Systems Analysis Speeds Up Chipita's Food-Processing Line

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This paper was refereed.

Chipita International, Inc., one of Greece's largest manufacturers of bakery products and snacks, makes croissants on seven specialized processing lines in Lamia, Greece. A rise in the demand for croissants over the past years called for an increase in output. We undertook a project to determine cost-effective ways of speeding up the croissant-processing lines. We found that the efficiency of a typical line (the ratio of the effective processing rate to the nominal processing rate) was 86 percent because of equipment failures. To reduce the impact of failures and increase the efficiency of the line, we proposed to modify the line by inserting an in-process buffer-refrigerator having a capacity of 40,000 croissants in the middle of the line and by speeding up the part of the line upstream of the buffer. We found that the efficiency of the modified line would rise to just under 98 percent at a cost of a minor increase in in-process inventory. We estimated that the modified design of the line would bring in extra earnings and savings of $19,150 per week because of the resulting increase in output, the elimination of the first shift of the week, and the reduction of scrapped material during long failures.
(*Industries: agriculture–food. Manufacturing: automated systems. Reliability: failure models.*)

The bakery-products-and-biscuits sector is one of the most stable sectors in the food-and-beverages industry worldwide. In a recent market-analysis report covering the five-year period from December 1993 through December 1998, the global intelligence group Euromonitor International reported that the growth in volume of bakery products during that period was only six percent, as changing eating habits, such as the waning of traditional family meals and the replacement of bread by a variety of products in poorer markets, had a negative impact on sales (Euromonitor 1999). Euromonitor also found that, although the global market for bakery products as a whole had remained fairly stable, breakfast goods showed the most dramatic growth (18 percent), reaching 9.7 million tons and rising by eight percent in terms of value.

Chipita International, one of Greece's largest food manufacturers specializing in bakery products, with extensive activities in Greece and abroad, has been facing a significant rise in the demand for croissants—popular morning pastries—during the past few years. In view of this situation, in the early summer of 1999 we undertook a project to find cost-effective ways of speeding up the croissant-processing lines at Chipita and determining the benefits from the resulting increase in sales and market share. We used operations research to reach this goal.

The Company

The Chipita International, Inc. Group started in 1973 with the production of salted snacks and has grown remarkably. In 1990, it increased its share capital by $0.82 million (based on an exchange rate of 400 drachmas or 0.852 euro to the dollar) and constructed a new

0092-2102/02/3203/0062$05.00
1526-551X electronic ISSN

plant in Lamia Industrial Park, Greece. In 1991, it penetrated the croissant market, and in 1994, it joined the Athens Stock Exchange, increasing its share capital by $5.35 million. In 1996, Chipita began manufacturing its products abroad (in Bulgaria and Portugal) through joint ventures. A year later, the company entered the bread market, and its manufacturing joint venture in Egypt began production. In 1998, Chipita realized fixed investments totaling more than $17.5 million. In addition, the company made major acquisitions in Greece, Poland, and Romania, becoming the market leader in packaged croissants in these countries. Today, Chipita is a $105 million company that dominates the Greek croissant market, with a market share of about 70 percent (in volume).

The Product

Croissants have a long history. The first croissants were made in Austria in 1697 after the victorious battle of the Austrians over the Turks near Zenta in modern Hungary. To commemorate this victory, Austrian Emperor Leopold's personal chef created a new delicacy shaped as a crescent, a symbol of the Muslim world and in particular the Turks. Years later the French adopted this delicacy, named it croissant, and placed it among French bakery specialties. From France, the croissant spread to other European countries and to the rest of the world. In Greece, the first croissants appeared in the 1960s, but up until 1983, they could be found only in a handful of bakery and confectionery shops. In the meantime, many companies in the food-ingredients and food-machine industry seized the opportunity created by consumer interest in croissants and began producing ingredients and equipment specially for making croissants. Today, croissants can be found in many places and in many varieties. Their basic ingredients are flour, water, butter or margarine, yeast, and sugar. Fillings of various sweet flavors, such as chocolate, hazelnut cream, strawberry and apricot jam, as well as salty flavors, are often added to the basic recipe.

The Process

Chipita makes croissants on seven specialized processing lines in its Lamia Industrial Park plant in Greece. All lines are similar, but for the sake of preciseness in our presentation, we focus on a particular line here. This line consists of several workstations in series integrated into one system by a common transfer mechanism and a common control system. The movement of material between stations is performed automatically by mechanical means. Apart from load and unload stations, operations at all other stations are automated. There are five distinct stages in making croissants: kneading, forming, proofing, baking, and wrapping. Each stage takes place in a separate section of the processing line (Figure 1). The process flow of the line is as follows:

In stage 1, flour and water are automatically fed into the removable bowl of the spiral kneading machine. Additional ingredients in small quantities, such as sugar and yeast, are added manually. After the dough is kneaded, the bowl is manually unloaded from the spiral machine and loaded onto the elevator-tipping device that lifts it and tips it to dump the dough into the dough extruder of the lamination machine in the next stage.

> When a failure occurs, everything upstream stops.

In stage 2, the dough fed into the lamination machine is laminated, buttered by a butter extruder, folded, reduced in thickness by a multiroller, and refolded a few times by a retracting unit to form a multilayered sheet. The multilayered dough is then automatically fed into the croissant-making machine, which cuts it into triangles. Finally, the triangles are rolled up and formed into crescents. The entire process is fully automated. A standby operator occasionally feeds the butter extruder and makes sure that the process runs properly. At the exit of the croissant-making machine, the croissants are laid onto metal trays, and the trays are automatically inserted into carts. A standby operator makes sure that the croissants have the right shape.

In stage 3, the carts are manually pushed into the proofing cell, where they remain under strict uniform temperature and humidity conditions for a precise amount of time as the croissants rise to their final size.

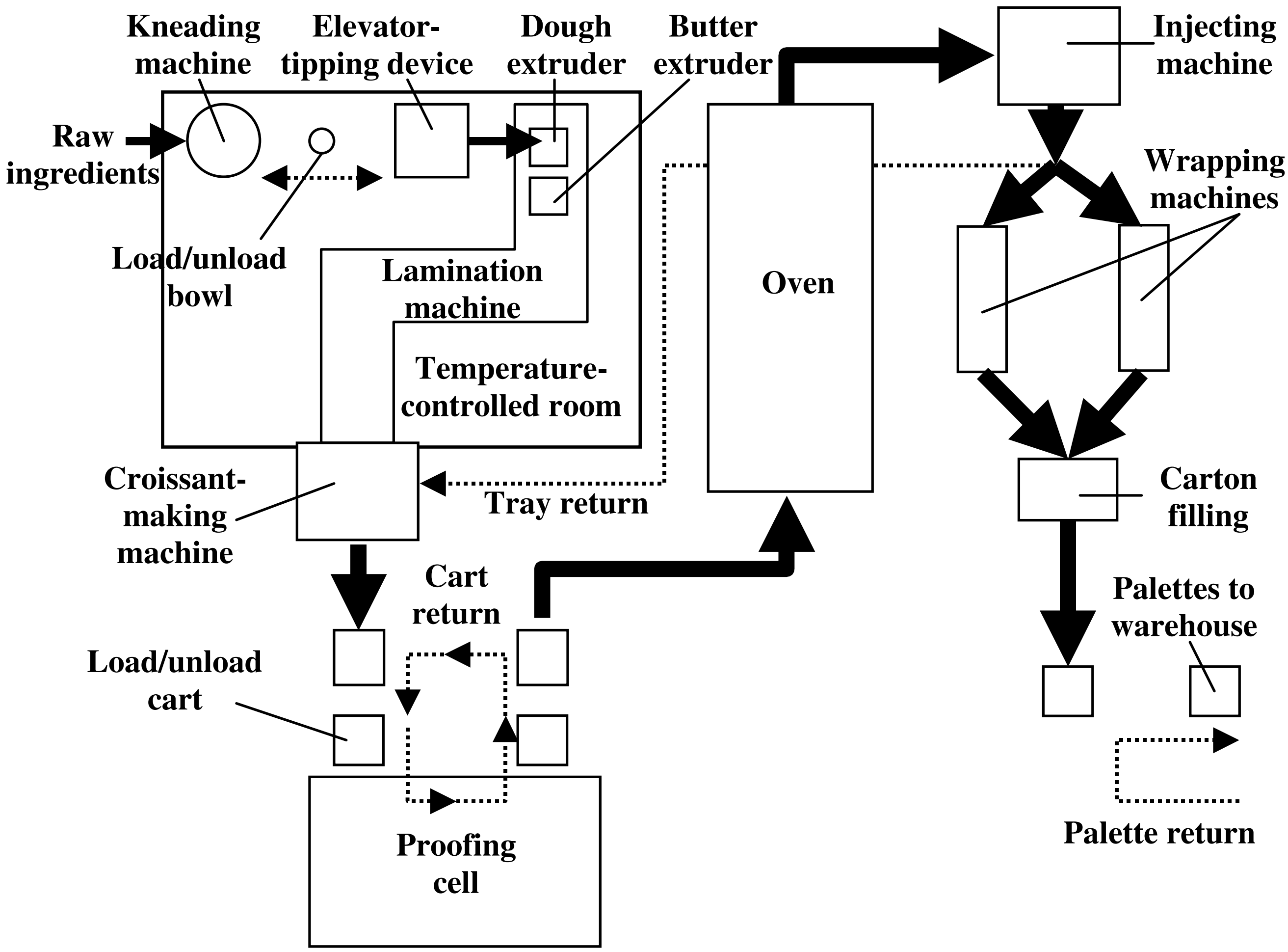

Figure 1: The original croissant-processing line.

In stage 4, the carts are manually pushed from the proofing cell to the oven. The trays are automatically unloaded from the carts and are placed onto a metal conveyor that passes through the oven. The trays remain in the oven for a precise amount of time until the croissants are baked. Upon exiting from the oven, the trays stay on the conveyor and follow a trajectory for a certain time as the croissants cool. The croissants may then be filled with an optional sweet or salty filling by an automatic injecting machine.

In stage 5, the croissants are automatically lifted from the trays and are flow-packed and sealed by two parallel, horizontal, electronic wrapping machines. A specially trained operator constantly checks the wrapping machines to make sure that the wrapping is done properly. The empty trays are automatically returned to the croissant-making machine.

The final products that exit from the croissant-processing line are loaded onto a conveyor. Four workers remove them from the conveyor and put them in cartons. The filled cartons are placed on a different conveyor that takes them to a worker who stacks them on palettes and transfers them to the finished-goods warehouse.

There are no in-process buffers between the workstations in the line. Consequently, material is transferred directly from station to station. Chipita monitors the entire process constantly to ensure that it meets the highest quality and sanitation standards. The kneading machine, the elevator-tipping device, and the lamination machine are kept in a temperature-controlled clean room to ensure that the dough remains free from contamination and does not rise. Apart from the five operators working at various points along the line and the five workers working on filling and stacking the cartons of final products, only five workers are required in the process: a person responsible for raw-ingredients inventory, a person responsible for sanitation, a mechanic, an electrician, and finally a supervisor, that is, a total of 15 people.

The line operates 24 hours a day, with three eight-hour shifts during the week, and pauses during the weekends. The first shift of the week starts late on Sunday evening to produce the first finished products for shipment early on Monday morning. The last shift of the week ends early on Saturday morning. The rest of Saturday is spent on scheduled maintenance operations on the line.

The Problem

The slowest station in the line is the oven. The manufacturer of the line designed all the other machines "around the oven," in that he made sure that they would not process croissants faster than the oven since they would anyway be forced to work at the nominal processing rate of the oven. The nominal processing rate or throughput of the oven is equal to 12,000 croissants per hour. Given that the nominal processing rate of any processing line is equal to the nominal processing rate of the slowest workstation in the line, the croissant line has a nominal processing rate of 12,000 croissants per hour. Unfortunately, because of wear and tear on the individual machines and on the electronics and hardware for common controllers and transfer mechanisms, various pieces of equipment can break down in the line. When a failure occurs anywhere on the line, everything upstream of the failure stops, creating a gap in production down the line. Moreover, material in some parts of the stopped line may have to be scrapped. Thus, the actual or effective processing rate of the line can be substantially less than the nominal production rate.

Chipita's records covering the first 10 months of 1999 show that the effective processing rate of the line for that period was 10,123 croissants per hour, 84.36 percent of the nominal processing rate. Managers noticed and tacitly accepted the difference between the nominal rate and the effective processing rate but became really concerned about it when demand for croissants picked up, reaching levels close to the effective production capacity. Because of this concern, in early summer 1999, we began working on a project with the goal of finding ways to increase the croissant-processing capacity at Chipita in a cost-effective way.

The Alternatives

One can increase the effective processing rate of a transfer line in four ways: (1) by increasing the processing rates of the workstations, starting with the slowest; (2) by reducing the frequency of failures; (3) by reducing the duration of failures; and (4) by reducing the impact of failures (Buzacott and Shanthikumar 1993, Gershwin 1994). The first three approaches are primarily determined by good engineering and operating practices. The fourth approach is a matter of design and requires a systems perspective.

In the case of the croissant-processing line, to pursue the first approach, Chipita would have to invest in a new oven with larger capacity, since the throughput of the oven is equal to oven capacity divided by baking time, by Little's law (Buzacott and Shanthikumar 1993). We considered this to be unappealing both from a financial point of view and because of space limitations. To follow the second approach, Chipita should pay careful attention to the reliability of machine components through improved monitoring and on-line control of operations. If it were to adopt the third approach, we should devise appropriate management and operating practices regarding repair and maintenance as well as component inventory control. We considered both approaches as necessary steps towards

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overall system improvement, but we put them on hold at the time because they required a long-term study of many aspects of the system. This left us with the fourth approach, to reduce the impact of failures.

We considered several design alternatives for reducing the impact of failures. One alternative was to introduce redundant stations in the form of standby stations; however, as was the case with the first approach, we found this to be too expensive to justify, especially since the section that caused most of the disruption, the forming section, contained two high-priced pieces of equipment (the lamination machine and the croissant-making machine) at the heart of the whole process. Another alternative was to use cross-paths, so that entire sections of different lines would act as backups to one another. Using cross-paths means that if the first half section of one line and the second half section of another identical line are simultaneously down, then a cross-path between their midpoints would allow the combined two lines to work at one-half capacity. In the case of the croissant-processing lines, providing such a situation seemed ineffective because very rarely, if ever, did failures in two lines coincide in such a convenient way. Even if there were such a coincidence, however, establishing cross-paths would be impractical because the lines were too far apart and transferring material between lines would cause quality problems. The last but not least alternative was to install in-process buffers between stations. We pursued this approach.

The Buffer Alternative

It is well known among manufacturing systems researchers that installing in-process buffers in a transfer line can reduce the impact of failures and increase the effective throughput of the line at the price of extra in-process inventories and delays (Buzacott and Shanthikumar 1993, Dallery and Gershwin 1992, Gershwin 1994). This simple fact often escapes the notice of manufacturing systems practitioners, perhaps because the companies that operate the lines are not those that design them. Companies like Chipita, which are in the business of producing bakery products, often buy complete automatic transfer lines from a single food-machine manufacturer. Food-machine manufacturers worry more about the processing and engineering aspects of the lines they make than about their operations management aspects. Typically, they design transfer lines that consist of several workstations in series integrated into one system by a common transfer mechanism and a common control system. Material moves between stations automatically by mechanical means, and no storage exists in between stations other than that for material-handling equipment (for example, conveyors and load-and-unload carts). If the food-machine manufacturers inserted in-process buffers, they would have to worry about all sorts of technical and technological problems and they would be implicitly admitting that some of their machines fail more often than others. As a result, food-machine manufacturers design lines that have no buffers between stations, and food-processing companies that buy and operate such lines take this design for granted.

However, installing in-process buffers in a transfer line can reduce the impact of failures and increase the effective throughput of the line. In a recent paper, Burman et al. (1998) reported that Hewlett-Packard obtained impressive earnings and savings by inserting in-process buffers in an ink-jet printer line.

An in-process buffer between two workstations in a transfer line acts like a spring that decouples the line into two sections: an upstream section and a downstream section. When the downstream section fails, the upstream section continues operating, as long as the in-process buffer has space for the parts it has worked on. If the failure lasts so long that the buffer becomes full, the upstream section will be blocked and forced

We counted 37 types of failures.

to shut down. When the upstream section fails, the downstream section continues operating as long as the in-process buffer contains parts for it to work on. If the failure lasts so long that the buffer becomes empty, the downstream section will be starved and forced to shut down. In the absence of an in-process buffer, a failure in either the upstream section or the downstream section will force both sections to shut down at once. The bottom line is that on average a line with an in-process buffer produces more items than the same line without an in-process buffer. A key issue in designing transfer lines is where to insert in-process buffers and how big to make them to most increase the effective processing rate of the line. To find out, one must first study failures.

Analysis of Machine Failures

Buzacott and Shantikumar (1993) classify failures according to their extent, cause, and effect. The extent of a failure refers to the part or parts of the line that are affected by the failure. The cause refers to whether the failure can occur only when the station is processing material or at any time, even when the station is idle. In the first case, the failure is called operation dependent, whereas in the second case, it is called time dependent. Finally, the effect refers to whether the material in process at the instant of failure must be reworked, repaired, or scrapped.

In our croissant-processing line, we counted 37 different types of failures. Each failure affected only one station, and most failures were operation dependent. For many failures, at the instant of failure, the material in process in the failed workstation, and in some cases in other workstations too, had to be scrapped. For instance, any failure downstream of the forming section (lamination machine plus croissant-making machine) that lasted for over a certain amount of time would cause material in the kneading and forming sections to deteriorate in quality, and it would then have to be scrapped.

We collected and analyzed records of failures during the first 10 months of 1999. The failures ranged in average duration or mean time to repair (MTTR) from very short failures, such as the 10-minute adjustment of the photocell of an ice machine at the kneading stage, to medium failures, such as the three-hour replacement of the fan in the proofing cell, to long failures, such as the 16-hour replacement of the ball bearings at the dough extruder in the lamination machine. The failures also ranged in average frequency from very infrequent failures with long mean times to failure (MTTF), such as the rupture of the conveyor following the wrapping machines every 15,845 hours, to more frequent failures, such as the failure of the oven burner every 1,584 hours, to very frequent failures, such as the jamming of the croissant-carrying metal trays on their way out of the croissant-making machine and into the carts every 24 hours.

Using the MTTR and the MMTF of every failure in each of the five sections of the line and assuming operation-dependent failures, we estimated the availability or efficiency of each section, that is, the percentage of time it was operational. We found the following section efficiencies: kneading: 99.38 percent, forming: 87.62 percent, proofing: 99.69 percent, baking: 99.75 percent, and wrapping: 99.47 percent. From this analysis, we realized that the impact of failures in the forming section overshadowed the impact of failures in any other section. We then estimated the efficiency of the entire line. It turned out to be 86.32 percent. A similar estimation using the assumption of time-dependent failures yielded a line efficiency of 86.13 percent. The two estimates were so close because all sections except the forming section had efficiencies close to 100 percent. In all estimates, we assumed that no material would be scrapped during a failure and that the line would run continuously when there was no failure. Had we taken into account the scrapping of material during long failures and the gap in production when the line empties out at the end of the week and fills up at the beginning of the week, the efficiency of the line would turn out to be slightly lower. Indeed, Chipita's records showed that the output efficiency reported for the same period was 84.36 percent, approximately two percent lower than the efficiency we estimated (86.32 percent).

Croissants are not mechanical parts that can be kept in a buffer indefinitely.

Design of Buffer Location

Our analysis showed us that the drop in efficiency of the line came almost exclusively from disruptions in production caused by failures in the forming section. To reduce the impact of these failures, all we had to do was insert an in-process buffer right after the forming section and before the proofing cell. The idea was to speed up the part of the line upstream of the buffer so that it would fill the buffer with formed croissants faster than the proofing cell would deplete it. Once the buffer was full, we would reduce the speed of the line upstream of the buffer back to the nominal speed of 12,000 croissants per hour. This way, if there were a failure in the forming section, the rest of the line downstream of the failure would be fed by the in-process buffer for some time and not be forced down immediately.

In addition, if a buffer were to be inserted between the forming section and the proofing cell to store trays with formed croissants, then another "mirror buffer" would also have to be inserted between the wrapping section and the forming section to store the empty trays. This buffer would be filled with empty trays at the speed of the oven divided by the tray capacity (in croissants per tray) and would be depleted at the speed of the forming section divided by the tray capacity.

We almost had the answer to our problem. Before setting out to design the capacity of the buffer between the forming section and the proofing cell (and the capacity of the mirror buffer), we had to address certain technological and technical issues first.

Technological and Technical Issues

The first category of issues concerned the process technology for making croissants. Croissants are not mechanical parts that can be kept in a buffer indefinitely. The formed croissants exiting from the forming section (lamination machine plus croissant-making machine) must immediately enter the proofing cell, where they must remain under strictly uniform conditions of temperature and humidity for an exact amount of time to rise properly to their final size. If we inserted an in-process buffer between the forming section and the proofing cell, the croissants would spend time in the buffer before entering the proofing cell and would no longer rise properly. This was unacceptable. We had to find a solution.

The solution did not take long to surface. In one word, it was *refrigeration*. Dough can keep its characteristics for over 48 hours if it is kept refrigerated at no more than 5°C (41°F). Therefore, if the in-process buffer was a refrigerator operating at around 5°C, the croissants would keep for some time without rising or deteriorating. While making inquiries about the buffer-refrigerator option, we found out that some bakeries and confectionery shops form dough products during the day and keep them refrigerated until they want to bake them. The purpose of doing this is not to increase productivity, which was our goal, but rather to avoid starting the kneading process very early in morning, mumbling "time to make the doughnuts," to quote an old TV commercial. Moreover, frozen (and part-baked) dough is used in restaurants and the retail trade for baking by in-store bakeries, hot bread shops, and kiosks, so that they can provide freshly baked bread at any time (Euromonitor 1999). In our case, a refrigerated buffer would keep dough from rising and deteriorating, and it would also keep it protected and clean just as the proofing cell does. In a sense, the buffer-refrigerator would be an additional processing stage whose main purpose would be to provide storage so that the line would not have to process the croissants right after the forming section.

Before inserting a buffer-refrigerator between the forming section and the proofing cell, we had to determine several parameters to ensure that the croissants would retain their dimensions and other quality characteristics (for example, humidity and texture) throughout their lifetime (which with the original line design was 90 days). These parameters were (1) the exact portion-control standards, that is, the mix of ingredients in the recipe for croissants, particularly the percentage of yeast, which causes the dough to rise; and (2) the exact conditions in the buffer-refrigerator, particularly the temperature and humidity. In addition, we wanted to reexamine the exact atmospheric conditions in the proofing cell following the buffer-refrigerator because storage in the buffer-refrigerator would change the condition of the formed croissants entering the proofing cell.

We first considered the mix of ingredients in the basic recipe for the croissants. We found that for dough that is cooled and stored in the buffer-refrigerator for short periods of time (a few hours at most), which would be the usual case during day-to-day operations, the recipe used for the nonrefrigerated dough in the original system seemed to work fine and the loss in quality of the final product was negligible (if any at all).

For dough that is cooled and stored in the buffer-refrigerator for longer periods (one to two days), which would be the case for dough stored over the weekend, however, the recipe used for the nonrefrigerated dough in the original system should be slightly modified. Cooling, storing, and thawing over long periods of time decreases the strength of the dough, the viability of the yeast, and the volume of the final product. To counteract these effects and maintain the quality of croissants made from refrigerated dough, Chipita would have to modify the basic recipe in various ways, the most important of which are the following: (1) Use medium to strong flour with higher protein quality, which is apparently more important than protein content. (2) Use higher yeast quality to insure yeast activity at the same level as that in nonrefrigerated dough. (3) Use a slightly greater percentage of fat to improve dough structure. (4) Use a slightly greater percentage of enhancement agents and oxidants to maintain yeast viability after thawing and to accomplish complete and uniform maturing of the dough. (5) Use a slightly greater percentage of sugar, and use dextrose instead of sugar to help dough mature. (6) Add milk powder to improve the external color of baked products.

We also found that dough cooled and stored in the buffer-refrigerator over the weekend is slightly compromised in final product quality, though not enough to make the final products unacceptable. Specifically, the final products are slightly more elastic and less tasty than those produced from nonrefrigerated dough in the original system. Moreover, their expected lifetime drops around 20 percent. The croissants stored in the buffer-refrigerator over the weekend, however, represent only four hours of production per week.

As far as the conditions in the buffer-refrigerator are concerned, to cool the croissants quickly and uniformly, (1) Chipita should equip the buffer-refrigerator with powerful fans to circulate air among the croissants, and (2) it should replace its Teflon-coated iron trays holding the croissants, with perforated, silicon-coated, aluminum trays, which cost more but conduct heat better. Moreover, the carts of croissants cooled and stored in the buffer-refrigerator over the weekend should be covered with plastic or cellophane bags to keep the croissants from drying out and forming a hard skin. Finally, croissants coming from the buffer-refrigerator should spend slightly more time in the proofing cell than those that come directly from the croissant-making machine.

The second category contained technical issues that required engineering solutions. For the buffer solution to increase the throughput of the line, we had to speed up the part of the line upstream of the buffer. We wanted to know whether we could do this technically and, if so, by how much. The part of the line upstream of the buffer consists of two sections: kneading and forming. We could speed up kneading easily by increasing the quantities of ingredients mixed by the kneading machine. The manufacturer of the line assured us that we could also speed up the forming section by up to 40 percent after replacing three constant-speed motors with three variable-speed motors. This meant we could increase the nominal processing rate of the part of the line upstream of the buffer from 12,000 to $12{,}000 \times 1.4 = 16{,}800$ croissants per hour.

Another less important technical issue was how to automatically adjust the speed with which the mirror buffer unloaded empty trays. Automatic control systems are commercially available that detect the distance between returning trays and compare their speed to the speed of the forming section.

Apart from these technological and technical issues we had to resolve an important managerial issue. We had to determine the capacity of the buffer-refrigerator and evaluate its impact on the processing rate of the line.

Design of Buffer Capacity

To calculate the effect of the size of the in-process buffer on the effective processing rate of the line, we used Gershwin's (1994) analytical two-machine, continuous-flow line model. This model assumes a transfer line of two machines in series with a finite-capacity buffer between them. The model treats the material processed by the machines as though it were a continuous fluid. Each machine can operate at a maximum nominal processing rate when it is not constrained by the other machine or the buffer. Both machines have random failures and repairs. The model assumes that the times to failure and the times to repair of the machines have exponential probability distributions. This practically means that their failure and repair rates are constant.

A machine is said to have a constant failure (or repair) rate if the likelihood that the machine fails (or is repaired) in the next instant is independent of how long it has been running (or has been under repair). This implies that the machine has no memory of the time since the last failure (or repair) and for this reason the exponential distribution, which is the only distribution that yields constant failure (or repair) rates, is often said to possess the so-called memoryless property.

In a comprehensive study of the failure data for transfer lines that machine transmission cases at Chrysler Corporation, Hanifin (1975) found that the up times, that is, the times between failures in many cases had exponential distributions. Here is the explanation: When complex pieces of equipment, which are composed of many subcomponents, fail, the firm replaces only the affected components, not the entire system. After a while, the equipment becomes a mix of old and new components, with a wide range of life expectancies. The time elapsed since the last failure becomes irrelevant for predicting future failures, because it reveals nothing about the age of most of the components in the equipment. Hence the expected time until the next failure becomes independent of the length of the time since the last failure. In the same study, Hanifin (1975) also found that the observed down times were due to a mixture of different repairs, where the time to make each repair usually had an exponential distribution.

The project revealed the esoteric technology of operations research to the technical management.

Coming back to Chipita's system, the first machine in Gershwin's model represents the part of the croissant-processing line upstream of the buffer-refrigerator, that is, the kneading and forming sections, and the second machine represents the part of the line downstream of the buffer-refrigerator, that is, the proofing, baking, and wrapping sections. Thus, we used Gershwin's model of a two-machine line with a single buffer as a surrogate for the original line. The first machine would have a maximum nominal processing rate of 16,800 croissants per hour with the planned engineering modifications. The maximum nominal processing rate of the second machine had to remain at 12,000 croissants per hour, because it was constrained by the speed of the oven in the baking section.

We calculated the MTTF and the MTTR of the two machines in the model using Chipita's failure records. In the case of the second machine, we calculated them directly from the records. In the case of the first machine, however, we had to modify the data from the failure records because they concerned the section when its nominal processing was 12,000 instead of 16,800 croissants per hour. We increased the frequency of failures of the kneading and forming sections by the same factor that we increased its processing rate: 1.4. Instead of deriving empirical reliability distributions directly from failure data, we assumed that the times to failure and the times to repair had exponential distributions. We considered this to be a reasonable assumption, particularly for failure times, because a lot of components could fail in each section of the line. Specifically, the kneading and forming sections had 23 different types of failures with ratios of MTTR ÷ MTTF ranging from 7,89E-5 to 4,17E-2. The proofing, baking, and wrapping sections had 14 different types of failures with ratios of MTTR ÷ MTTF ranging from 3.16E-5 to 2.08E-3.

The Results

Gershwin's model allowed us to calculate the mean effective production rate of the two-machine continuous-flow line—a surrogate for the original croissant-processing line—as a function of the in-process buffer capacity (Figure 2). It also allowed us to calculate the mean time that a croissant spends in the buffer as a function of the in-process buffer capacity (Figure 3). We give details on the model and the analytical methodology used to solve it in the Appendix.

The mean processing rate of the line increases at a diminishing rate with buffer capacity, approaching the

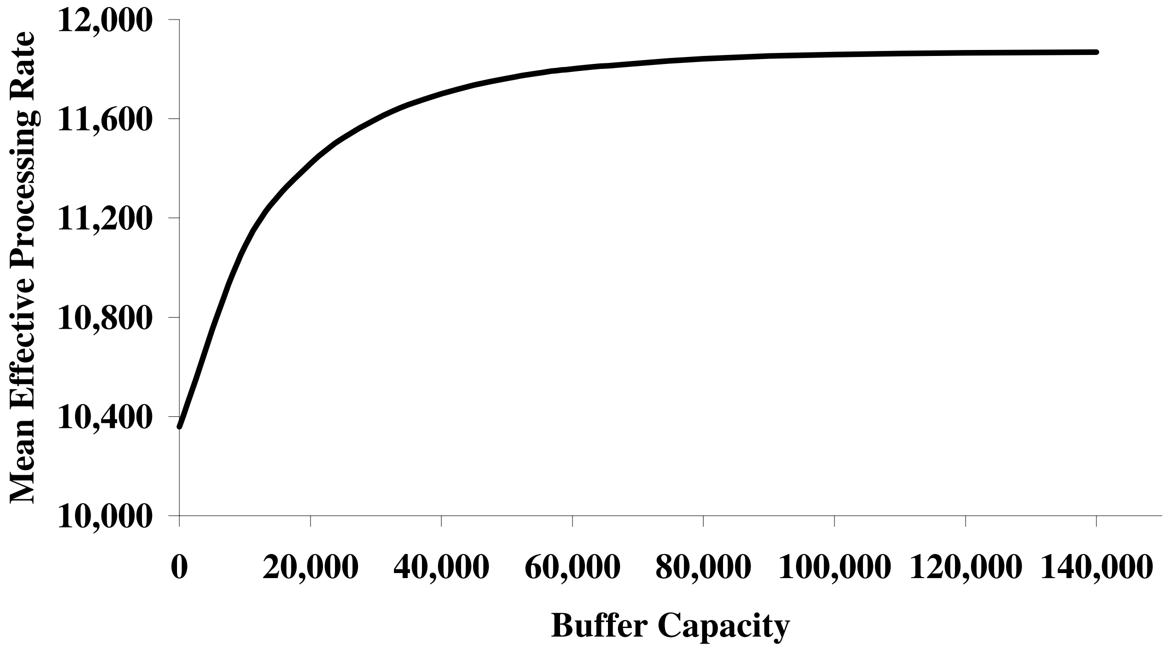

Figure 2: The mean effective processing rate (croissants per hour) of the croissant-processing line approaches the effective processing rate of the part of the line downstream of the buffer (12,000 croissants per hour) as the buffer capacity (croissants) increases.

effective processing rate of the part of the line downstream of the buffer, that is, 12,000 × 0.9969 × 0.9975 × 0.9947 = 11,870 croissants per hour, where the last three terms in the product are the efficiencies of the three sections downstream of the buffer (Figure 2). The mean storage time, on the other hand, increases almost proportionately with buffer capacity (Figure 3).

Based on our results, we thought that a buffer capacity of 40,000 croissants would be enough to raise the effective processing rate from 12,000 × 0.8632 = 10,358 to 11,700 croissants per hour, that is, by a factor of 12.96 percent, and the corresponding efficiency from 86.32 percent to 97.5 percent, at a cost of an extra mean storage time of one hour in the buffer. Moreover, a buffer capacity of 40,000 croissants would require about the same amount of physical space as the proofing cell. Such a space was available. Finally, with a buffer capacity of 40,000 croissants, the maximum storage time in the buffer, if the part of the line downstream of the buffer had not failed, would be 40,000 croissants ÷ 12,000 croissants per hour = 3.33 hours. This is the time that a croissant entering the buffer would have to wait in order for all other croissants ahead of it to move out of the buffer, if the buffer were full. This was more than good news, because dough can be stored in a refrigerator without loss of quality for up to 48 hours.

We further argued that raising the buffer capacity beyond 40,000 to, say, 60,000 croissants, would yield a gain of less than one percent in effective processing rate, namely, from 11,700 to 11,801 croissants per hour (Figure 2), but would increase the mean storage time by 70 percent, namely, from 1.0 to 1.7 hours (Figure 3). Most important, it would require extra space and power to accommodate and refrigerate 50 percent more croissants.

Based on our analysis, we concluded that an in-process buffer-refrigerator with a capacity of 40,000 croissants between the forming section and the proofing cell would do the job. Chipita would also need additional trays and carts to carry 40,000 croissants and a mirror buffer large enough to store the additional trays. We also calculated the costs and benefits of the modified design of the croissant-processing line,

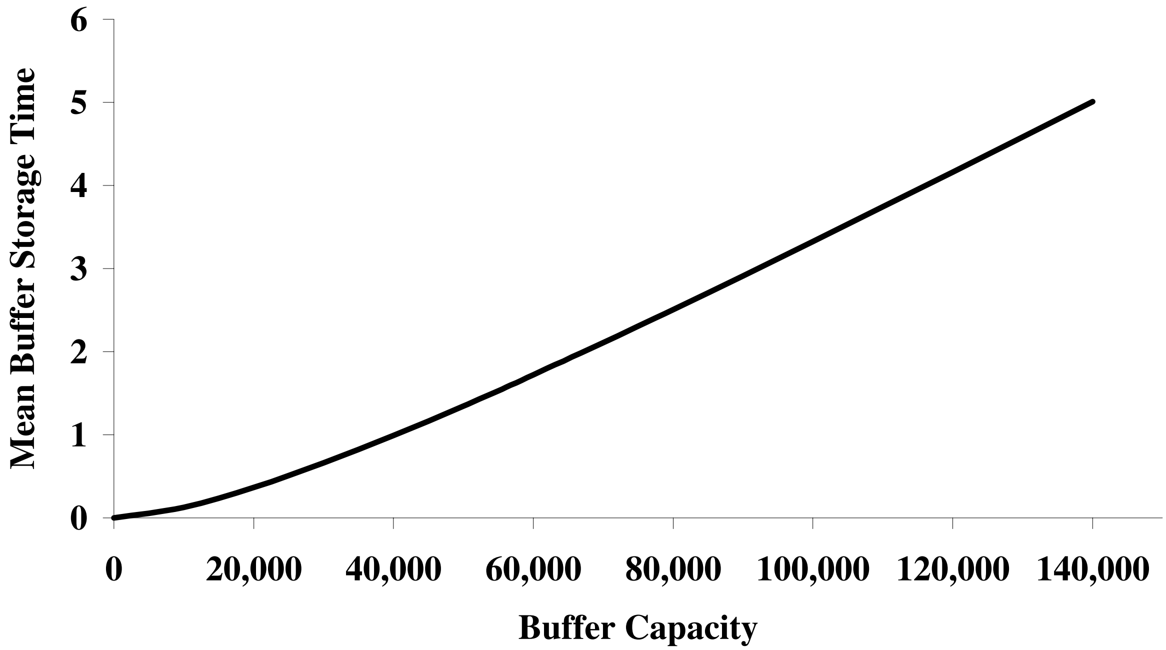

Figure 3: The mean time (hours) a croissant spends in the in-process buffer increases linearly with the size of buffer capacity (croissants).

with the in-process buffer-refrigerator and the mirror buffer of empty trays (Figure 4).

The Benefits

The benefits of installing an in-process buffer-refrigerator with a capacity of 40,000 croissants between the forming section and the proofing cell are multifold.

First, the financial benefits. We estimated that the resulting increase in the effective processing rate of the line would bring in extra earnings of approximately $18,000 per week, but it would also save money.

Having an in-process buffer filled with croissants before the proofing cell meant that Chipita would no longer have to start running the empty line late on Sunday evening in order to have the first croissants come out early on Monday morning. Instead, if the workers on the last shift on Saturday had left the buffer filled with formed croissants, only one person, instead of the entire shift, would have to show up at 2:00 am on Monday morning and start moving carts with croissants from the buffer to the proofing cell. The regular shift could then come in early on Monday morning and start packing croissants. We estimated savings in wages from eliminating the Sunday evening shift at $750 per week. But the buffer solution implied yet more savings.

In the absence of the buffer, every time a failure occurs in the proofing cell, the oven, or the wrapping machines, the entire line upstream of the failure is forced to shut down. If the failure lasts for over an hour, all material trapped in the kneading and forming sections must be scrapped because it deteriorates in quality. When this happens, the line loses about 55 minutes worth of production, which amounts to approximately $1,180 in lost revenues and $720 in material costs, that is, a total of $1,180 + $720 = $1,900. Our records showed that the frequency of failures lasting over an hour in the proofing cell, the oven, or the wrapping machines, was approximately 11 failures per year. This means that the average weekly cost of scrapping material was $1,900 per failure × 11 failures per year ÷ 52 weeks per year = $400 per week. With the in-process buffer, the part of the line upstream of the buffer would keep working even if there were a failure downstream of the buffer, as long as there was space

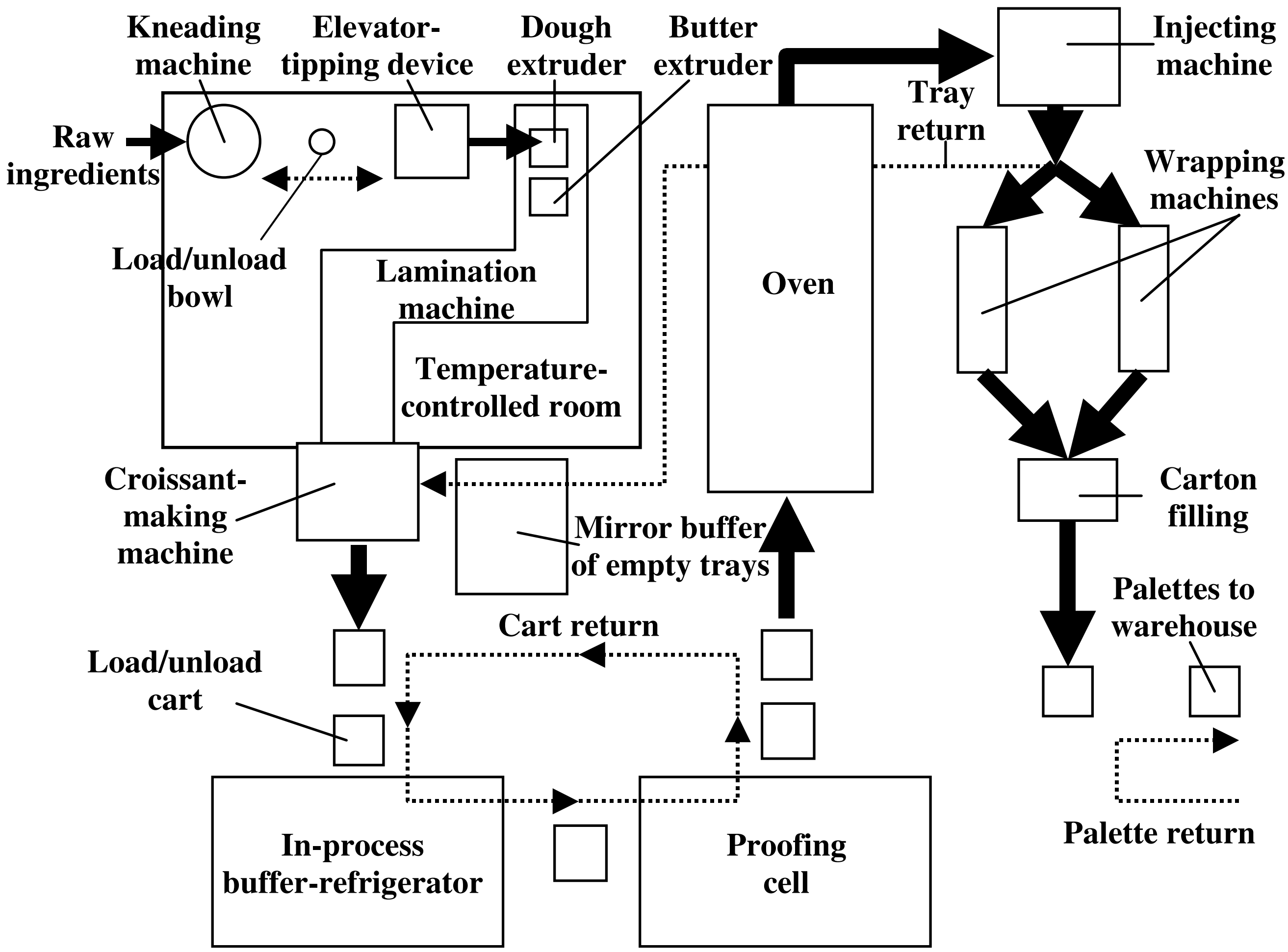

Figure 4: In the modified croissant-processing line, an in-process buffer-refrigerator is inserted between the croissant-making machine and the proofing cell.

in the buffer, so that material would not have to be scrapped. The savings from not scrapping material would therefore be approximately $400 per week.

Thus, the net weekly benefits would be $18,000 + $750 + $400 = $19,150 per week, which translates to just under $1 million per year. Given that we estimated the cost of a refrigerator big enough to hold 40,000 croissants at $91,250, we calculated that an investment in such a refrigerator would break even in five weeks ($91,250 ⊂ $19,150 per week), a very appealing prospect. Moreover, given that a new line costs approximately $2 million, Chipita could buy a new line in two years after implementing the buffer solution, with the $1 million yearly benefits of the solution.

Finally, the picture of the financial benefits of installing an in-process buffer would not be complete if we did not multiply all these earnings and savings by seven, since currently the plant has seven croissant-processing lines. Moreover, since most of Chipita's other bakery products have similar processes, our buffer solution could easily be applied to those processing lines too and bring in extra earnings and savings.

Besides its financial benefits, the buffer solution would have a positive effect on the morale of the people working on the line because it would minimize the upheaval and stress associated with shutting down the entire line, because it would allow parts of the line to run even when there was a failure.

In addition, the buffer solution would allow workers to briefly stop the part of the line upstream of the buffer, when the buffer was full enough, to do preventive maintenance or minor readjustments that could reduce overall failures.

Finally, we benefited and learned a lot from the project and from each other, a manufacturing-systems researcher and a manufacturing-systems practitioner. Our collaboration continues on the implementation of the solution and on a longer-term follow-up study of reliability, maintainability, and component-inventory-control issues related to the lines. The project revealed the seemingly esoteric technology of operations research to the technical management of Chipita and to a lesser extent one of its major food-equipment suppliers, who we occasionally consulted on the project and who was very interested by the findings. The project opened the doors of operations research for Chipita's technical management.

Appendix

Gershwin's (1994) analytical two-machine, continuous-flow-line model assumes a transfer line consisting of two machines in series with a finite-capacity buffer between them. The capacity of the buffer is N. The material processed by the machines is treated as though it were a continuous fluid. Machine i can operate at a maximum nominal processing rate μ_i when it is not constrained by the other machine or the buffer. Both machines have random failures and repairs. The state of machine i at time t is denoted by $\alpha_i(t)$. If $\alpha_i(t) = 1$, the macine is operational or up; if $\alpha_i(t) = 0$, the machine has failed (or is down or remains under repair).

The buffer level at time t is denoted by $x(t)$ and changes at a rate $dx(t)/dt = u_1(t) - u_2(t)$, where $u_i(t)$ is the processing rate of machine i at time t. More specifically, when $0 < x < N$, $u_1(t) = \alpha_1(t)\mu_1$ and $u_2(t) = \alpha_2(t)\mu_2$; when $x = 0$, $u_1(t) = \alpha_1(t)\mu_1$ and $u_2(t) = \min[\alpha_1(t)\mu_1, \alpha_2(t)\mu_2]$; when $x = N$, $u_1(t) = \min[\alpha_1(t)\mu_1, \alpha_2(t)\mu_2]$ and $u_2(t) = \alpha_2(t)\mu_2$.

The repair time of machine i is exponentially distributed with a constant repair rate r_i. The time to failure of machine i is exponentially distributed with an operation-dependent failure rate of $p_i u_i(t)/\mu_i$, where p_i is the maximum failure rate when the machine is operating at its maximum nominal processing rate. At any time t, the state of the system is $(x(t), \alpha_1(t), \alpha_2(t))$.

We calculated the maximum failure rate and the repair rate of each machine from the data as follows:

$$p_1 = \beta \sum_{j\in J^U} p_j^U, \; r_1 = \frac{\sum_{j\in J^U} p_j^U}{\sum_{j\in J^U} p_j^U / r_j^U},$$

$$p_2 = \sum_{j\in J^D} p_j^D, \; r_2 = \frac{\sum_{j\in J^D} p_j^D}{\sum_{j\in J^D} p_j^D / r_j^D},$$

where p_j^U and r_j^U denote the failure rate and repair rate, respectively, of the jth type of failure upstream of the buffer, and J^U is the set of all failures upstream of the buffer. Similarly, p_j^D and r_j^D denote the failure rate and repair rate, respectively, of the jth type of failure downstream of the buffer, and J^D is the set of all failures downstream of the buffer. Coefficient β denotes the factor by which we have to increase the processing rate of the first machine, that is, 1.4.

Gershwin sets up differential equations for the steady-state probability distribution of the state of the system, $f(x, \alpha_1, \alpha_2)$, and solves these equations using boundary conditions at $x = 0$ and $x = N$ and the normalization condition, which states that the cumulative distribution over the entire state space must be equal to 1. Once the steady-state probability distribution of the state is known, the mean effective production rate of the line and the mean buffer level can be found easily.

We wrote a program using the software Mathematica to solve for the steady-state probability distribution and compute the mean effective production rate of the line and the mean buffer level for different values of the buffer size. The solution converged with no problem, and we obtained the smooth curves shown in Figure 2 and Figure 3.

A wide range of two-machine, single-buffer models like the one we described can be solved analytically. For longer transfer lines, exact analytical solutions are practically impossible to develop, so analysts use approximate methods to solve them. Most of these methods are based on decomposition. A typical decomposition method decomposes the original line of, say, K

machines and *K*-1 buffers into *K*-1 two-machine, single-buffer subsystems. In each subsystem, the buffer represents one of the buffers in the original line, the first machine represents the part of the original line upstream of that buffer, and the second machine represents the part of the original line downstream of that buffer. Each subsystem is analytically tractable once its parameters have been determined. The method derives a set of equations that determines the unknown parameters of each subsystem from the parameters and performance measures of other subsystems and uses an algorithm to solve these equations.

The earliest studies of stochastic models of transfer lines were reported in the former Soviet Union in the early '50s. Since then, a great deal of literature on transfer-line analysis has accumulated. Buzacott and Gershwin have contributed much to the research in this area (Buzacott and Shanthikumar 1993, Gershwin 1994). Dallery and Gershwin (1992) give a comprehensive review of models developed for transfer lines and flow lines.

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Panagiotis Tsarouhas, Technical Director, Chipita International, Inc., Lamia Industrial Park, GR-35100 Lamia, Greece, writes:

"This is to attest to the impact of our work with Professor G. Liberopoulos to increase the production rate of the packaged croissants processing lines at Chipita International's plant in Lamia, Greece. . . .

"This research has come at a critical time when the demand for packaged croissants is growing rapidly. This increase in demand is reflected in the rapid gowth of Chipita's packaged croissants-related operations world-wide. Here is some hard evidence of this:

• On January 5, 2001, Chipita International's subsidiary Chipita Russia Ltd. purchased 100% of the share capital of two Russian companies, ZAO Krasnoselskaya and ZAO Eldi. Starting in autumn of this year a new packaged croissants production line is expected to be operating in the Eldi factory. Sales of the Russian company are expected to reach USD 8 million this year and USD 14 million in 2002, while pretax profits are estimated to reach USD 500,000 this year and USD 1.2 million in 2002.

• Delyug, Delta Participation's subsidiary in Yugoslavia, will commence distributing Chipita's range of individual packaged croissants and mini croissants in Yugoslavia through its distribution network. This year sales are expected to reach GRD 1.3 billion (EURO 3.8 billion). Yugoslavia will experience rapid development in the next few years. In this event, the establishment of a factory for packaged croissants, together with the participation of Delta, will be considered close to Delta's existing ice cream plant.

• Recently, Chipita International had an agreeement with Pepsico Inc. to create a joint venture for the production of packaged croissants in a Latin American country. Possibilities exist for expanding this cooperation to other countries in Latin America, the U.S.A. and Europe.

• Chipita International signed an agreement for the buy-out of its principal competitor in Romania, Best Foods Romania, which owns and operates a manufacturing facility for packaged croissants and other bakery products in Bucharest. With this move, Chipita increases its share of the fast-expanding Romanian market for packaged croissants to over 80%.

"The above evidence shows how important it is for our company to be able to increase the production rate of packaged croissants and increase our market share in an expanding market for them.

"As strange as it may sound now, the solution of inserting an in-process buffer to help increase the productivity of the packaged croissants processing lines would never have occurred to us had we not been involved in this project.

"Now, we are in the process of preparing to implement this solution. The technical issues associated with speeding up the lamination, and the croissant-making machines can be resolved by our processing equipment supplier, so we are mostly working on quality assurance issues. Since the quality and uniformity of our products is our number one concern, it may take us some time to optimize our processing parameters to ensure the same high quality standards that we are achieving now. We are confident, however, that we can resolve these issues.

"At this time I can see no reason why we should not be able to reap all the benefits that we mention in the paper. Although the financial benefits are of primary concern to our company as a whole, being a technical director responsible for running the lines, I particularly value the benefit of being able to keep the lines running even when there is a stoppage on the part of the line upstream of the buffer.

"Let me conclude by saying that this collaboration has been extremely useful for us, as we have learned to understand and analyze our lines. This collaboration continues to date and is focused on a more detailed analysis of failure and repair data."