatively influence
35 the performance criteria (as was also illustrated in the example in figure 2).
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42 [Figure 8 about here.]
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46 Finally, the amount of waste (figure 8) is significantly higher if the storage con-
47 straint does not allow storing overnight. This can be explained by the fact that,
48 on every day, all remaining intermediate storage has to be disposed of as waste.
49 Around $T_{\max} = 1000$, it can be seen that the setup frequency has quite an effect on
50 the amount of waste.
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54 For small values of T_{\max} , the sequencing rule used is again important. In figure
55 9(a), the number of unfinished orders is shown for different values of T_{\max} . It can
56 be seen that with the SPT rule, almost all order are fulfilled for $T_{\max} \geq 160$ minutes.
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7 For the LPT rule, this is true for $T_{\max} \geq 200$ minutes. The amount of unfinished
8 orders are also resembled in the amount of waste, as shown in figure 9(b).
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11 [Figure 9 about here.]
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14 An explanation for this behaviour can be found in the fact that with the LPT
15 rule the packaging of the first batch can take more time than the production of
16 the following batch. This can in turn cause blocking effects which means that a
17 product already starts its decay before it is even transferred to the intermediate
18 storage.
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25 **6 Conclusions and further research**

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27 In this paper, we addressed intermediate storage tanks with capacity and storage
28 time constraints in a two-stage production system with a batch processor in the
29 first stage and several packaging lines in the second stage. The combination of
30 capacity and time constraints has not been studied before. Our contribution in
31 this paper is seeing how several common-sense scheduling and sequencing rules
32 perform in the presence of these constraints, and analysing how various capacity
33 and time constraints influence the systems performance.
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41 First, the type of sequencing rule in the second stage has significant effects
42 on performance criteria like makespan and flow time. This effect is stronger as
43 the variation in packaging times is higher. Although flow time is minimised by
44 using the SPT rule, the makespan is minimised by the LPT rule. The latter is
45 caused by less starvation in the packaging stage, and can also result in an overall
46 increase in production volume per day. This is an interesting result, because of the
47 intuitiveness of using the SPT rule to empty the storage tanks as soon as possible.
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53 Secondly, we conclude that to manufacture an acceptable number of orders,
54 the number of tanks should be at least equal to the number of packaging lines.
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57 When adding one additional tank above that number, almost all orders can be
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7 finished in time, but there still are some blocking and starvation effects, which in-
8 fluence the time needed to finish the set of orders. From our analysis, it follows
9 that more additional storage tanks reduce flow time, makespan, blocking time,
10 and starvation time. This effect decreases significantly with every additional stor-
11 age tank. However, increasing the number of tanks does result in more waste, due
12 to violation of the time constraint. If the number of tanks is more than twice the
13 amount of packaging lines, the increase in waste results in more unfinished orders.
14 This is mainly caused by the need to produce additional batches in the processing
15 stage to replenish the waste. Interestingly, this means that adding tank capacity to
16 the production system could negatively influence some performance measures.

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26 Finally, the storage time constraint has been varied and it clearly shows that it
27 is beneficial to use a different setup frequency if it is not possible to store the inter-
28 mediate product until the next day. For different storage time constraints, using
29 different sequencing heuristics only has influence for tighter constraints. The SPT
30 rule can cope with tighter storage time constraints than the other rules because of
31 less blocking. There is more starvation, but this does not affect product perish-
32 ability and waste. As seen earlier, starvation is more important when considering
33 performance criteria like makespan.

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41 The managerial implications of these results could be summarised as follows.
42 First, the intuitive idea of emptying the intermediate storage tanks as soon as pos-
43 sible has a significant drawback in terms of makespan (through increased starva-
44 tion time). Secondly, the results show that one additional storage tank already has
45 a significant impact on the system performance. Additional tanks can be used to
46 further decrease flow time or makespan, but these investments should carefully
47 be considered. Also, adding tank capacity can lead to more waste and unfinished
48 orders, which is something that needs to be carefully monitored. Third, for tight
49 storage time constraints, emptying the storage tanks as soon as possible does result
50 in the lowest amount of unfinished orders. It turns out that, under tight storage
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7 constraints, it is important to realize that both blocking and starvation negatively
8 effect the performance of the production system in terms of flow time and make-
9 span, but only blocking is relevant in causing waste. Finally, an analysis as the one
10 described in this paper is a very useful tool for evaluating the effects of design or
11 expansion decisions.
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16 We realise that the first and the third implication represent a trade-off. If one
17 has to implement a sequencing policy in practice, both implications should be
18 considered and choices have to be made depending on the situation. The devel-
19 opment of tools to support managers in making such decisions is an interesting
20 direction for further research.
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25 The results in this paper are based on specific production characteristics. This
26 also raises interesting directions for further research. For instance, we assumed
27 a symmetrical demand pattern for the different product families. Studying the
28 impact of a non-symmetrical demand pattern would be an interesting next step.
29 Also, an interesting suggestion would be to include a distinction between storage
30 tanks that are dedicated to a single product and storage tanks that can be used
31 for multiple products. This would also result in more capacity constraints for the
32 intermediate storage, which could require special treatment in the scheduling and
33 sequencing process. Finally, the analysis could be extended to include other char-
34 acteristics of the food-processing industry, such as random yields or sequence-
35 dependent setup times.
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List of Figures

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9	Average amount of unfinished orders and waste against T_{max} for various heuristics.	33

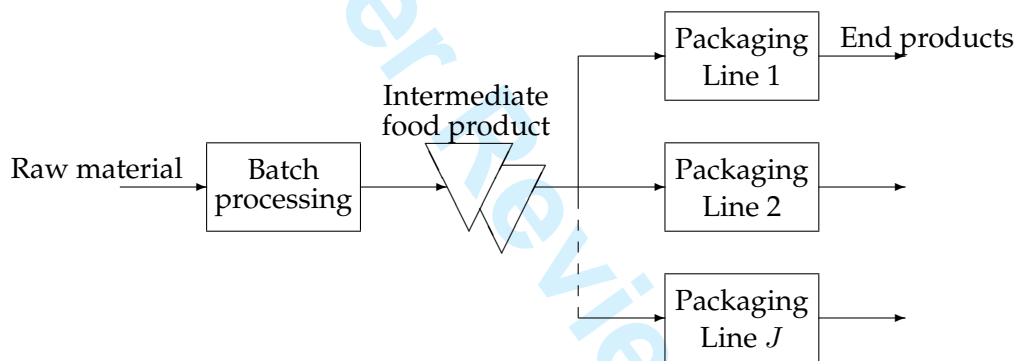


Figure 1. General form of the two-stage production process with a batch processor in the first stage and J parallel packaging lines in the second stage.

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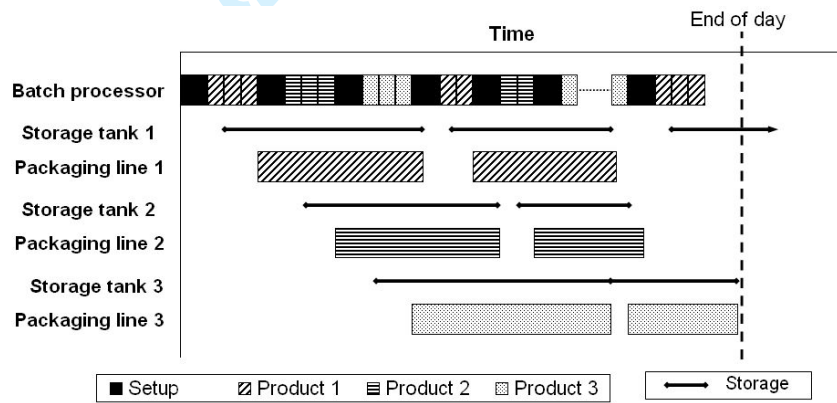


Figure 2. Schedule for the example case.

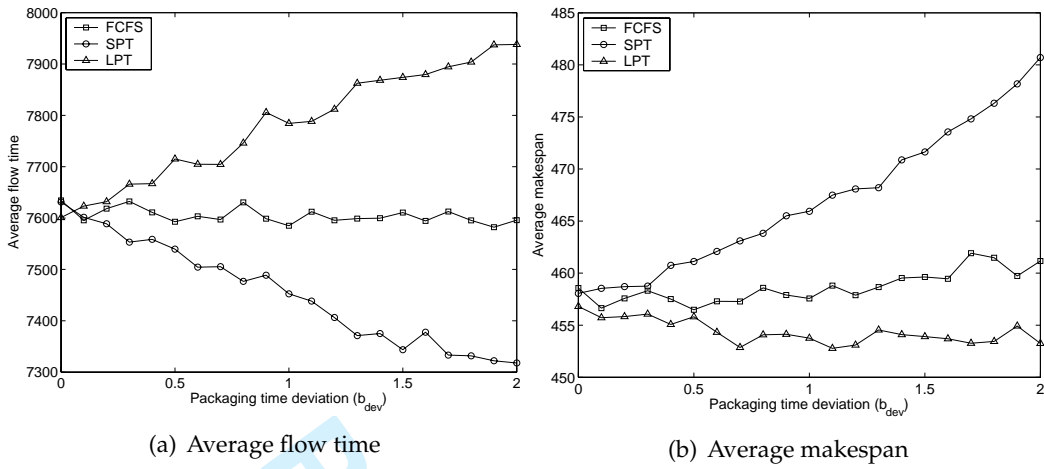


Figure 3. Average flow time and average makespan against b_{dev} for various heuristics.

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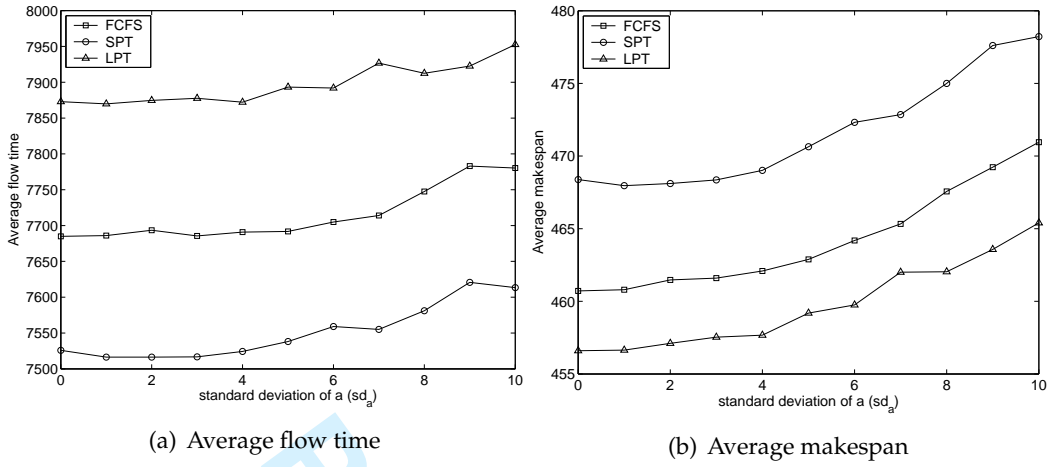


Figure 4. Average flow time and average makespan against sd_a for various heuristics.

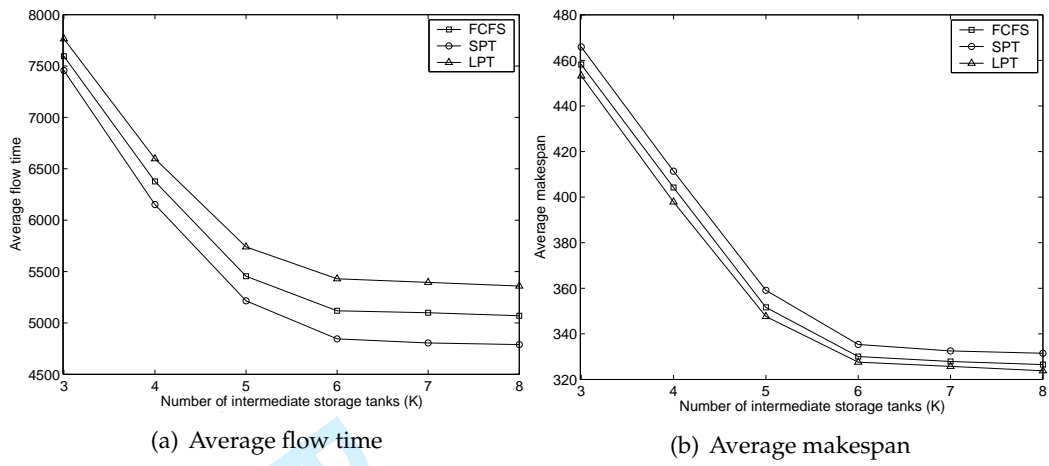


Figure 5. Average flow time and average makespan against K for various heuristics.

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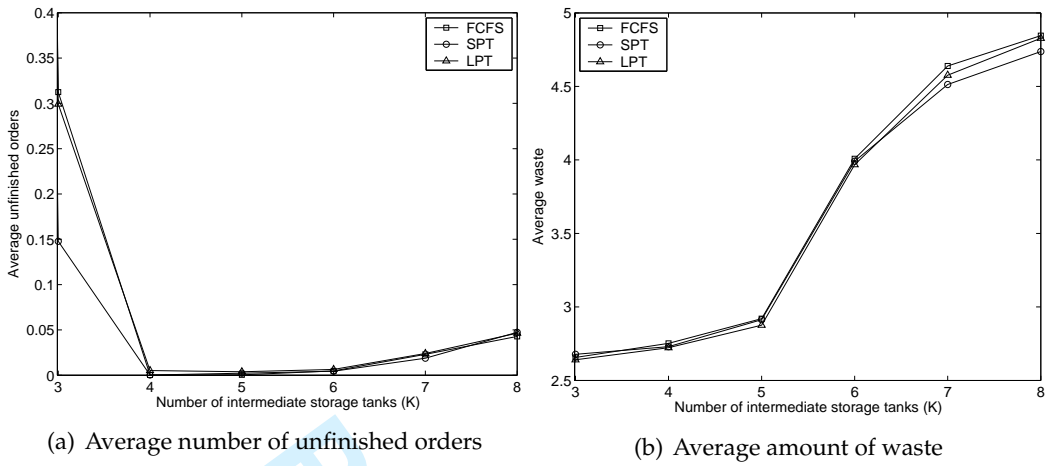


Figure 6. Average amount of unfinished orders and waste against K for various heuristics.

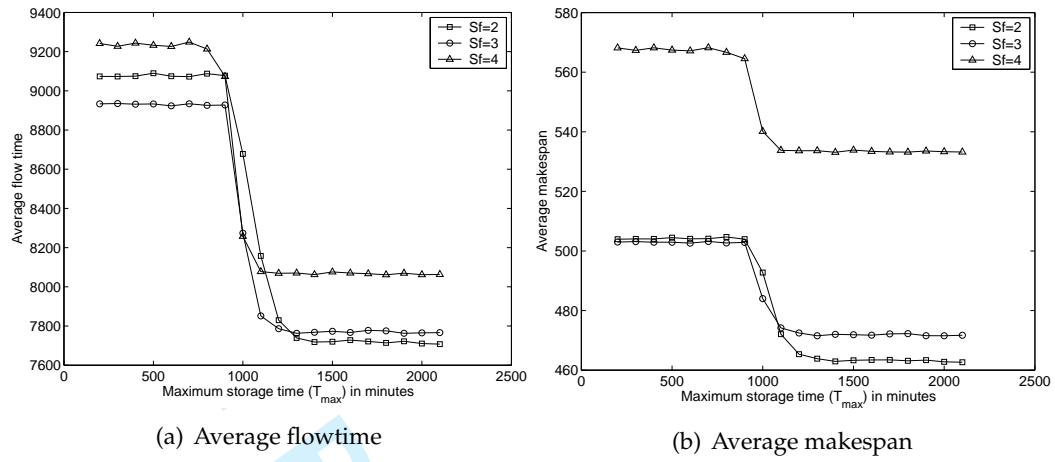


Figure 7. Average amount of unfinished orders and waste against T_{max} for various heuristics.

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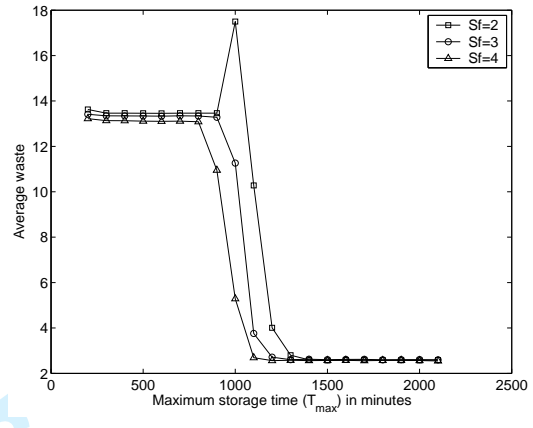
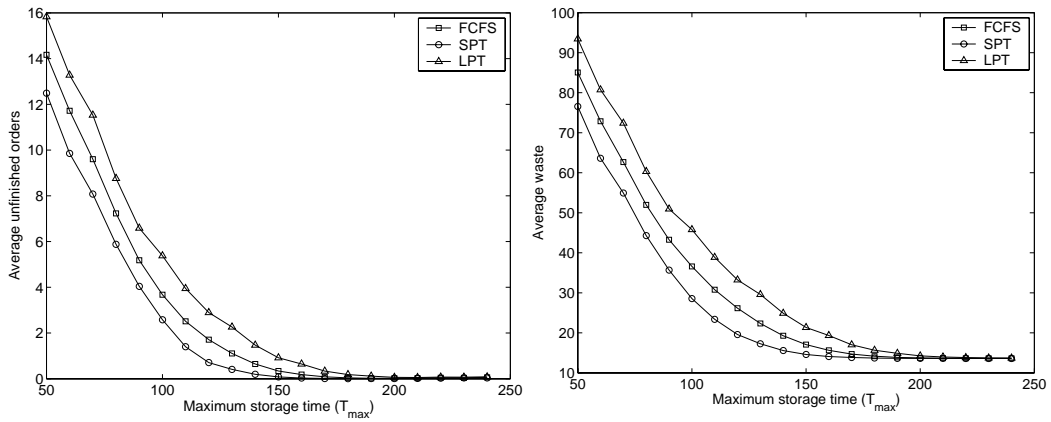


Figure 8. Amount of waste against T_{max} for various setup frequencies.

For Peer Review Only



(a) Average number of unfinished orders

(b) Average amount of waste

Figure 9. Average amount of unfinished orders and waste against T_{max} for various heuristics.

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List of Tables

1 Initial values of parameters used in the model. 35

For Peer Review Only

Table 1. Initial values of parameters used in the model.

Parameter	Value	Parameter	Value	Parameter	Value
λ	50 units/day	K	3 tanks	\bar{a}	15 minutes
J	3 families	M	5 kettles	cv_a	0.2
S_{up}	25 minutes	B	10 units	\bar{b}	5 minutes
S_f	2 cycles	T_{max}	1 day	b_{dev}	1