

Reliability and Availability of Industrial Bakery Plant: Modeling and Analysis. A case study

Francesco Bertocci¹, Marco Mugnaini¹, Ada Fort¹, Valerio Vignoli¹, Laura Spicciarelli

¹*Department of Information Engineering and Mathematics, University of Siena
via Roma, 56, 53100, Siena, Italy, tel. +39 0577 23 48 50, int. 1057
bertocci@diism.unisi.it*

Abstract – In this paper the modeling of an industrial bakery plant aimed at evaluating its Reliability and Availability is described. In order to individuate the production capabilities and the weak points of an complex high-tech food production plant, the authors obtained the prediction of the reliability of the production line by considering sub-systems and apparatus. In this context a complex Reliability Block Diagram (RBD) of the production site has been built from components and from operative steps. The analysis is aimed at providing a strategy for the implementation and improvement of the design and the machineries arrangement. This allows for optimizing the operation of the production lines and for setting appropriate priorities for the development of activities that have the largest impact on cost efficiency. The production phases, the machines performance and the system capacity of the bakery plant are studied by means of the availability prediction (current and historical) based on the experimental data of the production behavior (operating, faulty, standby).

Keywords: System availability, Industrial food plants, RBD modeling, Weibull distribution

I. INTRODUCTION

Reliability and availability issues have been the topic of many scientific studies in recent decades [1]. Up to now, the scientific research has turned its attention towards the performance optimization of industrial systems at the design phase [2] or at project stage [3], with the further aim of achieving an efficient maintenance management [4]. Nowadays, repairable systems provide scenarios wherein operating and maintenance activities interact in a complex manner [5][6], in which multiple entities (people, machines and environments) are involved.

In the literature there also publications that focus on the improvement of Reliability and Availability parameters, providing guidelines regarding the type of maintenance to be used in different industrial contexts [7]. There are also researches based on the improvement

of the system availability [8] and on the flexibility of operability conditions in order to assure quality and maintenance of the productive assets [9].

However, we can find a lack of studies that describe and analyze the practical problem of getting an implementation of a simulation model for an entire and complex industrial system able to provide a reliability estimation. The added benefit of a tailored simulation model consists in the opportunity to perform experiments and simulations on the basis of the plant layout by considering the redundancy policies of equipment, allowing thus for improving the reliability. In order to study the reliability of a system, composed by a large quantity of sophisticated electronics, machineries and high-speed controllers, the implementation of a Reliability Block Diagram, RBD, becomes mandatory [10]. Once studied the faults of the whole system, the problem is analyzed and the system is divided into gradually simpler units, i.e. sub-systems, subsequently assets (apparatus) and finally in the constituent components/elements of each individual subsystem. RBD provides an easy approach for modeling of the overall information, derived by the experimental data through the flow-chart representation, which giving a systematic, integrated and very compact view of the system.

Following this approach the modeling technique illustrated in this paper starts from the investigation and analysis of the complex system architecture of a production line for a bakery industry, and faces the problem of improving its current system availability status.

Simulations are implemented in order to gather the system performance values by proceeding backwards with a bottom-up perspective for obtaining the reliability assessment as explained in the following sections. Moreover, in this work it is shown how the choice of both an appropriate maintenance strategy and an ad-hoc redundancy policies can improve the system availability.

The organization of the paper is the following: in the second section the production cycle and the implementation of the corresponding RBD are presented. The third section illustrates the reliability and availability modeling. In section IV some simulations and results obtained by means of Weibull++ and BlockSim and

ReliaSoft® are described: the availability of the weakest assets is individuated and reported. Discussion and final remarks conclude the paper.

II. THE PRODUCTION CYCLE AND ITS RELATED DESCRIPTION

The production process consists of a cycle of about four hours consisting of seven main phases of bakery product manufacturing, so the overall process can be represented as shown in figure 1. The first step, Dough Preparation, includes the preparation and the dosage of dough starting from raw materials, i.e. flour, then mixed and kneaded by two mechanical machines, Mixer 1 and Mixer 2, that work in parallel n:n redundancies with n=2 in the same way.

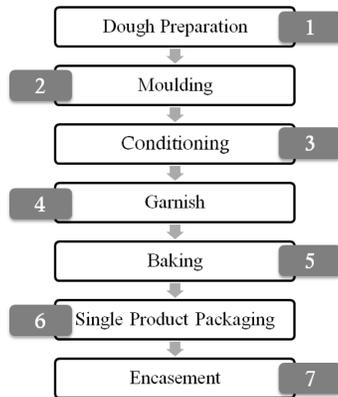


Fig. 1. Bakery production cycle

The overview of human experience is important in order to mix the right dosage of ingredients; an electronic equipment measures the optimal compound weight [11]. Then, the mixture is dumped into a Divider Hopper (by a Tasks Translator and a Tanks Tipper) to get initial portions with a fixed weight. This mixture portioning is needed for preventing the overload of the Conveyor Belt, which would not be able to hold up the entire mixture weight. The initial portions are transferred by conveyor belts through Divider Over-Hopper into a Volumetric Divider, in which an electronic balance with high accuracy is embedded, to get smaller fixed weight portions, from which French sticks will be produced through processes of rolling, molding and coiling (step 2, Moulding). The loaves pass through two Conical Rounders that work together equally for splitting the load and for providing a preliminary “skin” to the loaves, giving them a spherical shape. Automatic devices, Automatic Scale 1 and 2, check the compliance in terms of weight of loaves made in the previous step, rejecting non complying items. The Pre-rising Prover houses the bread spheres for a specific period favoring a perfect surface consistency. This asset operates in controlled temperature and humidity conditions by means of robust

ambient sensors. Successively, the loaf is initially laminated and pre-rolled by Coiling Machines and cut by a sort of automatic knife, Scarpatrice, then shaped into required length loaves and automatically conserved in baking pans by Loaf Moulders.

The loaves pass towards the next conditioning phase (step 3, Conditioning) that consists in two series components: Proofer, with controlled temperature and humidity conditions, and Conveyor Belts that provides the transport of the products to the step 4, Garnish. The product in baking pan may or not be decorated with dusting flour by one of the two parallel Decorators, one of which is in reserve mode (standby redundancy).

Later the decorated product passes through a Baking Oven with controlled temperature for around 25 minutes: the oven is composed by several zones and works through heat cycle (step 5, Baking). This sub-system is composed by five series blocks. All zones are managed by two methane powered burners. The baked loaves, leaving the Baking Oven, pass through a Demoulder that removes the products from the baking pans without degradation or damage; the Demoulder is able to reject the non-compliance pans through an optical scan. After a preliminary cooling operated by Loaf Moulders, the loaves are transferred to a Seasoning Room where they stay for the time required for the bread to cool down, in order to facilitate both the cutting into slices and the homogeneity of the product under controlled temperature and humidity. Step 6, Single Product Packaging, consists in the packing of the products. The cooled loaves are sliced by Cutters 1, 2, 3 and 4, then packaged with a heat-sealed film packaging by the Packaging Machines. Finally the items pass through Metal Detectors that detect the presence of any metal parts and then they are transferred to eight Automatic Tiers which apply the twist band to the package. The load is equally distributed among the 1st, 2nd and 4th lines that work simultaneously; the 3rd, line_3, is in cold standby redundancy with 4th line. In the final step, (step 7, Encasement), Cartons Opening Machines prepare cartons to place the packaged products. The packs are loaded into open boxes by the Packers 1 and 2 (in warm redundancy, in fact the first one (line_5) which follows the lines_1 and line_2, works at full capacity, and the other one (line_6) works at reduced capacity (at the system starting only line_4 works). The cartons are sealed (with adhesive tape) through two Cartons Sealing Machines placed at Packers. Boxes are, then, palletized and transferred to the finished product warehouse.

The technical design of the considered plant consists of 56 different blocks (later defined as assets too), selected as representative of whole system. The organization described above and the analysis on the entire food system produce the RBD (Fig. 2), that describes the production plant and process. In the figure the blocks are labeled with the line machineries names and the diagram

intuitively defines the precedence relations between the phases. In order to analyze a complete system RBD the bakery plant is broken down into a composition of seven main steps, that we considered as sub-systems: Dough Preparation, Moulding, Rising, Garnish, Baking, Single Product Packaging, Encasement. For this study the only possible combination is the simultaneous operation of all components. We chose to do not go deeper into the analysis of the components of electrical and mechanical machines because it would be very complex and time-consuming.

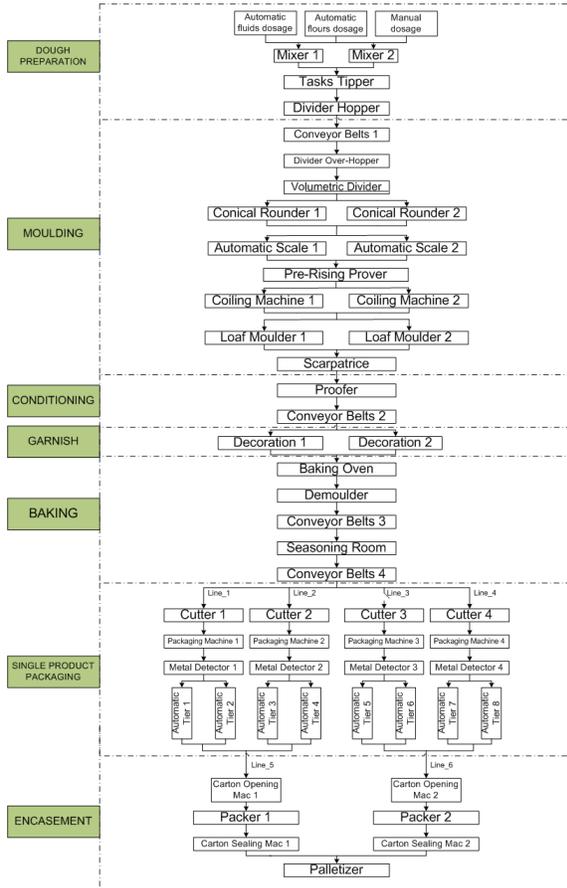


Fig. 2. RBD of the high capacity bakery plant

III. RELIABILITY AND AVAILABILITY MODELING

Experimental data have been collected and then processed. The selection of the temporal range is correlated to the need of a significant quantity of data and observations for the analysis. In order to obtain useful and representative information regarding reliability and availability of the industrial plant under study, a sufficiently long observation period becomes a strong requirement. The chosen time interval for data extraction is 3 years. These data do not include micro-interruptions of machineries. Failure rate has been computed through

the MTBF, Mean Time Between Failures, [12]. In this way the failure rate of the component is the arithmetic mean of the failure rate of the component/asset in time unit (hour). The company exercises in a controlled closed environment and we assume an environmental temperature of 30°C (worst case) and humidity of 50%.

A. Reliability Analysis

In the first part of this paper the components failure rates are assumed to be constants and therefore their reliability behavior can be described by an exponential distribution.

The failure rate of the each sub-system composed by n elements each of an established constant failure rate λ_i is given by the sum of all its n components failure rates in case they are connected as series, as shown in the following equation, (1),

$$\lambda_{sub-system} = \sum_i^n \lambda_i \quad (1)$$

Overall system reliability is given by the product of the estimated sub-systems values for the whole production cycle.

For completeness the subsystems reliability parameters are summarized in Table 1.

Table 1. Reliability parameters for the system under study

PHASE NUMBER	SUB-SYSTEM	λ [failures / 10^3 h]	MTBF [h]
1	Dough Preparation	2.4	417
2	Moulding	3.3	303
3	Conditioning	0.577	1,733
4	Garnish	0.0484	20,661
5	Baking	3.69	271
6	Single Product Packaging	5.6	179
7	Encasement	6.235	160
SYSTEM		21.85	46

In particular, the reliability estimate for sub-system 6st, Single Product Packaging, has been complicated due to redundancies k of n . In fact, the RBD consists of 4 lines. Line 3, which comprises Cutter 3, Packaging Machine 3, Metal Detector 3 and Automatic Tiers 5 and 6, has a cold stand-by which, therefore, comes into operation to compensate for the unavailability of 4th line. So, it has been need to calculate the reliability of the series of each line accounting for a 1:2 redundant parallel.

By this preliminary analysis we identify the most critical sub-subsystems under reliability point of view, as “Encasement”, “Single Product Packaging” and “Baking”.

B. Availability Analysis

The procedures for estimating the Availability, A , aims at emphasizing the impact of stops linked to faults/repairs allowing the definition of short-term goals and identifying the item (sub-system – asset/block or component) on which to take actions to increase the production line availability (and, consequently, the yield in gear). Availability differs from Reliability because it takes into account the Time To Repair, TTR. An item might not be very reliable, but it can be repaired very quickly when it fails: in this case its availability is high. Fig. 3 shows what is meant by Up-Time, the time during which components are available, and Down-Time, the time during which components are down due to breakdowns, to preventive maintenance services and to other factors induced by process specificity.

These times correspond to:

- Mean Up Time: known as MTBF already described previously;
- Mean Down Time, MDT, is the mean or average downtime, in which the system is not operational due to repair (or preventive maintenance), which includes logistics and administrative delays.

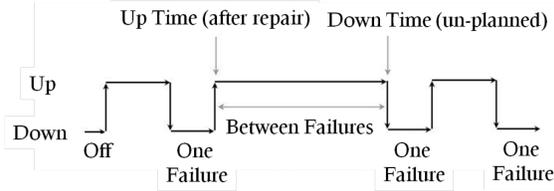


Fig. 3. Up-Time and Down-Time of a component

Assuming a known MDT, equal to the MTTR (Mean TTR) value, and under the assumption that the system components have constant failure rates and repair rates, we derived the availability from [13].

$$A_o = \frac{UpTime}{TotalTime} = \frac{MeanUpTime}{MeanUpTime + MeanDownTime} = \frac{MTBF}{MTBF + MDT} \quad (2)$$

The equation (2) allows to assess the operational availability, A_o , in steady state conditions.

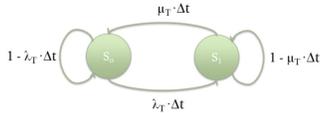


Fig. 4. Available/Non-Available transitions for the system

The availability of the system is assumed by modeling the ON/OFF states by a two-states first order Markov chain with transition probabilities, $\lambda_T \cdot \Delta t$ (from S_0 to S_1) and $\mu_T \cdot \Delta t$ (from S_1 and S_0). Fig. 4 represents two-states,

Available – S_0 and Non-Available – S_1 for the industrial plant under study, where, (3),

$$\lambda_T \cdot \Delta t = \sum_i^n \lambda_i \cdot \Delta t \quad (3)$$

is the transition probability from S_0 to S_1 , and, (4),

$$\mu_T = \max(\mu_i) \quad (4)$$

is the transition probability from the S_1 to S_0 (i is in the range (1 – 7), that corresponds to the number of sub-systems).

Up-time includes operating time plus non-operating time when the equipment is assumed to be operable. Down-time takes into account both the time of repair and supplementary logistic times (i.e. waiting for maintenance services, waiting for spare parts, testing, etc.). Corrective maintenance is not implemented for this case study. A_o is intended to provide a realistic measure of equipment availability; in fact, using the MDT, calculated by field data for each sub-system, we predict the availability by means of failure events and of service maintenance ability to perceive this status. The last step involves computing the availability of each components and then of the entire system. These estimates have been based on serial and parallel availability calculation formulas [14]. The resulting estimates by means of the availability prediction in terms of probability combinations are showed in Table 2.

Table 2. Availability estimates of the sub-systems

PHASE NUMBER	SUB-SYSTEM	MDT [h]	A_o
1	Dough Preparation	1.498	0.9964
2	Moulding	1.446	0.9952
3	Conditioning	1.325	0.9992
4	Garnish	1.667	0.9999
5	Baking	1.934	0.9929
6	Single Product Packaging	0.767	0.9957
7	Encasement	1.779	0.9890
SYSTEM			0.9689

IV. SIMULATIONS AND RESULTS

The choice of exponential distribution can allow to obtain an explicit calculation method of reliability and availability, but the assumption of constant failure rates of components/apparatus is often not consistent, especially when we deal with food systems for which both the simplifications allowed by strong hypothesis, and the use of exponential distribution, lead to the development of models with very limited robustness.

Therefore, the determination of the trend of failure

rate curve, especially for mechanical components, becomes very important, and this allows to consider system-aging effects. In order to verify the effect of more realistic assumptions for Reliability and Availability parameters estimate, the case of components lifetime with a Weibull distribution is simulated.

Simulations have been implemented by Weibull++ and Blocksim of ReliaSoft®.

A. Data Pre-Processing

In the data preparation stage, the analysis showed the inability to use the Weibull function to describe the trend of failure probability for all components, especially because of the limited number of available observations for these components (none, one or two observations).

By analyzing these data, we chose to describe failure probability density by means of the Weibull function with two positive parameters: for these components the shape parameter, β , estimated in Weibull++ software package has a value in $0 \leq \beta \leq 3$. We decided not to increase the number of Weibull function parameters due to the scarce improvement in data fitting and to the increase of model complexity. Based on the value of the shape parameter, β , estimated for each component, the identification of early failures (Table 3) and wear failures (Table 4) becomes possible.

Table 3. Assets with early failures

ASSET	β	η (h)	SUB-SYSTEM
Mixer 1	0.37	938	Dough P.
Coiling M. 2	0.79	4,047	Moulding
Conveyor B. 2	0.57	3,720	Conditioning
Baking Oven	0.90	681	Baking
Line 4	0.98	357	Single Product P.
Packer 1	0.89	1,111	Encasement

The fact that components listed in Table 3 have suffered early failures can lead to multiple considerations. These failures are typical of the early period of components life by definition but, in most cases, may also be due to inadequate process planning techniques and lack of quality control during the production. It's also conceivable that some of these components, i.e. Mixer 1, had structural defects: it suffered different failures from those typical of components with the same technology, structure and location along the production line. These structural failures could be linked both to manufacturer fabrication errors, design errors and/or to defective spare parts assembled during maintenance services.

Table 4. Assets with wear failures

ASSET	β	η (h)	SUB-SYSTEM
Automatic Flours D.	1.13	2,240	Dough P.
Volumetric Divider	1.20	736	Moulding
Decoration 1	1.27	6,260	Garnish

In Table 4 the components critical in terms of aging are shown. This type of failure can generally be prevented, or reduced, by means of maintenance techniques whose purpose is to reduce the wear by means of spare parts preventive replacement (before failure occurring).

The failure probability density can be described by means of exponential function. (Table 5). The exponential function corresponds to the Weibull function in which the shape factor is equal to 1 ($\beta = 1$). The time behavior of the failure rate coincides with the middle section, random failures, in Bath-tube curve.

Table 5. Assets with random failures

ASSET	λ (failures / 10^3 h)	SUB-SYSTEM
Tasks Traslator	0.06	Dough Preparation
Loaf Moulder 2	0.09	Moulding
Decorator 2	0.08	Garnish
Conveyor Belts 3	0.10	Baking

Random failures don't fit in previous classification because they are generally due to sudden and unexpected stress accumulation over the maximum component strength.

B. Simulations

The RBD showed in Fig. 2 has been modeled by BlockSim. The aim of these simulations is to understand failure problems that make the industrial plant unavailable for manufacturing activities. The system availability, A_o , has been estimated through one thousand simulations with a fixed mission time (chosen equal to 1 year). The estimated value of the system availability in 1 year is equal to 97.66% (Table 6). It's a value very close to the estimated one assuming independent random failures ($A_o = 96.89\%$ from Table 2), but is more significant because it also takes into account an appropriate probability distribution of TBF. The new assumptions concerning failures probability distribution have changed the estimated availability value for each processing step, as showed in Table 6.

Table 6. Availability estimates by simulations

PHASE NUMBER	SUB-SYSTEM	A_o
1	Dough Preparation	0.9962
2	Moulding	0.9938
3	Conditioning	0.9992
4	Garnish	0.9999
5	Baking	0.9933
6	Single Product Packaging	0.9983
7	Encasement	0.9957
	SYSTEM	0.9766

“Moulding” and “Baking” are the most critical phases under the availability point of view. Analyzing the subsystems, the availability is intrinsically dependent on the RBD configurations that compose them; this relationship explains the highest values of availability for “Conditioning” and “Garnish”. Regarding “Encasement” it can certainly be said that the Packer 1 and 2 (belonging to this sub-system) are assets much less critical than the other ones because it’s physically located at the end of the production chain, so its unavailability causes neither loss of production nor rejections.

V. CONCLUSIONS

This research resulted in a useful approach for the industrial plants, starting from the analysis and the optimization of the observed field data. The Reliability and Availability modeling has proven to be a strategic tool and the simulations allowed us to quantify the behavior of each sub-system, showing whether requirements of the production line can be satisfied or not. The model showed the relevance of the analysis, which will be decisive to make any changes to the plant configuration. By adopting this method it was possible to identify the most critical machines/items under the reliability and availability point of view. The MTBF indicator addressed the optimal scheduling of preventive maintenance with the benefits that maintenance works can be performed by means of specific time intervals on the most critical machines of the industrial plant provided by this study. In order to continue our research activity for this real industrial case, further analysis through FMECA, Failure Modes, Effects and Criticality Analysis, of the most critical blocks, i.e. the Volumetric Divider and the Baking Oven, will be planned in order to understand if and how it is possible to isolate the failure causes and to limit the stops. In this way the implementation of a detailed FMECA will allow to quantify the severity of each failure mode effects and, therefore, to classify them according to a quantitative index.

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