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Operational performance of two-stage food production systems

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CHAPTER 4

Prioritization of Products

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Abstract

In the food-processing industry, usually a limited number of storage tanks for intermediate storage is available, which are used for different products. The market sometimes requires extremely short lead times for some products, leading to prioritization of these products, partly through the dedication of a storage tank. This type of situation has hardly been investigated, although planners struggle with it in practice. This paper aims at investigating the fundamental effect of prioritization and dedicated storage in a two-stage production system, for various product mixes. We show the performance improvements for the prioritized product, as well as the negative effects for the other products. We also show how the effect decreases with more storage tanks, and increases with more products.

4.1 Introduction

Typical food-processing companies have a two-stage production process. The first stage consists of processing the product with typical activities such as mixing or heating to change basic food ingredients into basic products. Production can be continuous, but batch-like processes are also frequently encountered. The second stage changes a homogeneous product into a packaged discrete product —often customer-specific— ready for (consumer) use. Mostly, these two stages are distinct in a number of ways, *e.g.* with respect to the labour intensity, the level of capacity utilization, the magnitude and influence of set-ups, and the production rate. In order to find production sequences that are optimal for each stage and to compensate for differences in production rates, the two stages are generally separated by tanks or silos that temporarily store the unpacked, basic product. Typical examples can be found in the dairy industry (Lütke Entrup *et al.*, 2005), the production of beverages (Fey, 2000), the tobacco industry (Van Dam *et al.*, 1998), or the production of breadcrumbs (Van Donk, 2001).

Due to the different nature of the two stages, managing the intermediate storage is necessary to find a balance between opposing demands. The processing stages might prefer long production runs and a specific sequence (like from light to dark colours or from low to high fat), while the packaging stage groups and sequences production based on packaging sizes and aims at combining orders for one customer. Moreover, tanks are usually limited in number and size, as high investments are involved for this type of storage facilities. The time of storing an unpacked product is limited by its shelf life.

A main complication is however that usually the number of products exceeds the number of tanks. Storing a product is thus more than just allocating a production batch to an arbitrary tank. On the one hand availability of products for packaging is needed, leading to the wish to fill as many tanks as possible with basic product. On the other hand, availability of empty tanks is required to enable continuous processing in the first stage of the production process. Planners tend to believe that building extra tanks is the solution for this problem, but, as said before, that is expensive. What makes this situation even more complex is the fact that market demands can be different among products. Lead times for products can be under extreme pressure, which creates a situation where certain products need to get priority over other products. This prioritization often results in fixed assignments —or dedication— of storage to the prioritized product. In this paper, we specifically look at the effects of allocation policies for storing products in tanks, based on product prioritization. The literature in operations management hardly pays attention to this important decision area.

The aim of this paper is to address the effect of prioritization of a product versus treating all products equally. An important result of the prioritization is a specific type of storage allocation: the permanent allocation, further addressed as dedication, of a tank to a prioritized product. This type of storage allocation can also be found in situations where production is hybrid make-to-order (MTO) and make-to-stock (MTS), which is quite common in the food-processing industry (Soman *et al.*, 2004). In those situations, the decision to make a product to stock or to storage is mainly based on its share in the product mix; high-volume products are normally MTS, and low-volume products MTO (see *e.g.*, Youssef *et al.*, 2004). However, this decision can also be forced on the company by market demands. Therefore, we specifically investigate the effects of prioritization by means of dedication policies for various shares of a product in the product mix.

With the present study we are able to assess the overall effect on system's performance of dedicating a tank for low-demand and high-demand products that get prioritized to be delivered within a relatively short lead time.

The overall contribution is to better understand intermediate storage in typical food processing companies in order to improve planning and scheduling in such situations and to improve decision making with respect to the required number of tanks. In general, the situation with intermediate storage can be assessed using a common performance measure like lead time. There are two specific effects of interest: blocking and starvation. Blocking refers to the non-availability of storage tanks for finished product which has to wait in the processing stage, while starvation means idle capacity in the packaging stage due to non-availability of basic product. For instance, in the situation described in this paper, blocking happens if a batch is produced in the first stage, but no intermediate storage tank is available for the product. Then the product has to remain in the batch processor, which delays further batch processing until a storage tank becomes available. Possible prioritization and storage dedication have a large impact on these blocking and starvation effects, which in turn highly influence the behaviour of a production system with limited intermediate storage.

The remainder of this paper is organized as follows. Section 4.2 gives some background information on previous research. In Section 4.3, the production model studied in this paper is described. Subsequently, a deterministic analysis of the production system is presented in Section 4.4. Following that, Section 4.5 presents a numerical study and its results. Finally, Section 4.6 presents conclusions and suggestions for further research.

4.2 Background

In the food-processing industry, reducing lead times is becoming increasingly important as improved customer service is important, especially when dealing with powerful food retail chains (see *e.g.*, Meulenberg and Viaene, 1998). Das and Abdel-Malek (2003) also investigate the effects of a varying lead time in a supply chain on flexible delivery. They state that lead times are one of the main causes for supplier-buyer grievances in a supply chain. As such, reducing lead times creates more pressure on these relationships in the supply chain.

Lead time reduction also relates to the current interest in hybrid MTO-MTS production systems (see *e.g.*, Huiskonen *et al.*, 2003; Soman *et al.*, 2004). For the food-processing industry, a significant share of the production is customer-specific, which often results in a large MTO part in their production system. The reducing lead times interfere with these policies, as it is no longer possible to produce the required product from raw materials within this lead time. The answer usually lies in the storage of certain basic products, which can be packaged for customer-specific orders This results in a hybrid MTO-MTS system at the intermediate storage.

In the literature on hybrid MTO-MTS systems (see Soman *et al.*, 2004, for an overview), demand characteristics (*e.g.*, the share of the product in the product mix) are mostly used to determine whether products should be made to order or to stock. As Soman *et al.* (2004) also argue, other market characteristics are often ignored. In our study, we focus on one specific characteristic: lead time. A short lead time requires MTS at the intermediate storage level and prioritization of the product to be able to meet the required lead time. This is closely related to the work of Sox *et al.* (1997), who denote this required lead time with their service window. Sox *et al.* (1997) then prioritize the MTO products to ensure a good overall customer service. They also note that when the service window becomes very short (compared to the average flow time of the factory), prioritization degrades performance. In our study, the reason for prioritization and dedication is the fact that the required lead time (or service window) is shorter than the average flow time of the factory. Therefore, we explicitly aim at investigating the effect of prioritization ánd dedication (and treating all products equally with flexible storage allocation as the alternative policy) on the performance of a production process.

Next to the prioritization of a product, dedicated storage in the intermediate storage facility is also required to meet the demand. In the literature, we see that several papers address intermediate storage in scheduling. Most papers develop techniques to incorporate these storage tanks in mathematical, mostly MILP-based, scheduling models (*e.g.*, Belarbi and Hindi, 1992; Ha *et al.*, 2000; Rajaram *et al.*, 1999; Yi *et al.*, 2000). In the majority of these papers, the distinction between dedicated and flexible storage is mentioned and considered in the techniques developed. However, this distinction is assumed to be predetermined and known. While the decision to dedicate a storage tank or not is not explicitly discussed, the literature pays some attention to the issues of dedication and flexibility in a qualitative sense.

The main objection against dedication of storage tanks might be the loss of flexibility. One might assume that without dedicated storage, assigning products to tanks is easier and results in higher performance of the overall production system. If each product has its own tank, assignment is even easier. However, in food processing, the number of products usually exceeds the number of storage tanks, so only a partial dedication is possible. In the literature, dedication has hardly been discussed, but flexibility (as being its natural opposite) has been extensively treated. The main question seems to be how much flexibility should be added, as it is assumed that flexibility and flexible equipment are more expensive. For instance, Jordan and Graves (1995) develop principles on the benefits of process flexibility. One of the main outcomes is that a small amount of flexibility can have almost the same benefits as total flexibility. In other words, after a certain flexibility is reached, there are rapidly decreasing benefits when adding additional flexibility. This argument might be transformed for dedication of storage tanks by posing that removing some flexibility could initially be relatively harmless to production performance. However, this is less likely in situations where only a small number of storage tanks are available, as the dedication of one of those tanks removes a significant amount of flexibility.

In summary, the above discussion clearly shows that the effects of prioritization and the decision to dedicate storage have not yet been systematically investigated. For production planning and scheduling —and also for the (re)design of production processes— it is important to understand these effects.

4.3 Production model

4.3.1 Production system

The production system studied in this paper consists of two distinct stages, connected by intermediate storage tanks (see Figure 4.1). The first production stage concerns a (non-preemptive) batch process with a single batch processor with a fixed batch size B. This fixed batch size resembles a technical constraint that is often encountered in the food-processing industry (*e.g.*, kettle size). Due to variability in raw material quality, processing times are variable (see Fransoo and Rutten, 1994).

In the second stage, the intermediate food product is packaged in small and large packaging sizes, depending on customer orders. This translates

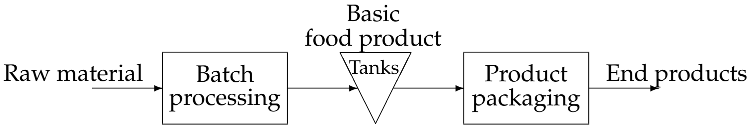

Figure 4.1. General form of the two-stage production process with intermediate storage tanks in the food-processing industry.

into different packaging times; for small sizes more time is required to package a certain amount of product (*e.g.*, more packages moving through the line). This variability influences performance through the blocking and starvation effects mentioned in the introduction.

The intermediate storage consists of K storage tanks, which are used to store N different intermediates. An important aspect is that in a storage tank only one production batch can be stored concurrently —even in case of the same product. This is due to (i) traceability requirements and (ii) not mixing batches to ensure quality. This also makes the size of the storage tanks irrelevant, as long as they can at least contain one batch of product from the processing stage. We assume this is the case.

Furthermore, we make the following assumptions:

- The production system operates in one daily shift of 8 hours.
- Raw materials for the batch processing stage, as well as packaging materials for the packaging stage are always available with negligible lead times.
- Products immediately leave the production system after packaging.
- Transportation time to and from storage tanks is negligible.
- No changeover times for processing, packaging, and storage.
- The quality of the product remains constant in the storage tanks for a fixed period, after which it is discarded at no extra cost (see also Nahmias, 1982; Raafat, 1991, for discussions on modeling perishability).
- Dedication of a storage tank is assumed to be implemented to assure a short lead time for the prioritized or 'dedicated' product.
- Packaging can only start if a customer order has arrived: packaging is customer-specific and order-specific.

4.3.2 Production scheduling

Customer orders arrive continuously during the day. They have several distinct characteristics: (i) product type, (ii) packaging size, and (iii) arrival time.

To study the effect of dedication, we use two different storage policies:

$$P = \begin{cases} F, & \text{a fully flexible policy, in which every tank can} \\ & \text{be used for every product;} \\ D, & \text{a policy in which one storage tank is dedicated} \\ & \text{to a specific (prioritized) product.} \end{cases} \tag{4.1}$$

Without loss of generality, product 1 can be used as the prioritized product with a dedicated storage tank in policy D (also referred to as the dedicated product).

For policy F, the arriving orders are collected in an orderpool until a full batch of a certain product can be produced in the first stage. The 'batch order' is then placed in a FCFS (first-come-first-serve) queue for the batch processor while the orders are moved from the orderpool to the queue at the packaging line.

For policy D, a runout time procedure is used for the dedicated product, because we need to keep this product on stock on the intermediate storage level. The batch order for the dedicated product (a replenishment order) is generated when the runout time of the content of the dedicated tank is smaller than the average batch processing time. The runout time is calculated as follows for product i:

$$RO_i = (I_i - O_i)/D_i, \tag{4.2}$$

where I_i is the inventory level of product i in the intermediate storage, O_i is the number of waiting orders for product i, and D_i the average number of orders arriving per time unit.

Because orders for the dedicated product (in policy D) are immediately packaged from intermediate storage, arriving orders for this product move straight to the packaging queue. For the other ('non-dedicated') products, the orders are processed like in policy F (collected until a full batch is realized). In the batch order queue, the product with dedicated storage has priority over the other products (to ensure the timely replenishment and short lead time).

For the second stage, a basic sequencing rule is used for scheduling the packaging line. The customer order in the packaging queue with the earliest arrival time is packaged first (FCFS). If the required basic product is not (yet)

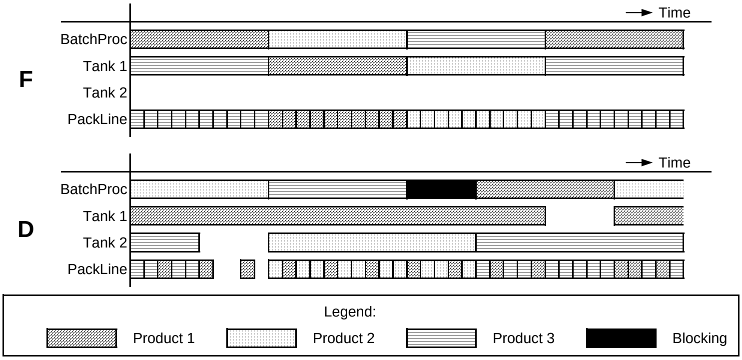

Figure 4.2. Gantt charts that illustrate the effect of dedication of intermediate storage for a product with a share of 33%.

available, the next order in the queue is selected. In case of policy D, this FCFS rule comes second after a priority rule for the dedicated product.

4.4 Deterministic Analysis

To explore the described system, we will perform a deterministic analysis of the behaviour of the simplest system configuration (K = 2 storage tanks and N = 3 basic products) that still enables us to study the effects of dedication for several scenarios with different product shares for the dedicated product. Two storage tanks are needed to be able to distinguish between dedicated and flexible storage; three products are the minimum to have more than one product in the flexible storage. For the sake of simplicity, all possible variability (in order arrivals, processing times, packaging times) is ignored and we assume a utilization of 100%, which we achieve by setting the order arrival rate equal to the production capacity.

4.4.1 Dedication for a product with a share of 33%

The first scenario we analyze is that of equal demand for all products. In Figure 4.2, two excerpts from Gantt charts illustrate the system behaviour. For policy F, we see that a cyclic production pattern emerges, which only needs one of the two storage tanks. The second Gantt chart in Figure 4.2 shows that this situation changes dramatically when policy D is implemented. Several important aspects in this chart are: (i) the possibility to package orders for product 1 from intermediate storage; (ii) the occurrence of blocking at the

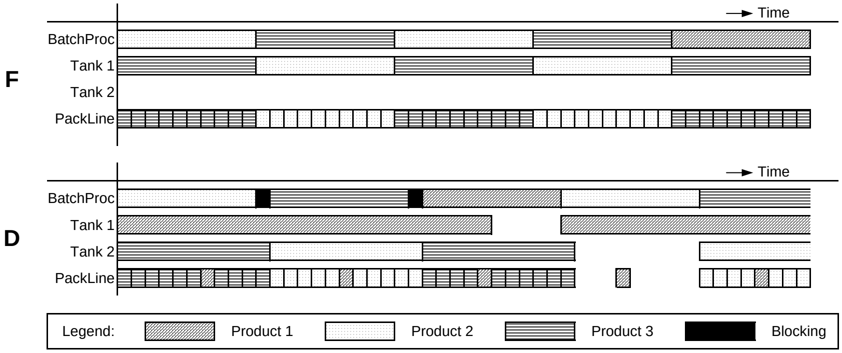

Figure 4.3. Gantt charts that illustrate the effect of dedication of intermediate storage for a product with a share of 10%.

batch processor due to unavailable flexible storage; and (*iii*) the fact that two storage tanks is getting restrictive, while only one was needed in the flexible case. This results in an unbalanced situation, characterized by an increasing backlog of orders in the long run.

4.4.2 Dedication for a product with a share of 10%

Here, we assume that a storage tank is dedicated to a product that only represents a small fraction of the product mix. Reduced lead times in the supply chain might be the main reason. Figure 4.3 shows partial schedules for policies F and D for a situation where product 1 covers 10% of the product mix, and product 2 and 3 together cover the additional 90%. For policy F, the schedule is still cyclic in nature, albeit that the cycle is getting rather large. In principle, product 2 and 3 are alternating, with one batch of product 1 being produced every ten batches. For policy D, we see that indeed the demand for product 1 can be met in a package-to-order fashion. However, this again results in blocking effects at the batch processor, and significant starvation effects at the time the dedicated tank needs to be refilled. This is again an unbalanced situation, in which the high utilization rate creates an ever-increasing backlog.

4.4.3 Dedication for a product with a share of 50%

Here we assume that a high demand product is stored in a dedicated tank. The reason could simply be the convenience in scheduling if a certain product always goes to a specific tank. This product has 50% of the demand,

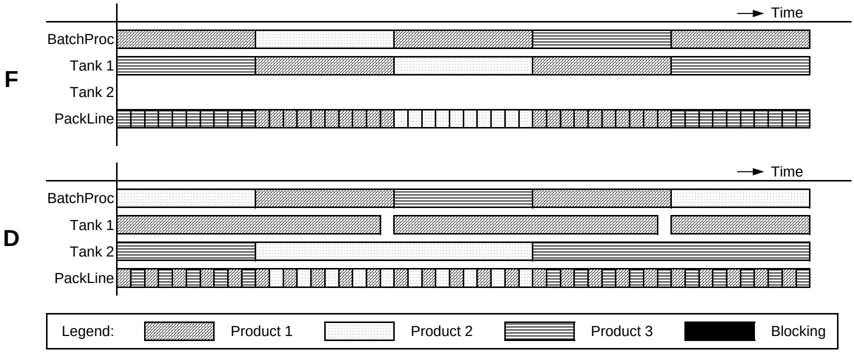

Figure 4.4. Gantt charts that illustrate the effect of dedication of intermediate storage for a product with a share of 50%.

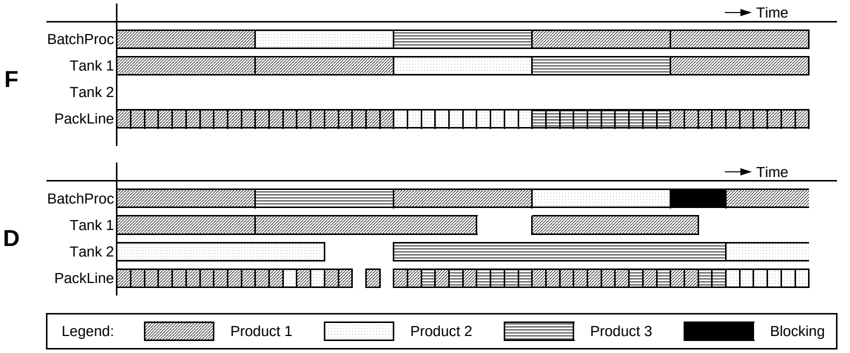

Figure 4.5. Gantt charts that illustrate the effect of dedication of intermediate storage for a product with a share of 60%.

while product 2 and 3 each have 25%. Figure 4.4 shows excerpts from the corresponding schedules. As in the previous scenarios, policy F results in a cyclic schedule (now 1-2-1-3), which only utilizes one storage tank. Policy D, however, shows different results. Here, the package-to-order possibility is again visible, but no blocking occurs at the batch processor. Both storage tanks are highly utilized, and the production system is in balance.

4.4.4 Dedication for a product with a share of 60%

Finally, we study a situation in which the first product has the largest part of the demand: 60%. The other products are each at 20%. Corresponding partial schedules are shown in Figure 4.5. The cyclic schedule still remains for policy

F (here it is 1-1-1-2-3). For policy D, the system is again getting unbalanced through blocking and starvation effects. This makes a growing backlog of orders.

4.4.5 Concluding remarks

The above analysis yields a better understanding of how flexible and dedicated assignment of storage influences systems performance. It shows that flexible assignment of products to tanks (policy F) results in cyclic schedules, while policy D creates more irregular schedules. While lead times for the 'dedicated' product are smaller it negatively affects overall performance and lead times of the other products. For some scenarios (50% product 1), the results showed balanced production systems for policy D. For other scenarios (33% product 1, 10% product 1, 60% product 1), the production system got unbalanced due to blocking and starvation effects, which in the long term results in an increasing backlog of orders.

4.5 Numerical Experiments

To account for variability in processing times, packaging times, and order arrivals, this section will present numerical experiments to further analyze the differences between policies F and D. We study several system configurations, which should provide insight into the interaction between the product mix and the system performance for both policies.

4.5.1 Experimental design

The experimental factors to be varied are (i) the number of storage tanks, (ii) the number of basic products, (iii) the dedication policy, and (iv) the product mix.

The number of storage tanks (K) is varied from 1 to 10 and the number of basic products (N) from 2 to 10. We expect that the effect of dedication is stronger if there are more products than storage tanks, but we also investigated other scenarios. In the paper, we present only scenarios where $N > K$, as these are the situations where the dedication and prioritization has the biggest effects. Furthermore, in practice, the number of products is normally larger than the number of intermediate storage tanks.

The two different dedication policies were already presented in equation (4.1) in section 4.4. For the product mix, 9 different situations will be considered. The share of product 1 (S_1) in the product mix will be varied from 10% to 90%. The remaining products all have an equal part of the remaining share. This is calculated as follows:

$$S_i = \frac{100 - S_1}{N - 1} \qquad \forall i = 2, \dots, N. \tag{4.3}$$

In the experiments, this is modeled by using the product mix shares as probabilities for the arriving orders.

The main performance criterion used in this paper is average lead time, which is calculated as the time in minutes between the arrival of an order and the completion of that order in the packaging stage. These average lead times are calculated for each of the products, to investigate the effects of different product mixes. Next to lead time, blocking will also be used as one of the important underlying aspects of lead times.

The simulations are performed in MATLAB. Before the experiments are conducted, a warmup period of one month is determined using a graphical method with average lead times. Furthermore, run lengths of one year with 5 replications are determined using a 95% confidence interval for the average lead time. This results in relative half-widths of the confidence interval between 0.8% and 5%. Before the actual simulation runs are conducted, numerous test runs for different parameter settings are performed, while closely watching the system's behaviour for verification purposes.

4.5.2 Parameter settings

Customers orders arrive continuously according to an exponential distribution with $\lambda = 0.16$ (per minute). This resembles a Poisson process with certain interarrival times (6.25 minutes), which is a common way of modeling arrival processes (Law and Kelton, 2000). Together with an average packing time of 5 minutes, this results in an maximum utilization degree of 80% for the packaging line. What percentage is actually realized, also depends on possible blocking effects in the processing stage and starvation effects on the packaging line.

The processing times for the batch processor are sampled from a truncated normal distribution with mean $\mu_a = 50$ (min.) and variance $\sigma_a^2 = 10$ (min.^{2}). This variability is common in the food-processing industry, due to inherent quality variability in the (agricultural) raw materials. The batch size B is 10 units.

For the packaging line we make a distinction between large and small package sizes. As mentioned before, the average packaging time μ_b is 5 min-

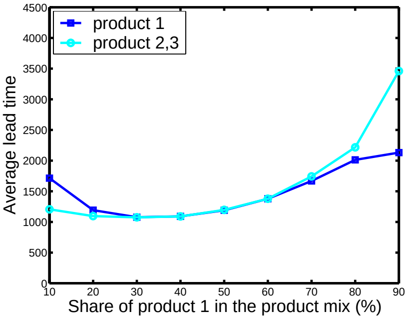

Figure 4.6. Average lead time against S_1 for policy F ($N = 3$, $K = 2$).

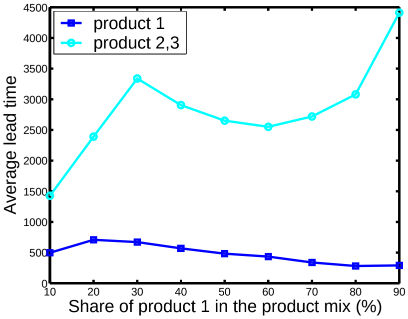

Figure 4.7. Average lead time against S_1 for policy D ($N = 3$, $K = 2$).

utes, but there are deviations for the package sizes. This deviation b_{dev} is added for small package sizes and subtracted for large packaging sizes. We randomly assign a packaging time $b_{\min}$ or $b_{\max}$ to an incoming customer order, where $b_{\min} = \mu_b - b_{\text{dev}}$ and $b_{\max} = \mu_b + b_{\text{dev}}$. For b_{dev}, a value of 1 minute is used.

4.5.3 Experimental results

As in the deterministic analysis, we start with the most basic system configuration: $N = 3$ and $K = 2$. To obtain further insight, we subsequently compare the results found in the basic configuration with other configurations. In the figures presented in the following sections, products 2 to N have equal curves. This is the result of their equal share in the product mix.

Basic configuration

For policy F, there is a difference in the lead time between product 1 and the other products for small and large values of S_1 (see Figure 4.6). This is the result of the difference in waiting time before a batch can be formed. For example, if S_1 is very high, it takes less time to collect enough orders to form a batch of product 1. This results in smaller lead times. As seen in the deterministic analysis, a batch of product 1 will occur more often in the production cycle. Another aspect is that the more asymmetry there is in the product mix, the higher the lead times are. Partly, this is related to the time until a batch is formed. However, analysis of the amount of blocking shows that for values of 30% and 40% for S_1, the lowest amount of blocking is experienced. We expect this follows from the regular arrival of batch orders in this symmetric situation. A more irregular arrival process is likely to create more variety in the length of the batch queue. This even distribution of the product mix possibly results in an efficient cyclic production schedule, as would be used in practice in similar situations, and is also reflected in the deterministic analysis.

The results for policy D show rather different curves (see Figure 4.7). First, as expected, a significant decrease of the lead time for product 1 is achieved (compared to policy F), and the higher the share S_1, the lower the lead time due to decreasing runout times and less interference with other products. For these other products, policy D results in an overall increase in lead times. Especially when these products make up a major part of the product mix, while product 1 also has a reasonable share. For small values of S_1 (10-30%), an increasing S_1 seems to cause more interference with the production of product 2 and 3. In this situation, these products are still the main products and can only use a single intermediate storage tank. Then, for higher values of S_1 (40-70%), the storage limitation for product 2 and 3 is likely to become less restricting. Their share in the product mix is decreasing and due to a decrease in blocking effects, the lead times are slightly lower. Finally, for very high values of S_1, the interarrival time for orders for product 2 and 3 increases, so the time to collect orders for a batch also increases. Together with the fact that product 1 is becoming very dominant and gets priority in scheduling, this explains the increase in lead times.

Extended configurations

To be able to make more general observations on the interaction between the storage policies and the product mix, we also present some of the results from other configurations. The focus in this section is specifically on policy D. For policy F, the results do basically not change for other values of N and K. For policy D, the influence of having a greater portfolio (larger N) is almost negligible for the dedicated product. For the non-dedicated products, interesting results are found. The main effects can be demonstrated with results for an increasing N (for fixed K) and an increasing K (for fixed N).

For a fixed number of tanks ($K = 2$), the number of products is increased. The average lead times for the non-dedicated products (for $N = 3$ to $N = 6$) are shown in Figure 4.8. For an increasing number of products, we see increasing lead times. This is largely due to the fact that there are longer waiting times before a batch can be formed. Interestingly, there is no increase in blocking or starvation for an increasing number of products. Because batches are handled separately for quality and traceability reasons, the number of

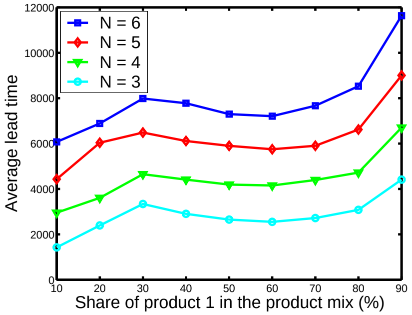

Figure 4.8. Average lead time against S_1 for product 2 to N in policy D for various values of N ($K = 2$ tanks).

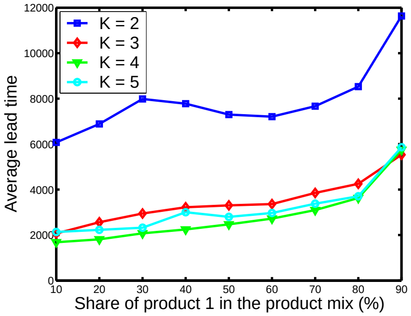

Figure 4.9. Average lead time against S_1 for product 2 to N in policy D for various values for K ($N = 6$ products).

products using the flexible tank does not matter; as long as the products have the same total share in the product mix, the performance is identical in terms of blocking or starvation.

Secondly, the effect of the number of tanks is shown. For a fixed number of products ($N = 6$), Figure 4.9 shows average lead times for the non-dedicated products for several values of K ($K = 2$ to $K = 5$). The figure shows that adding one tank initially results in a large reduction of the lead time. Here, reduction of blocking seems to be the main reason. Changing from $K = 3$ to $K = 4$ and $K = 5$ has far less effect. Furthermore, in the basic configuration we saw high lead times for values of S_1 between 20% and 50% (see Figure 4.7). For configurations with more tanks, this effect disappears.

4.6 Conclusions and further research

This paper studies the effects of product prioritization through dedication of intermediate storage tanks, related to the product mix. We specifically focus on the lead times for the individual products, as we assume prioritization and dedication are used to reduce the lead time for a certain product. Based on the results from the deterministic analysis and the numerical study, the following conclusions can be presented.

First, in a deterministic case, dedication results in irregularity in the production schedules. Also, blocking and starvation effects occur, which did not occur in the flexible case. For high-utilization systems, this results in long-term backlogs of orders.

Secondly, dedicated storage for a product results in significant lead time advantage. Dedication has a negative effect on the performance of the products that use the remaining flexible storage, as expected. For a small system like the basic configuration studied in this paper, there is a significant increase in lead times for these products. However, for configurations with more tanks there are significantly less blocking effects, which decreases the negative effects.

Finally, if all tanks are used flexible, the experimental results show that the performance of the production system benefits from an equal distribution of the products in the product mix. Asymmetry in the product mix seems to lead to an increase of blocking effects, which affect the lead times.

It might be clear that our results are limited as a number of real life issues are not incorporated: the number of products is much smaller than in most real life settings, cleaning and setups are ignored, we use a rather simple scheduling rule, we do not allow packaged product to be stored, etc. Still, we believe that some provisional managerial implications can be derived. Our study helps in deciding if prioritization through dedicated storage for one product will affect the lead time for others and to what extent. Secondly, it shows the positive effect of adding a storage tank on overall performance.

Future research could help in further studying managerial problems in designing this type of production system by analyzing the effects of dedicated storage induced by restrictions on the number of pipes between tanks and packaging lines, investment decisions on extra tanks, etc. Future research can also address a broader range of parameter settings and include other variables such as variability in demand or (sequence-dependent) changeover time for flexible storage tanks. Such characteristics are common in the food-processing industry (Akkerman and Van Donk, 2006a). It seems logical to further validate findings from such more realistic studies with empirical studies.