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Analysing Event Data from a Repairable Automated Systems: A Case Study

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Abstract: The study presents the detailed analysis of reliability data of an automated croissant processing line. The line consists of several workstations, each having one or more machines with several failure modes. Failure and repair times are collected at all levels of the hierarchical structure of the line (failure mode, machine, workstation and entire line) for a period of 10 months and it was observed that there is a significant difference between nominal and effective processing rate. Then some alternative solutions were analyzed and propose a maintenance policy for increasing the effective processing rate of the line, without raising the cost. It can also be served as a valid data source for researchers who want to model and analyze real manufacturing systems.

Key words: Agriculture/food, automated systems, reliability models, field failure data analysis

INTRODUCTION

The bakery products and biscuits sector is one of the most stable sectors in the food and beverages industry. A significant part of this sector is engaged in the production of bread products, such as bread, breadsticks, baguettes, croissants, pizzas, etc., on specialized, automated, high-volume processing lines. An important managerial concern in any high-volume production industry is to keep the production going with minimum interruptions. This concern is even more prominent in industries such as the bread products industry, where an interruption anywhere in the production process not only causes a gap in production but also creates quality problems such as the rise of dough. Unfortunately, because of wear and tear on the individual machines of the processing line and on the electronics and hardware for common controllers and transfer mechanisms, various pieces of equipment can break down in the line, forcing the line upstream of the failure to shut down and causing a gap in production downstream of the failure. The pressing need for assessing and improving the reliability of automated production systems forces production managers to collect and analyze field failure data from the systems they manage and take measures to reduce their downtime and increase their availability.

The literature on field failure data is substantial. Most of it deals with the analysis of failure and repair data of individual equipment types. Recent examples include pole mounted transformers[1], airplane tires[2], CNC lathes[3], offshore oil platform plants[4] and medical equipment[5]. The literature on field failure data of production line is scarce e.g. the downtime history recorded in a transfer line that machined transmission cases at Chrysler Corporation[6], actual production data from two automotive body-welding lines[7]. The literature on field failure data of food industry is limited. Recent presented a case study of speeding up a croissant-processing line by inserting an in-process buffer in the middle of the line[8].

In this study the detailed analysis of reliability data of an automated croissant processing line has been recorded. The analysis is based on a set of field failure data covering a period of 10 months. Given the extensive length of the period covered, this study will serve as a valid data source for researchers who want to model and analyze real manufacturing systems. The process of making bread products is very similar for a wide range of bread products; therefore, the analysis reported in this study for a croissant processing line is relevant for many other bread product lines as well.

DESCRIPTION OF AN AUTOMATED CROISSANT PROCESSING LINE

An automated croissant processing 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

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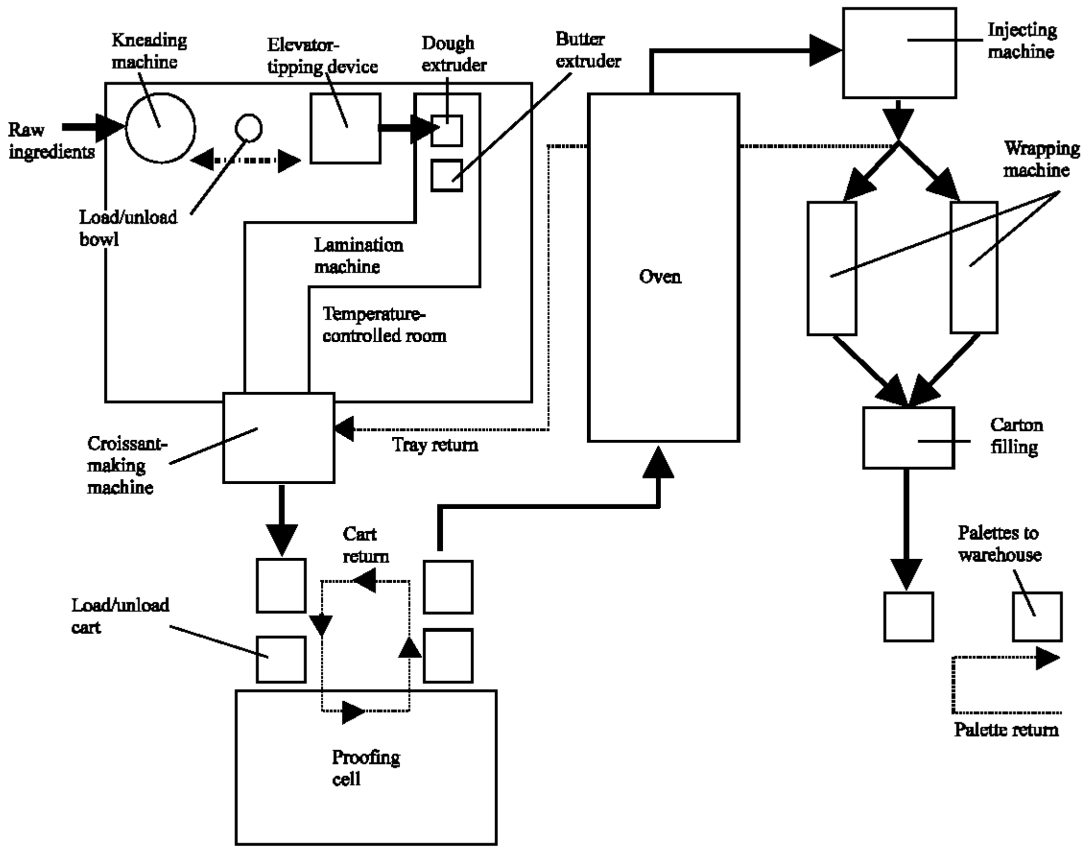

Fig. 1: The original croissant-processing line

wrapping. Each stage takes place in a separate section of the processing line (Fig. 1). The process flow of the line is as follows[8].

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.

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.

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. Each stage corresponds to one workstation.

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 h a day, with three 8 h shifts, during the week and pauses during the weekends that are spent usually on scheduled maintenance operations on the line.

COLLECTION OF FIELD FAILURE DATA

We had access to hand-written records of failures that the line technicians kept during each shift. These records covered a time period of 305 days, i.e. ten months. During this period, the line operated for 24 h a day, with three eight-hour shifts during each day (3*8 h=24 h), for a total of 218 working days. The records included the failure mode or modes that had occurred during the shift, the action taken to repair the failure and the down time.

The line was identical to that described in the previous section. It consisted of five workstations in series, where each workstation contained one or more machines and each machine had several failure modes. Apart from the failures in the equipment of the line, there are also a few exogenous failures that affect the entire line. To take into account these exogenous failures, a sixth pseudo-workstation is defined and calls it the "exogenous" workstation. The exogenous workstation has four pseudo-machines, which correspond to the electric, water, gas and air supply, respectively. Each pseudo-machine has a single failure mode corresponding to a failure in the supply of one of the four resources mentioned above. Failures at workstation 6 are very important because they affect the entire line. The most significant of these failures is the failure of the electric power generator that temporarily supplies the system with electricity in case of an electric power outage.

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 an unexpected failure occurs, the failed equipment stops and forces most of the line upstream of the failure to operate without engaging material and therefore without producing and this causes a gap in production downstream of the failure. 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.

The records covering 10 months show that the effective processing rate of the line for that period was 10,123 croissants per hour, 84.36% 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.

THE ALTERNATIVE

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 impact of failures[9,10]; 3) by reducing the frequency of failures and 4) by reducing the duration of failures. Good engineering and operating practices primarily determine the first, third and fourth approaches. The second approach is a matter of design and requires a systems perspective.

In the case of the croissant-processing line, to pursue the first approach, the manufacturer 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[9]. We considered this to be unappealing both from a financial point of view and because of space limitations. The second approach, to reduce the impact of failures is studied[8].

Several design alternatives for reducing the impact of failures are considered. One alternative was to introduce redundant stations in the form of standby stations; however, as was the case with the first approach, this found 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 backup 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 materials between lines would cause quality problems.

To follow the third approach, the manufacturer 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 fourth approach, appropriate management and operating practices should be devised regarding repair and maintenance as well as component inventory control.

Both (third and fourth) approaches are considered as necessary steps towards overall system improvement.

ANALYSIS OF MACHINE FAILURES

The reliability of a production system is often expressed in terms of probability that the system will operate satisfactorily (i.e. without failures) for at least a certain period of time[11,12]. Therefore, the reliability is the probability that the life T will exceed t, R (t) = Prob (T>t). In a similar way, the availability or efficiency of the production system is usually define as the probability that the system will operating satisfactorily at an arbitrary point in time, or equivalently as the long run average fraction of time that the system is operational. The availability (A) is often expressed in relation to breakdowns and maintenance activities and is closely to the breakdowns D (as a fraction of total available time). The availability can be estimated by A=1-D=total operational time/total operational time+total downtime=MTBF/MTBF+MTTR. The Mean Time Between Failures (MTBF) is the mean operating time between one down time and the next, where each down time can be due to maintenance or a breakdown. The Mean Time To Repair (MTTR) is the mean time that the process is inoperable when it is down for maintenance or because of a breakdown.

Failures can be classified 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[9]. Finally, the effect refers to whether the material in process at the instant of failure must be reworked, repaired, or scraped.

In croissant-processing line, 37 different types of failures are counted. 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 scraped.

Records of failures are collected and analyzed during 10 months. The failures ranged in average duration or Mean Time To Repair (MTTR) from very short failures, such as the 10 min adjustment of the photocell of an ice machine at the kneading stage, to medium failures, such as the 3 h replacement of the fan in the proofing cell, to long failures, such as the 16 h 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 Between Failure (MTBF), such as the rupture of the conveyor following the wrapping machines every 15,845 h to more frequent failures, such as the failure of the oven burner every 1,584 h 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 h.

Using the MTTR and the MTBF of every failure in each of the 5 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. The following section efficiencies are found: kneading: 99.38%, forming: 87.62%, proofing: 99.69%, baking: 99.75%, wrapping: 99.47% and exogenous: 99.56%. From this analysis, it is realized that the impact of failures in the forming section overshadowed the impact of failures in any other section. Then estimated the efficiency of the entire line. It turned out to be 85.93%. A similar estimation using the assumption of time dependent failures yielded a line efficiency of 85.75%. The two estimates were so close because all sections except the forming section had efficiencies close to 100%. In all estimates, we assumed that no material would be scraped 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, company's records showed that the output efficiency reported for the same period was 84.36%, approximately 1.5% lower than the efficiency estimated (85.93%).

The unavailability of the system is expressed as U=1-A=14.07%, which is the percent of the time that the line is downtime and not produce.

Specifically, the kneading and forming sections had 23 different types of failures with ratios of MTTR÷MTBF 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÷MTBF ranging from 3.16E-5 to 2.08E-3.

CONCLUSIONS

The negative impact of failures on the actual production rate of automated production lines puts a pressure on bread and bakery products manufactures to assess and improve the reliability of their lines. This pressure is heavier when the products are manufactured for immediate consumption than when they can be stored for several days or weeks. It forces production managers to collect and analyze field failure data from the production lines that they manage so that they can take measures to reduce the frequency and duration of failures. Such measures are primarily determined by good operating practices by the bread and bakery products manufactures that run the lines as well as good engineering practices by the food product machinery manufactures who design the lines. Thus a plan may be executed as:

- Prolonging the MTBF by dealing with visible defects and the avoidance of accelerated wear by adequate cleaning and lubrication.
- Periodic repair/replacement of wear by means of preventive maintenance programs before failures occurred.
- Implementations of diagnostic techniques e.g. oil analysis, vibration analysis and others, for making predictive maintenance decisions

The goal of preventive and predictive maintenance is to maintain the system in good condition and repair problematic areas before they turn into failures during production. It is clear that not only the production system, but also its maintenance plays an important role.

The proposed approach can be used for repairable systems and it can also be served as a valid data source for researchers who want to model and analyze real manufacturing systems.

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