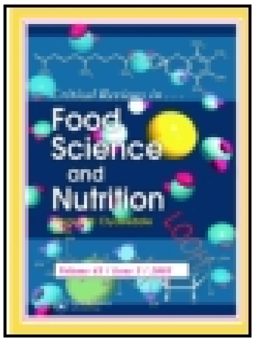


Taylor & Francis
Taylor & Francis Group

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: https://www.tandfonline.com/loi/bfsn20

Reliability and Maintainability Analysis of Bread Production Line

Panagiotis H. Tsarouhas & Ioannis S. Arvanitoyannis

To cite this article: Panagiotis H. Tsarouhas & Ioannis S. Arvanitoyannis (2010) Reliability and Maintainability Analysis of Bread Production Line, Critical Reviews in Food Science and Nutrition, 50:4, 327-343, DOI: 10.1080/10408390802544488

To link to this article: https://doi.org/10.1080/10408390802544488

Published online: 17 Mar 2010.

Critical Reviews in Food Science and Nutrition, 50:327–343 (2010)

ISSN: 1040-8398
DOI: 10.1080/10408390802544488

Taylor & Francis
Taylor & Francis Group

Reliability and Maintainability Analysis of Bread Production Line

PANAGIOTIS H. TSAROUHAS[1] and IOANNIS S. ARVANITOYANNIS[2]

[1]Alexander Technological Educational Institute of Thessaloniki, Department of Standardization and Transportation of Products - Logistics, Hellas (Greece)

[2]University of Thessaly, School of Agricultural Sciences, Department of Agriculture Ichthyology and Aquatic Environment, Hellas (Greece)

The statistical analysis of the bread production line of the failure and repair data at machine and line levels was displayed. The experiment covers a period of twenty-five months. The best fit of the failure data between the common theoretical distributions was found and its parameters were computed. The reliability and hazard rate modes for all machines and the entire production line were calculated as well. The models could prove to be a useful tool to assess the current conditions, and to predict the reliability for upgrading the maintenance policy of the production line. It was pointed out that (a) the availability of the bread production line is 90.74% and went down to 86.76% because the equipment's failures cause an additional production gap in the line, (b) the 53.5% of all failures occurred at the bread machine, cooling tower machine, and volumetric-divider machine, and (c) the machines of the bread production line that displayed increasing hazard rate functions were identified. This analysis will be very useful in terms of identifying the occurring and latent problems in manufacturing process of bread and improve it.

Keywords Reliability, maintainability, quality, bread production line, statistical analysis, failure and repair data

INTRODUCTION

The change of market and the explosion of product variety have led to increased automation and the need for complex equipment. Therefore, the reliability and the maintainability of the equipment play an important role in controlling both the quantity, and quality of the products. Quality improvement means elimination of waste products such as scrap material and rework thereby increasing productivity and leading to cost reductions. Groenevelt et al. (1992) studied the effect of machine breakdowns and corrective maintenance on economic lot size decisions. Ben-Daya and Duffuaa (1995) highlighted the relationship between maintenance and quality, stressed its importance, and proposed a broad framework for modelling the maintenance-quality relationship. Montgomery (1985) referred to the link between quality improvement and productivity. The study by Seifoddini and Djassemi (2001) observed that the impact of delays due to machine breakdowns is not limited to the production rate of the part only, but affects the scheduling and the productivity of the entire manufacturing operations.

The literature on field failure data of production lines is quite scarce. Inman (1999) presented four weeks of actual production data from two automotive body-welding lines. His aim was to reveal the nature of randomness in realistic problems and to assess the validity of exponential and independence assumptions for service times, inter-arrival times, cycles between failures, and times to repair. Barabady (2005) showed a preliminary study analysis on the Time between Failures (TBF) data of the crushing plant number 1 and number 2 at the Jajarm Bauxite Mine of Iran. The results of the study were useful for a better understanding of failures patterns that influenced the decision-making process concerning the planning of operation and maintenance activities of the plant. Diallo et al. (2001) carried out a reliability analysis of the individual machines and manufacturing system states in the presence of unreliable machines, and proposed an approach to design manufacturing cells which can change process plans to handle machine breakdowns. Jones and Hayes (1997) presented a methodology to collect field reliability data and analysis for identifying problems in manufacturing, design, and screening. Wang et al. (1999) described

Address correspondence to Ioannis S. Arvanitoyannis (Dr, Ph.D.), Associate Professor, University of Thessaly, School of Agricultural Sciences, Department of Agriculture, Ichthyology and Aquatic Environment, Fytoko Street, 38446 Nea Ionia Magnesias, Volos, Hellas (Greece). E-mail: parmenion@uth.gr

the failure analysis of computerized numerical control (CNC) lathes; the field failure data was collected over a period of two years on approximately 80 CNC lathes.

In the food industry when a failure occurs, the failed machine is constrained to stop, thus forcing most of the machines upstream of the failure to operate without producing (a gap in the productivity of the line). In addition, if the failure is rather long, it may cause an additional gap in the production line. Therefore, some or all of the work-in-process material downstream of the failed machine may be scrapped because of quality deterioration during the disruption. Liberopoulos and Tsarouhas (2002) presented a case study of speeding up a croissant production line by inserting an in-process buffer into the middle of the line to absorb some of the downtime, based on the simplified assumption that the failure and repair times of the workstations of the lines have exponential distributions. The parameters of these distributions were computed based on actual data collected over ten months. Liberopoulos and Tsarouhas (2005) also studied the statistical analysis of failure data of an automated pizza production line, covering a period of four years, computing the most important descriptive statistics of the failure data, and investigated the existence of auto-correlations and cross-correlations in the failure data.

In this manuscript a statistical analysis of the field of failure and repair data for a bread production line was performed. The descriptive statistics of data was performed and the parameters of the Weibull distribution that have the best index of fit among the theoretical distributions were estimated. Moreover, the reliability and hazard rate modes for all machines and the entire production line that can be a useful tool to assess the current condition, and to predict the reliability for upgrading the maintenance policy of the production line were calculated. The collection and analysis from the actual data of the line is extended over a period of twenty-five months. Therefore, this manuscript is anticipated to serve as a valid data source for food product machinery manufacturers, who wish to improve the design and operation of their production lines.

The rest of this paper is organized as follows: a) in Section 2, the production process of the bread production line was described, b) in Section 3, the failure field data were displayed, c) the most important descriptive statistics of the failure and repair data for all machines and in the entire line were presented in Section 4, d) in Section 5, the Reliability and Maintainability of the line were analysed, e) in Section 6, the Reliability and hazard rate models were estimated, and finally, f) the conclusions were drawn in Section 7.

DESCRIPTION OF AN AUTOMATED BREAD PROCESSING LINE

An automated bread 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. Tsarouhas (2009) described the bread production line and separated it in six distinct stages (Fig. 1)— kneading, forming, proofing cell, baking, cool down, and wrapping. Each stage corresponds to one workstation; the process flow of a bread production line is as follows:

In workstation 1, flour from the silo and water are automatically fed into the removable bowl of the spiral mixer machine. Additional ingredients such as salt and yeast are added manually in small quantities. Mixing and kneading take place on a two-speed gear. In the first gear, mixing of the dough with an ingredient is completed in five minutes, while in the second gear, kneading is completed in ten minutes. After the dough has been kneaded, the bowl is manually unloaded from the spiral machine and loaded onto the elevator-tipping device which is a hydraulic system that lifts the spiral mixer for dough discharge in the inlet funnel of the volumetric divider in the next workstation.

In workstation 2, the dough is fed into the volumetric divider which is cut and divided in same weight pieces, and then automatically fed into a conical rounder machine which does the partial rounding of the dough. The rounding is done with rotation on an aluminium Teflon cone, when the cone turns; it rounds the dough moving it in the helicon channels to the top where it is dropped out through the scoop. An additional moulding of the dough is carried out in the bread machine and the product takes the adequate bread loaves shape. The entire process is fully automated. At the exit of the bread machine, the loaves are laid onto metal baking pans that are automatically fed to the next workstation.

In workstation 3, the baking pans are automatically pushed into the proofing cell, where they remain under uniform temperature and humidity conditions for a precise amount of time as the loaves rise to their final size.

In workstation 4, the baking pans are automatically unloaded from the proofing cell and are placed onto a metal conveyor belt that passes through the oven. The trays remain in the oven for a precise amount of time until the loaves are fully baked.

In workstation 5, the baking pans are collated together and fed into the cool down machine entrance. As soon as they enter the cool down, they are moved onto the stabilized trays by means of a pusher bar. The trays are automatically transported inside the cool down machine by conveyors and paternoster type lifts in order for the loaves to cool down for a certain time and stabilize. The baking pans are pushed off the stabilized trays onto the out-feed belt and are automatically transported out of the cool down machine.

In workstation 6, the loaves are automatically lifted from the baking pans and are flow-packed and sealed by a horizontal, electronic wrapping machine. The empty pans are automatically returned to the bread machine. The final products that exit from the bread processing line are loaded onto a conveyor belt. From there, they are picked up by a robot system and put in cartons. The filled cartons are placed on a different conveyor belt that takes them to a worker who stacks them onto palettes and transfers them to the finished-goods warehouse.

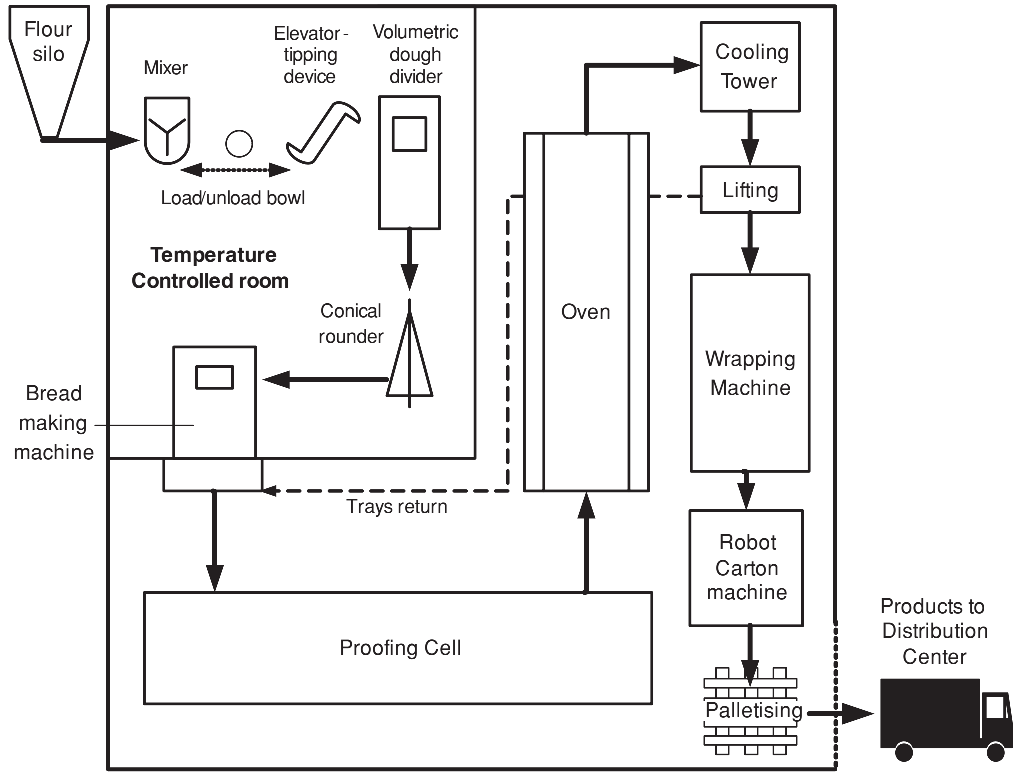


Figure 1 System block diagram of bread production line.

In this paper the following notation to distinguish among the different levels of failures in the production line was employed (Liberopoulos and Tsarouhas, 2005):

$WS.i$ = Workstation i,
$M.i.j$ = Machine j of workstation i.

Using the above notation, the workstations and machines of the bread production line are shown in Fig. 2.

The cycle time per bread at the machine or workstation level is indicated below the machine or workstation name. This time equals the capacity of the particular machine or workstation divided by the nominal production rate of the line, according to Little's formulas (1961) in Queueing Theory. Thus, the calculation of the cycle time for the entire line is as follows: $CT_{Line} = \sum_{i=1}^{6} WS_i = 210\ min$ or 3 hours and 30 minutes.

FAILURE FIELD DATA

The bread production line operates in three eight-hour shifts during each workday, including weekends seven days per week with no pauses. The maintenance policy that is used is corrective maintenance. When a failure occurs, the maintenance staff that is responsible for the proper operation of the line performs the necessary corrective maintenance operations to repair the failure. Corrective maintenance comprises actions taken to restore a failed component or machine to the operational state. The actions involve repair or replacement of all failed components necessary for successful operation of the production line. Corrective maintenance actions are unscheduled actions intended to restore the line from a failed state into a working state. The maintenance staff (mechanics and electricians) is also responsible for keeping hand-written records of the failures per shift.

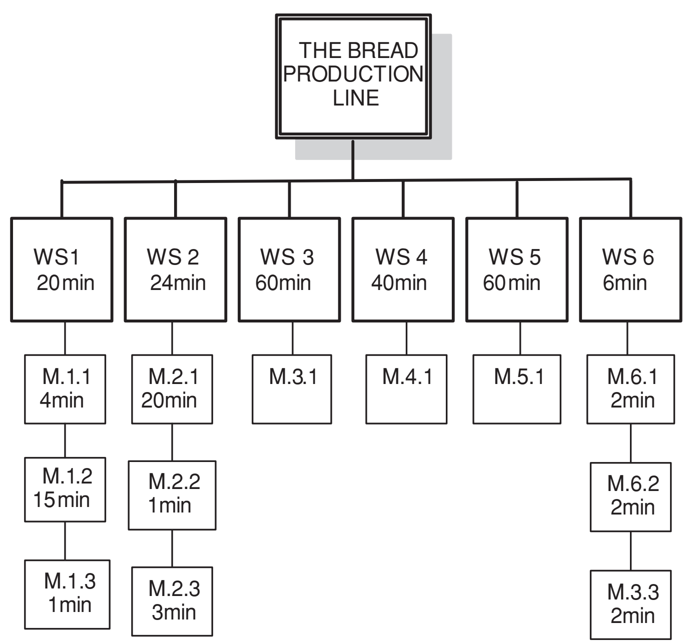


Figure 2 Workstations and machines of bread production line.

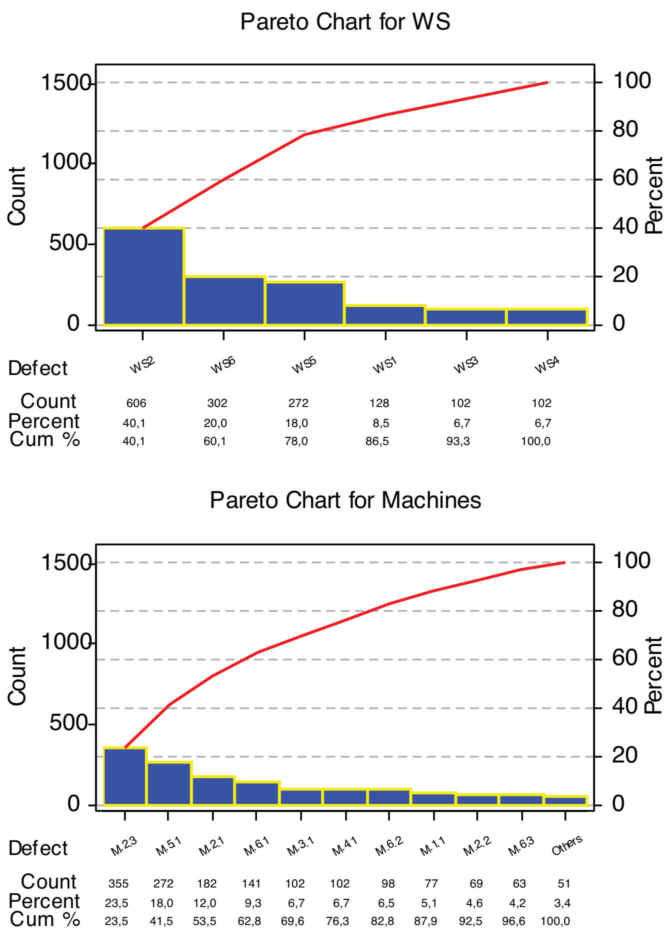


Figure 3 Pareto diagrams for the failures of bread production line at work-station and machine levels.

The field data of 1512 failures recorded of the maintenance staff of the bread production line for a period of 767 continuous working days (two years) were analysed. The records included the failures that had occurred per shift, the action taken to repair the failure, the down time, and the exact time of failure. In the control panel of each machine there is a counter that counts the time whenever the machine is in function. When the machine is down, due to a failure, then the counter stops and starts to recount automatically when the machine is up. Therefore, one can have the exact time that the machine fails and the exact time between failures. This means that the precision in computing the time to failure (TTF) of a failure for machine and the entire line itself is in the order of hours. The time to repair (TTR) a failure, on the other hand, was recorded in minutes. From the records, we counted a total of 1512 failures for the entire line, confirming the data recorded by the maintenance staff.

The TTF of the equipment is defined as the time that elapses from the moment the equipment goes up and starts operation after a failure, until the moment it goes down again and stops operation due to a new failure. The TTR of the failed equipment was defined as the time that elapses from the moment the equipment stops functioning and stops until the moment it starts operating again.

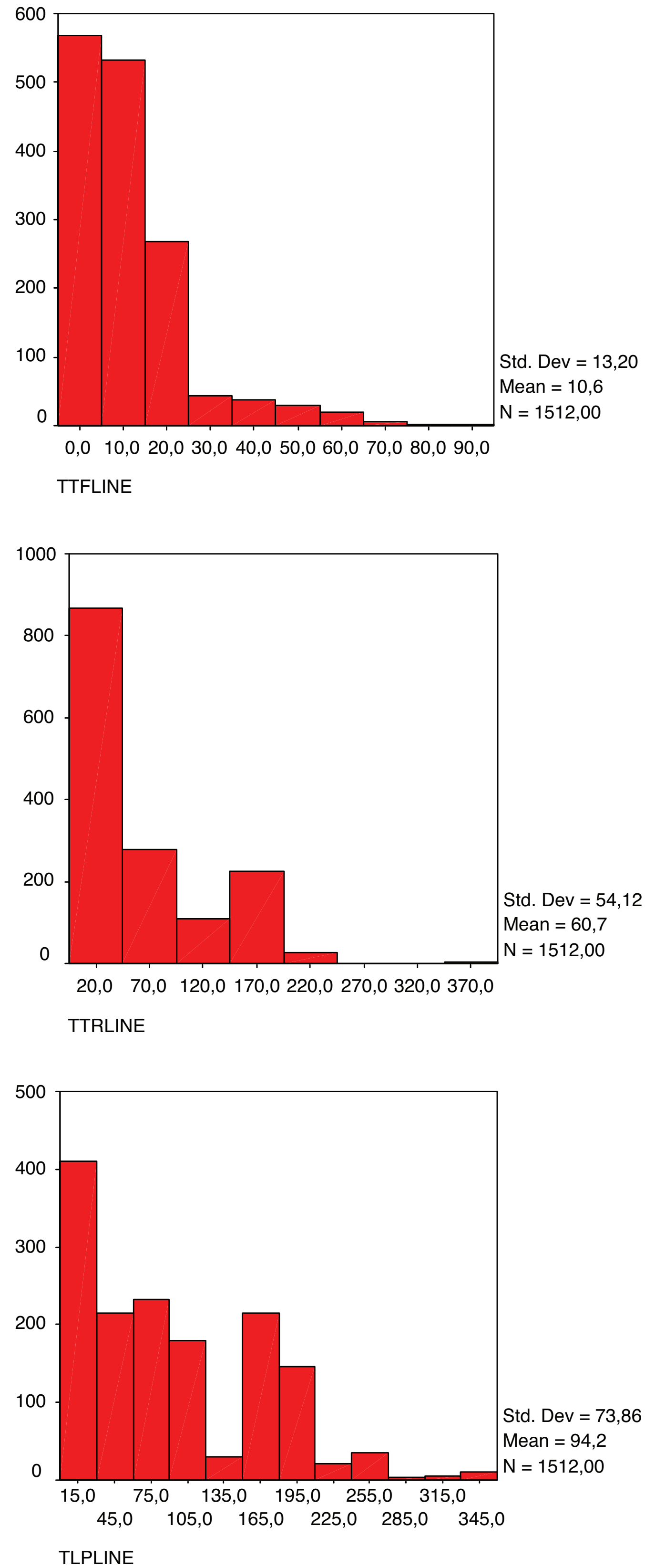


Figure 4 Histograms of TTF, TTR and TLP for bread production at line level.

Table 1 Computation of TLP at different parts of the bread production line

IF	THEN
TTR(M.1.2) > 50	TLP(M.1.2) = TTR(M.1.2) + 15 (scrap material in M.1.2)
TTR(M.1.3) > 50	TLP(M.1.3) = TTR(M.1.3) + 15+1 (scrap material in M.1.2 and M.1.3)
TTR(M.2.1) > 50	TLP(M.2.1) = TTR(M.2.1) + 15 +1 + 20 (scrap material in M.1.2- M.2.1)
TTR(M.2.2) > 50	TLP(M.2.2) = TTR(M.2.2) + 15 +1 + 20 +1 (scrap material in M.1.2-M.2.2)
TTR(M.2.3) > 50	TLP(M.2.3) = TTR(M.2.3) + 15 +1 + 20 +1 +3 (scrap material in M.1.2-M.2.3)
TTR(M.3.1) > 50	TLP(M.3.1) = TTR(M.3.1) + 15 +1 + 20 +1 +3 +60 (scrap material in M.1.2- M.3.1)
5 < TTR(WS.4) < 10	TLP(WS.4) = TTR(WS.4) + [TTR(WS.4) – 5] (reheat oven)
10 < TTR(WS.4) < 60	TLP(WS.4) = TTR(WS.4) + [TTR(WS.4) – 5] + 15 +1 + 20 +1 +3 + 60 +40 (reheat oven and scrap material in M.1.2-M.4.1)
TTR(WS.4) > 60	TLP(WS.4) = TTR(WS.4) + 60 +15 +1 + 20 +1 +3 +60 +40 (reheat oven and scrap material in M.1.2-M.4.1)
TTR(WS.5) > 50	TLP(WS.5) = TTR(WS.5) +15 +1 + 20 +1 +3 +60 +40 (scrap material in M.1.2 - M.4.1 and manually unload material after WS.4 in order not to block the line)
TTR(WS.6) > 50	TLP(WS.6) = TTR(WS.6) + 15 +1 + 20 +1 +3 +60 +40 (scrap material in M.1.2 - M.4.1 and manually unload material after WS.5 in order not to block the line)
Otherwise	TLP(X) = TTR(X), where X is any workstation or machine.

In Fig. 3, the Pareto's diagrams for all failures presented in a bread production line at each machine and workstation are displayed. The following observations were made at workstation level—(a) the workstation for forming of bread (WS_2) has the highest number of failures 40.1%. (b) Equally important is the workstation for wrapping (WS_6) that has 20% of failures. Whereas at machine level we remark that the bread machine (M.2.3), the cooling tower machine (M.5.1), and the volumetric-divider machine (M.2.1) stood for the 53.5% of all the failures.

According to Liberopoulos and Tsarouhas (2005), if the failure is sufficiently long, an additional production gap follows upstream of the failure, because some or all of the in-process material upstream of the failure will have to be scrapped due to quality defect over the stoppage. The most important type of quality defect in bread and bakery products manufacturing is the rise of dough. For the bread production under study, the maximum acceptable standstill time is 50 minutes. Thus, the total gap in production caused by a failure called time of lost production (TLP) is equal to the TTR of the failure plus the total processing time of the material that is scrapped downstream of the failure, if the TTR of the failure is greater than 50 minutes. In Fig. 4, the histograms of failure and repair data for TTF, TTR and TLP at line level were shown. The histograms arise from grouping the failure and repair times into classes and plotting the frequency of observations per class versus the interval times of each class. Both TTF and TTR have the Weibull distribution shape whereas the TLP has a double-peak. This is obvious, because when TTR >50 min, then TLP = TTR + extra time of scrapped material (see Table 1). Moreover, from Table 1 it can be concluded that if TTR(WS_4) is greater than 60 minutes, then the extra time required to reheat the oven is exactly 60 minutes. However, the extra time required to reheat the oven is exactly 60 minutes. In this case, the TLP(WS_4) becomes TTR(WS_4)+ 60 + time of scraped material. If TTR(WS_4) lies between 10 and 60 minutes, the extra time to reheat the oven is roughly equal to TTR(WS_4) – 5. In this case, the TLP(WS_4) becomes TTR(WS_4)+ [TTR(WS_4) – 5] + time of scraped material. If the TTR(WS_4) amounts to less than 10 minutes, no extra time of the scrapped material is required.

DESCRIPTIVE STATISTICS OF THE FAILURE AND REPAIR DATA

In this section the Descriptive Statistics of the basic features of the failure and repair data for TTF, TTR, and TLP are presented in order to obtain qualitative and quantitative analysis of the failure data for the bread production line. Thus, it is possible to extract the minimum and the maximum value of the sample, mean, standard deviation (SD), coefficient of variation (CV), skewness and kurtosis of the failure data at machines, and the entire line level. The standard deviation of the random variable is defined as the square root of the variance, and is often used in place of the variance to describe the distribution spread. Since the coefficient of variation of a random variable is defined as the ratio of the standard deviation over the mean of the random variable, it is a dimensionless measure of the variability of the random variable. Moreover, the steady–state availability and efficiency are defined as follows:

$$\text{Availability} = \text{mean TTF}/(\text{mean TTF} + \text{mean TTR}) \tag{1}$$

$$\text{Efficiency} = \text{mean TTF}/(\text{mean TTF} + \text{mean TLP}) \tag{2}$$

Table 2 Descriptive statistics of the TTF at machine and line levels

	N	Min	Max	Mean	SD	CV	Skewness	Kurtosis
TTF M.1.1	77	1	312	110.1429	95.7733	0.8695	0.5967	−0.8814
TTF M.1.2	49	1	680	239.5306	186.8238	0.7800	0.7245	−0.3662
TTF M.1.3	2	1	8	4.5000	—	—	—	—
TTF M.2.1	182	1	272	62.3352	67.6319	1.0850	1.4177	1.0980
TTF M.2.2	69	1	256	63.6667	61.1374	0.9603	1.2192	1.2018
TTF M.2.3	355	1	200	37.2592	42.0456	1.1285	1.6948	2.5150
TTF M.3.1	102	1	400	120.1667	97.3412	0.8101	0.7289	−0.3821
TTF M.4.1	102	1	350	94.8333	86.6571	0.9138	1.2484	1.0244
TTF M.5.1	272	1	358	50.8272	63.6993	1.2533	2.5674	7.5129
TTF M.6.1	141	1	320	80.1773	74.1741	0.9251	1.3093	1.2691
TTF M.6.2	98	1	462	66.0510	88.2324	1.3358	3.7694	14.7644
TTF M.6.3	63	1	200	58.1429	50.6722	0.8715	1.0635	0.3375
TTF LINE	1512	1	88	10.6118	13.2040	1.2443	2.2888	6.0792

Table 3 Descriptive statistics of the TTR at machine and line levels

	N	Min	Max	Mean	SD	CV	Skewness	Kurtosis	Availability
TTR M.1.1	77	15	360	48.8961	58.0700	1.1876	4.2257	20.5170	0.9927
TTR M.1.2	49	15	50	26.1224	8.0536	0.3083	1.3648	2.7708	0.9982
TTR M.1.3	2	20	20	20.0000					1.0000
TTR M.2.1	182	15	210	43.7363	22.6868	0.5187	3.4929	19.4812	0.9885
TTR M.2.2	69	15	150	39.8551	19.9073	0.4995	2.6654	12.6511	0.9898
TTR M.2.3	355	15	210	43.1690	24.4464	0.5663	3.7001	20.2270	0.9808
TTR M.3.1	102	10	70	31.0784	11.0047	0.3541	1.3739	3.0691	0.9957
TTR M.4.1	102	15	180	33.1373	37.3233	1.1263	2.7948	6.8495	0.9939
TTR M.5.1	272	10	200	25.8824	22.6344	0.8745	5.4365	37.5672	0.9915
TTR M.6.1	141	10	120	29.9645	20.9634	0.6996	2.5285	7.6839	0.9938
TTR M.6.2	98	15	80	35.3061	19.8034	0.5609	0.9740	−0.2078	0.9888
TTR M.6.3	63	10	180	37.4603	29.7825	0.7950	2.7939	10.2017	0.9895
TTR LINE	1512	10	360	60.7110	54.1199	0.8914	1.1921	0.6216	0.9074

From Table 2 the following observations were made—(a) in the bread production line the mean TTF is 10.6118 hours, meaning that every 10.6118 hours a failure occurs in the production line. (b) The CV at line level is greater than one, meaning that the TTF have high variability. The machines with the major variability that have CV greater than one are the mixer (M.2.1), the bread making machine (M.2.3), the cooling tower machine (M.5.1), and the wrapping machine (M.6.2). The rest of the machines have low variability, CV less than one. (c) All the machines are positively skewed, meaning that the TTFs have mode < median < mean. The same is valid at line level. (d) Since the sample size of failures at the elevator–tipping machine (M1.3) is quite small, the implication is that there is not enough data to compute TTF.

Table 3 shows the following—(a) in the bread production line the mean TTR is 60.7110 minutes, with low variability because the line CV is less than one. Therefore, it is positively skewed and the availability of the line is equal to 90.74%. (b) All the machines have highest availabilities, besides the volumetric–divider machine (M.2.1), the conical rounder machine (M.2.2), the bread making machine (M.2.3), the wrapping machine (M.6.2), and the robot carton machine (M.6.3) that have 98.85%, 98.98%, 98.08%, 98.88%, and 98.95%, respectively. (c) All the machines have low variability with CV less than one. The flour silo machine (M.1.1) and the oven (M.4.1) have high variability with CV greater than one, and (d) the TTF of the production line for all machines were positively skewed.

In the case of Table 4—(a) the genuine efficiency of the bread production line is 86.78%, the mean TTR from 60.7110 minutes becomes 94.1501 minutes due to scrap of material in machines of the line. Moreover, the line exhibits low variability because the CV is less than one. (b) About half the machines that is the mixer (M.1.2), the volumetric–divider machine (M.2.1), the conical rounder machine (M.2.2), the bread making machine (M.2.3), and the proofing cell machine (M.3.1) show low variability, because the CVs are less than one. The rest of the machines have CVs greater than one. (c) The machines that have low efficiency are—the volumetric–divider machine (M.2.1), the conical rounder machine (M.2.2), the oven (M.4.1), the cooling tower machine (M.5.1), the wrapping machine (M.6.2) and the robot carton machine (M.6.3) with 98.57%, 98.74%, 98.94%, 98.85%, 97.55%, and 98.20%, respectively. (d) All machines of the bread production line are positively skewed for TLP.

Table 4 Descriptive statistics of the TLP at machine and line levels

	N	Min	Max	Mean	SD	CV	Skewness	Kurtosis	Efficiency
TLP M.1.1	77	15	365	50.2597	59.6585	1.1870	4.0548	19.1470	0.9925
TLP M.1.2	49	15	75	37.8571	19.4722	0.5144	0.3026	−1.5024	0.9974
TLP M.1.3	2	20	20	20.0000					1.0000
TLP M.2.1	182	15	245	54.5055	36.1286	0.6628	1.7212	4.2406	0.9857
TLP M.2.2	69	9	187	49.3043	34.3230	0.6961	1.4766	2.2969	0.9874
TLP M.2.3	355	15	250	55.2254	39.3604	0.7127	1.8006	4.5105	0.9755
TLP M.3.1	102	10	170	40.8824	38.8282	0.9498	2.6220	5.3843	0.9944
TLP M.4.1	102	15	380	57.9412	100.1147	1.7279	2.4390	4.2772	0.9894
TLP M.5.1	272	10	340	35.1471	53.4646	1.5212	3.8298	14.8032	0.9885
TLP M.6.1	141	10	260	44.8582	61.2954	1.3664	2.5783	5.1935	0.9907
TLP M.6.2	98	15	220	78.1633	83.1264	1.0635	0.8598	−1.2332	0.9755
TLP M.6.3	63	10	723	64.9841	92.5008	1.4234	5.9981	42.4392	0.9820
TLP LINE	1512	10	400	94.1501	73.8610	0.7845	1.0399	1.0295	0.8676

RELIABILITY AND MAINTAINABILITY ANALYSIS OF PRODUCTION LINE

The bread production line, as mentioned above, exhibits availability and efficiency, 90.74% and 86.78%, respectively. In the production time there are 20 minutes break per shift, thereby allowing all the workers to move out of the line. Thus, there are 3 shifts per day*20 min per shift = 60 min per day. This means that one hour per day is spent for the break of the workers, thereby causing finally an additional 4.16% gap in the production rate of the line. Therefore, the actual production rate of the line becomes 86.78% − 4.16% = 82.62%. It is well known that a production line is profitable when the production rate is up to 85%. The bread production line under study is found to operate negatively.

To avoid the erroneous operation of bread line, the actual production rate of the line may increase. There are four ways to increase the actual production rate of the line—(1) increase the processing rates of the workstations, starting with the slowest; (2) reduce the impact of failures; (3) reduce the frequency of failures; and (4) reduce the duration of failures (Buzacott and Shanthikumar, 1993; Gershwin, 1994). The first approach requires re-engineering of the line, which is very difficult to apply to the already existing equipment and the oven must be replaced because it is the bottleneck of the line. The second approach required buffers in series between the machines that may increase the line availability. However, this approach is responsible for serious technical and technological problems i.e. appropriate space for installing buffers in the existing line, the capacity, and the dimensions of the buffers, the products do not survive over a long time without processing etc. Therefore, in the food production line and, especially, in bakery products no production line exists in buffer machines.

The last two approaches are determined by a good operation practice (GOP). Both approaches standing for as necessary steps towards the overall system improvement were considered. The main objective was to reduce the downtimes of line by prolonging the TTF and accelerating the repair time.

In Figs. 5 and 6, the survival functions and the hazard functions for TTF from machine and line levels were presented. The hazard rate functions at the entire line, the mixer (M.1.2), the cooling tower machine (M.5.1), the lifting machine (M.6.1), the wrapping machine (M.6.2) and the robot carton machine (M.6.3) were shown to increase. Therefore, the probability of failure is relatively high, for an extended period of time. This means that the current maintenance policy is not adequate for those machines and for the entire line. The rest of the machines displayed decreasing failure rate.

To predict reliability and maintainability for bread production line at machine, and line level, one has to analyze the failure and repair data in order to estimate the failure and repair distribution. To identify the distributions of TTF and TTR, at all levels, several candidate theoretical distributions (Weibull, Normal, Exponential and Lognormal distributions) are fitted. Each candidate

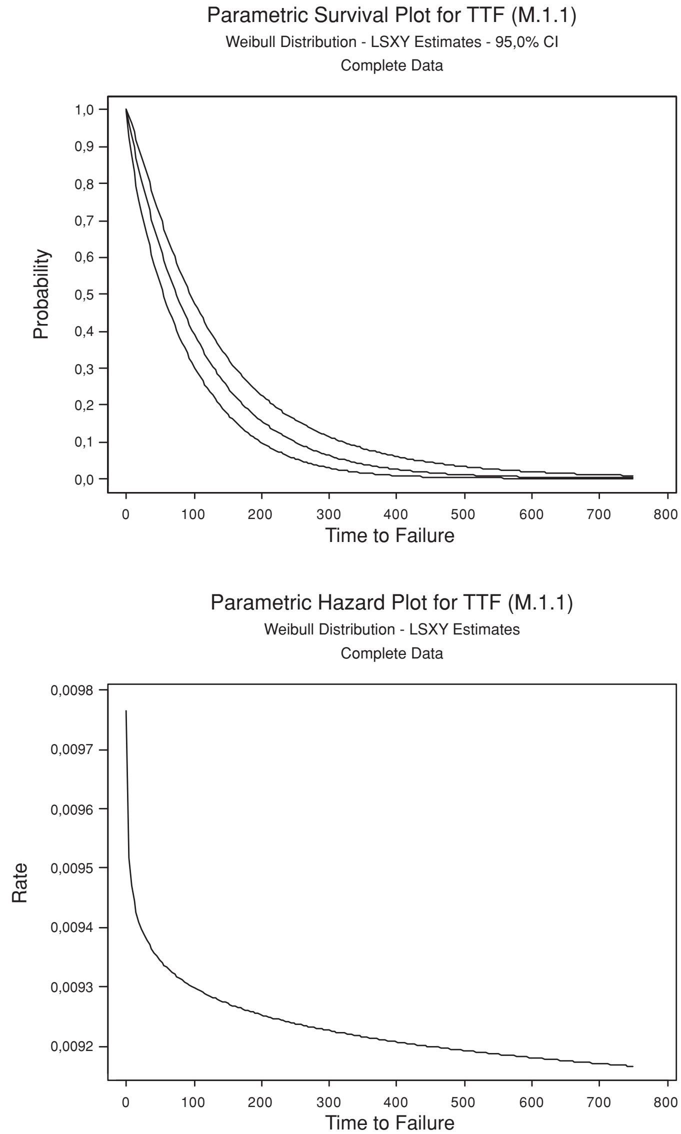


Figure 5 Survival functions and Hazard functions from M.1.1- M.6.3. *(Continued)*

distribution was analyzed by means of a least squares fit and estimated its parameters and performed a goodness of fit test. In Fig. 8, the identification of best fit of TTF and TTR for several theoretical distributions from failure data at machines and line levels was made. It was found that the best fit from the failure data is the Weibull distribution. The parameters of the Weibull distribution are shape (β) and scale (θ). The scale parameter of the Weibull distribution influences considerably both the mean and spread of the distribution. Moreover, it is called the characteristic life and it has units identical to those of TTF (or TTR). The parameter θ is equal to the duration of useful time t that is the 2/3 of failures approximately will have occurred at the machine or the entire line (or equivalent for TTR that is the 2/3 of failures approximately will have been repaired at the machine or the entire line).

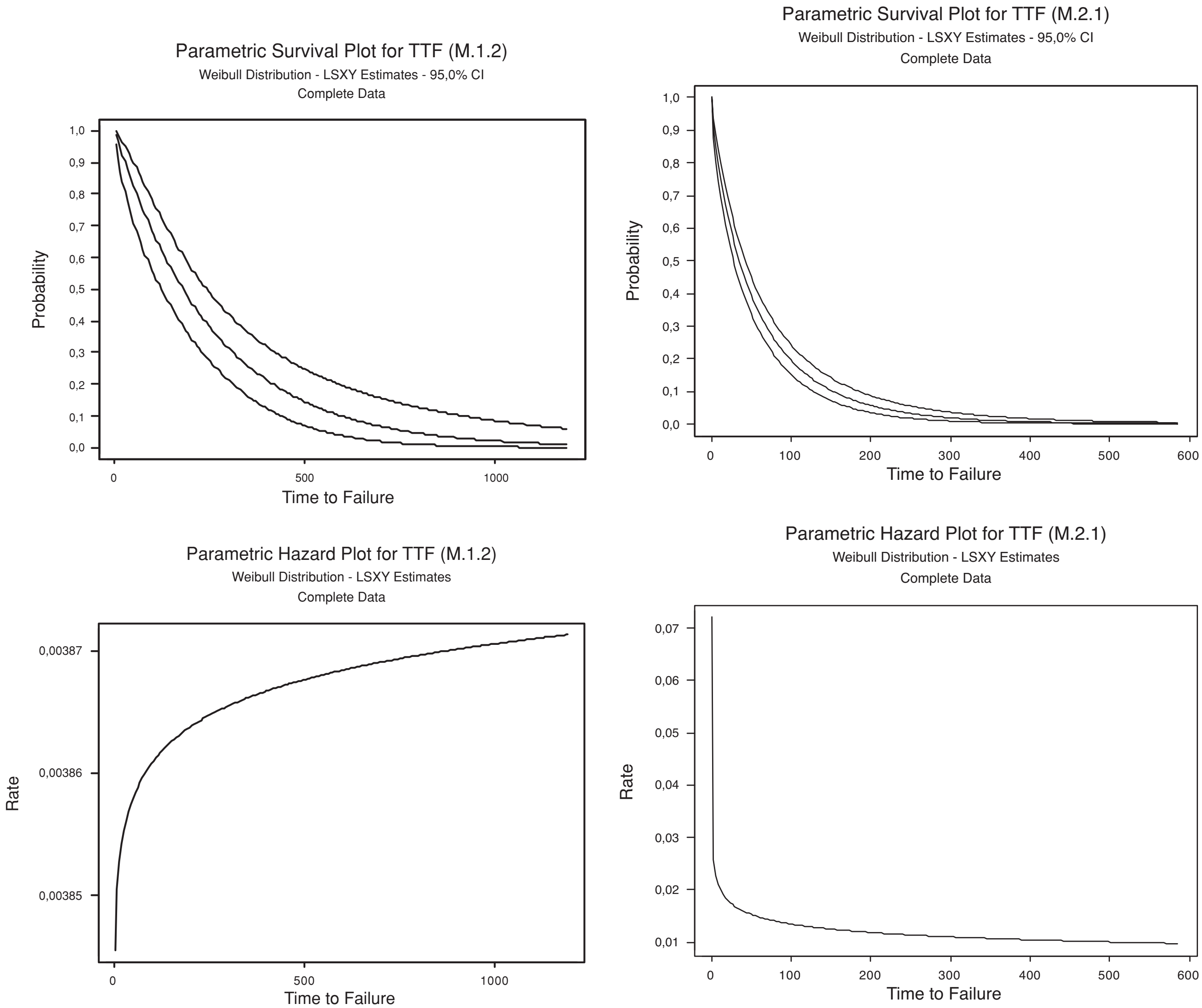


Figure 5 (Continued)

The parameters of the Weibull distribution for the TTF and TTR at machine, and line levels are summarized in Table 5. The scale and shape were estimated using the least squares method. The index of fit is defined as the upper bound of the Kolmogorov-Smirnov goodness-of-fit statistic, i.e. the maximum deviation between the observed cumulative distribution function and the candidate theoretical distribution. When the index of fit is below 1.2 it is an indication of a very good fit.

From Table 5 it is perceived that—(a) the shape parameter of Weibull distribution at line level is $\beta = 1.1158$, implying that there is an increasing failure rate. Therefore, the probability for a failure to occur by next time is high enough. (b) The same phenomenon is observed at machines M.1.2, M.5.1, M.6.1, M.6.2 and M.6.3 with shape parameters 1.0235, 1.0443, 1.0191, 1.2110, and 1.0403 respectively. (c) For TTR the shape parameter of Weibull distribution of all the machines and the production line for TTR is higher than one implying that the repair rates are increasing, due to the fact that the maintenance technicians

Table 5 Weibull parameters for TTF and TTR for all machines and entire line

	TTF			TTR		
Level	Scale Parameter θ	Shape Parameter β	Index of fit	Scale Parameter θ	Shape Parameter β	Index of fit
M.1.1	107.1330	0.9833	0.090	51.5945	1.4956	0.200
M.1.2	259.6345	1.0235	0.070	28.9715	3.6793	0.060
M.1.3	—	—	—	—	—	—
M.2.1	54.6625	0.8095	0.050	48.7192	2.7681	0.100
M.2.2	60.3035	0.8001	0.080	44.5012	2.6431	0.100
M.2.3	31.8594	0.8803	0.050	47.9858	2.6439	0.090
M.3.1	126.6890	0.9751	0.060	34.4610	3.3691	0.120
M.4.1	95.6222	0.9145	0.050	35.5764	1.2860	0.200
M.5.1	45.6595	1.0443	0.050	28.4982	1.9459	0.150
M.6.1	80.0858	1.0191	0.020	33.1954	1.9806	0.070
M.6.2	64.1261	1.2110	0.100	39.8594	2.0071	0.120
M.6.3	60.4131	1.0403	0.030	41.1353	1.7627	0.100
LINE	8.4157	1.1158	0.090	64.3615	1.2888	0.150

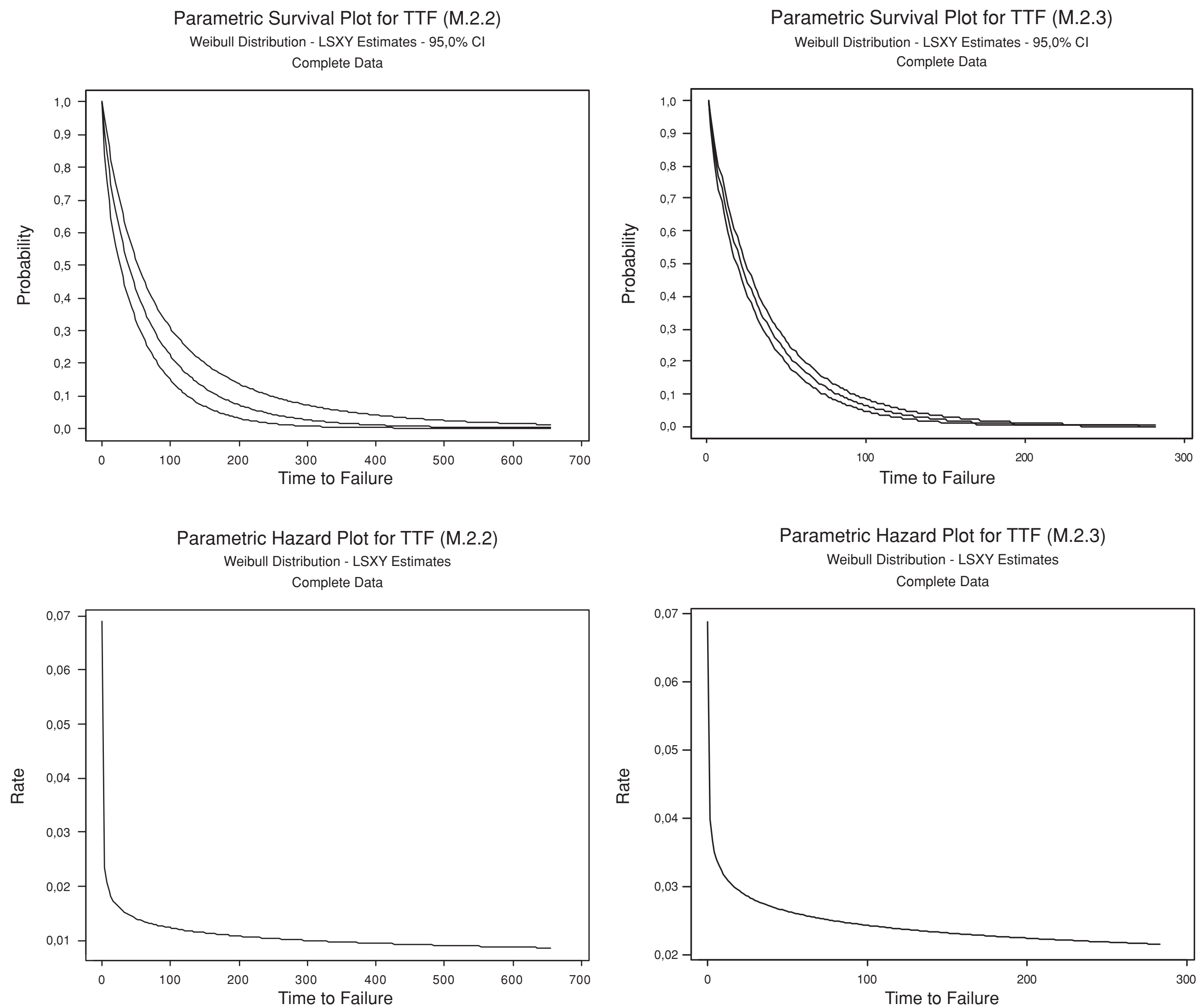


Figure 5 (Continued)

get more expertise with time and the TTR lowers (see also Fig. 7).

DETERMINATION OF RELIABILITY AND HAZARD RATE MODELS FOR THE PRODUCTION LINE

Reliability is the probability that the entire line will perform a required function, under stated operating conditions, for a given period of time. The bread production line as mentioned above consists of six workstations in series with a common transfer mechanism and automated control system. A series system will function if and only if all of its components are properly functioning. If a component failed then the machine comprising the component stops, and as a result the production line stops too. It is assumed that all machines are independent i.e. the failure of one machine does not affect the reliability of the other machines. Thus the operation of the production line is ensured only if all machines are operating:

$$R_{Line}(t) = \prod_{i} R_{WS_i}(t) = \prod_{i,j} R_{M_{i,j}}(t), \quad \text{for } i = 1, 2, \ldots 6, \quad j = 1, \ldots 3. \qquad (3)$$

The TTF of machines, workstations, and the entire production line are following the Weibull failure low, and then the reliability of the line is found from:

$$R_{Line}(t) = \prod_{i=i}^{6} \exp\left[-\left(\frac{t}{\theta_i}\right)^{\beta_i}\right] = \exp\left[-\sum_{i=1}^{6}\left(\frac{t}{\theta_i}\right)^{\beta_i}\right] \qquad (4)$$

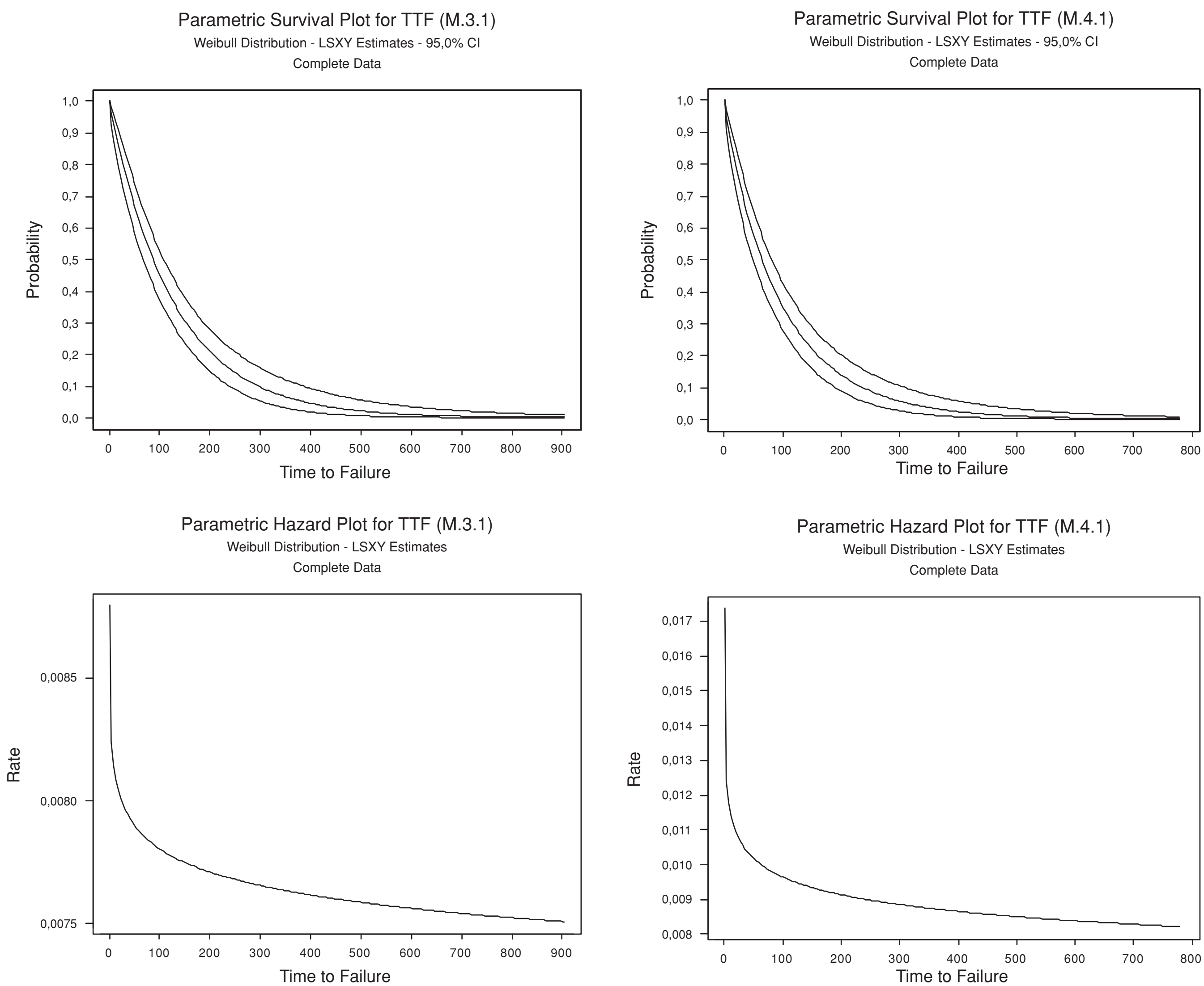


Figure 5 (Continued)

The hazard rate function of the production line is given by:

$$\lambda_{Line}(t) = \sum_{i=1}^{6} \frac{\beta_i}{\vartheta_i}\left(\frac{t}{\vartheta_i}\right)^{\beta_i - 1} \tag{5}$$

After having identified the failure distribution from data and the estimated the Weibull parameters (see Table 5) then, we can calculate the Reliability and hazard rate models for bread production line for all machines and the entire line can be calculated as follows:

$$R_{M1.1}(t) = \exp\left[-\left(\frac{t}{107.1330}\right)^{0.9833}\right],$$

$$\lambda_{M1.1}(t) = \left(\frac{0.9833}{107.1330}\right)\left(\frac{t}{107.1330}\right)^{0.9833-1} \tag{6}$$

$$R_{M1.2}(t) = \exp\left[-\left(\frac{t}{259.6345}\right)^{1.0235}\right],$$

$$\lambda_{M1.2}(t) = \left(\frac{1.0235}{259.6345}\right)\left(\frac{t}{259.6345}\right)^{1.0235-1} \tag{7}$$

$$R_{M2.1}(t) = \exp\left[-\left(\frac{t}{54.6625}\right)^{0.8095}\right],$$

$$\lambda_{M2.1}(t) = \left(\frac{0.8095}{54.6625}\right)\left(\frac{t}{54.6625}\right)^{0.8095-1} \tag{8}$$

$$R_{M2.2}(t) = \exp\left[-\left(\frac{t}{60.3035}\right)^{0.8001}\right],$$

$$\lambda_{M2.2}(t) = \left(\frac{0.8001}{60.3035}\right)\left(\frac{t}{60.3035}\right)^{0.8001-1} \tag{9}$$

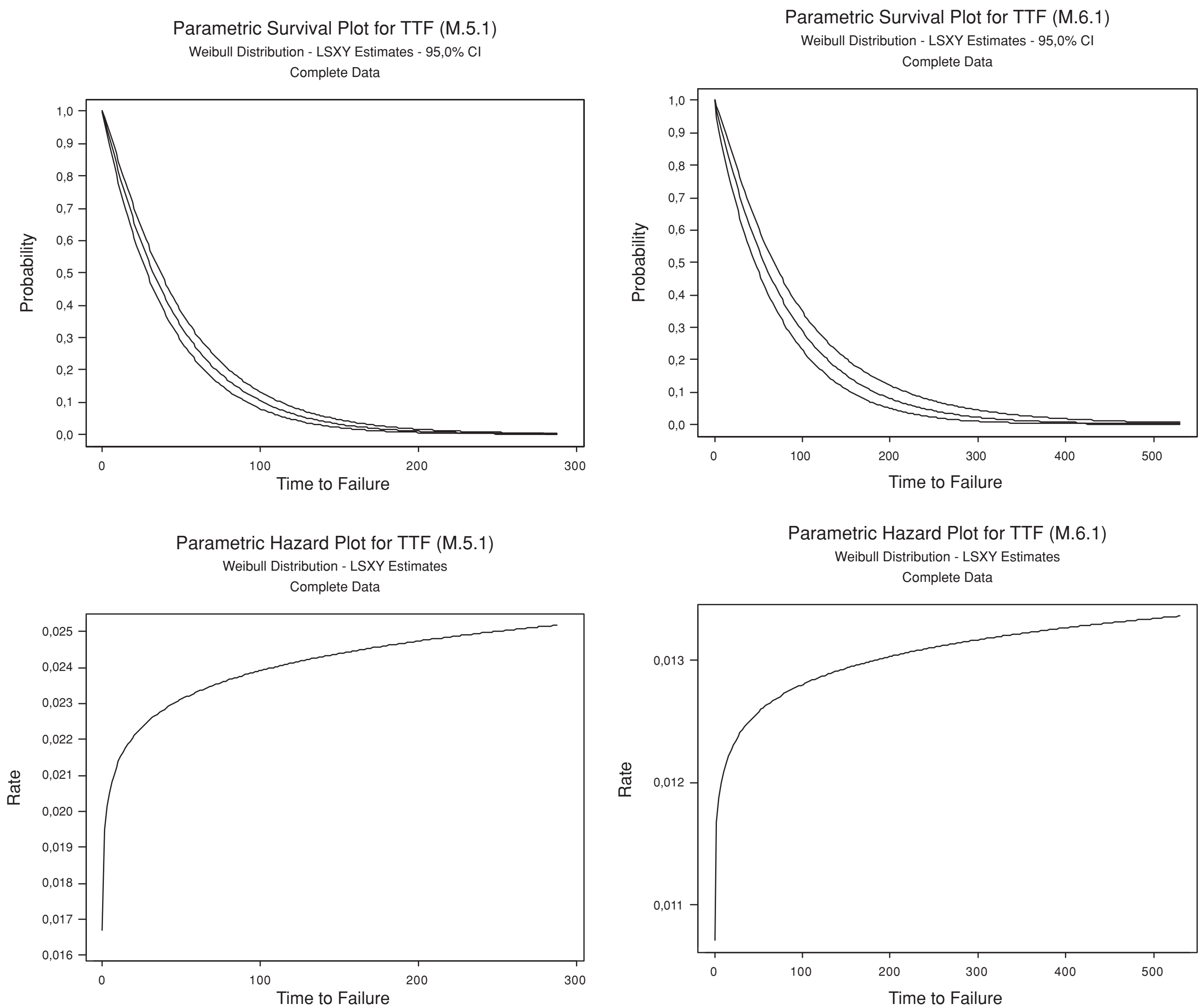


Figure 5 (Continued)

$$R_{M2.3}(t) = \exp\left[-\left(\frac{t}{31.8594}\right)^{0.8803}\right],$$

$$\lambda_{M2.3}(t) = \left(\frac{0.8803}{31.8594}\right)\left(\frac{t}{31.8594}\right)^{0.8803-1} \tag{10}$$

$$R_{M3.1}(t) = \exp\left[-\left(\frac{t}{126.6890}\right)^{0.9751}\right],$$

$$\lambda_{M3.1}(t) = \left(\frac{0.9751}{126.6890}\right)\left(\frac{t}{126.6890}\right)^{0.9751-1} \tag{11}$$

$$R_{M4.1}(t) = \exp\left[-\left(\frac{t}{95.6222}\right)^{0.9145}\right],$$

$$\lambda_{M4.1}(t) = \left(\frac{0.9145}{95.6222}\right)\left(\frac{t}{95.6222}\right)^{0.9145-1} \tag{12}$$

$$R_{M5.1}(t) = \exp\left[-\left(\frac{t}{45.6595}\right)^{1.0443}\right],$$

$$\lambda_{M5.1}(t) = \left(\frac{1.0443}{45.6595}\right)\left(\frac{t}{45.6595}\right)^{1.0443-1} \tag{13}$$

$$R_{M6.1}(t) = \exp\left[-\left(\frac{t}{80.0858}\right)^{1.0191}\right],$$

$$\lambda_{M6.1}(t) = \left(\frac{1.0191}{80.0858}\right)\left(\frac{t}{80.0858}\right)^{1.0191-1} \tag{14}$$

$$R_{M6.2}(t) = \exp\left[-\left(\frac{t}{64.1261}\right)^{1.2110}\right],$$

$$\lambda_{M6.2}(t) = \left(\frac{1.2110}{64.1261}\right)\left(\frac{t}{64.1261}\right)^{1.2110-1} \tag{15}$$

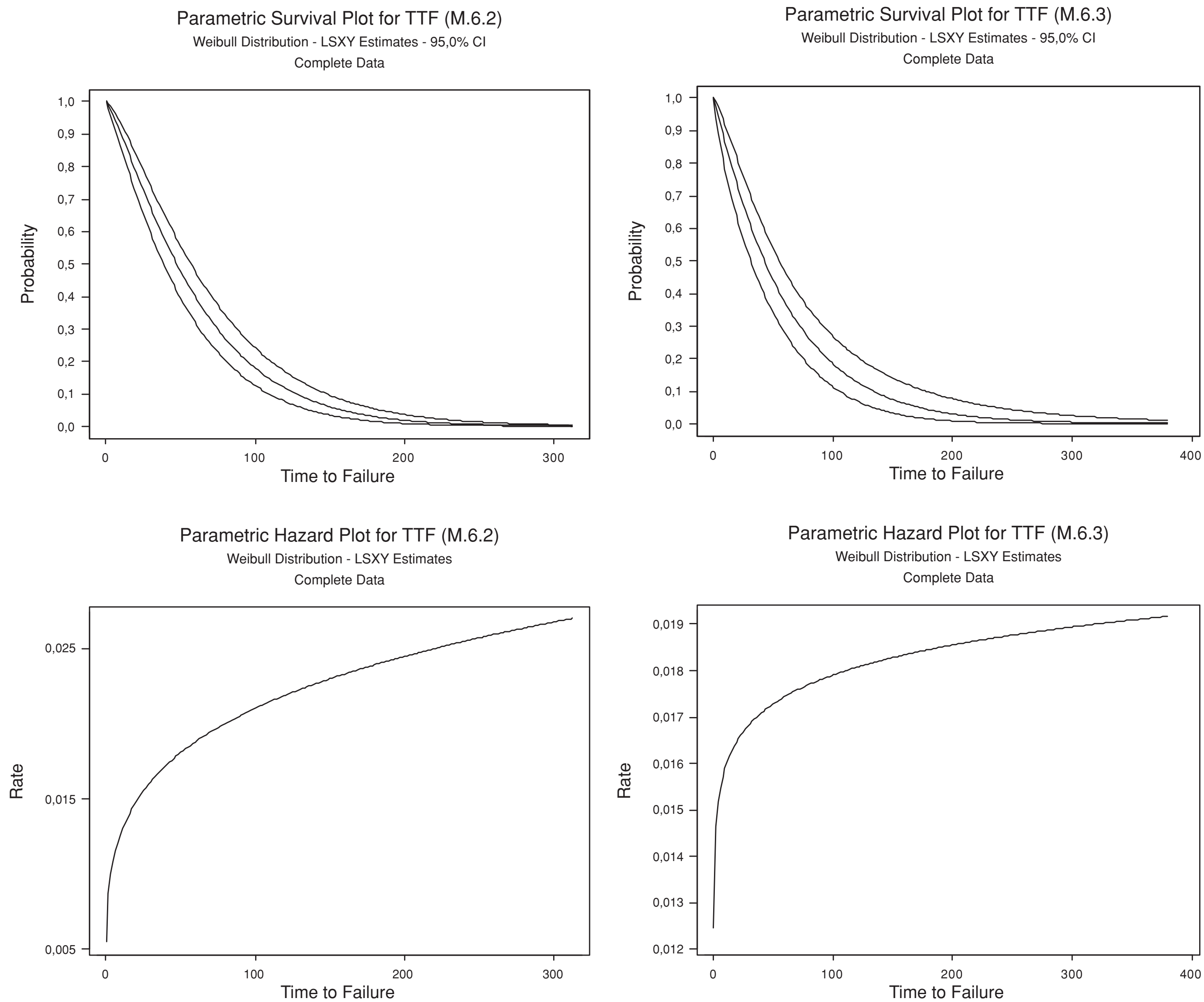


Figure 5 (Continued)

$$R_{M6.3}(t) = \exp\left[-\left(\frac{t}{60.4131}\right)^{1.0403}\right],$$

$$\lambda_{M6.3}(t) = \left(\frac{1.0403}{60.4131}\right)\left(\frac{t}{60.4131}\right)^{1.0403-1} \tag{16}$$

$$R_{Line}(t) = \exp\left[-\left(\frac{t}{8.4157}\right)^{1.1158}\right],$$

$$\lambda_{Line}(t) = \left(\frac{1.1158}{8.4157}\right)\left(\frac{t}{8.4157}\right)^{1.1158-1} \tag{17}$$

From Table 6, one can conclude the following for TTF of the production line—(a) the time within which, the 25% of the failures are expected to happen, is 2.7588 of the operating hours (first quartile), the time within which the 50% of the failures are anticipated to happen, is 6.0593 of the operating hours (second quartile), and the time within which the 75% of the failures are expected to occur, is 11.2659 of operating hours (third quartile). (b) The scale parameter (θ) of the Weibull distribution of the line indicates that the 2/3 of the failures will have occurred within 8.4109 operating hours. (c) From the Table of percentiles with 95% confidence, it is evident that the 20% of the failures will occur within time t which lies between about 2.0330 and 2.3761 operating hours. (d) From the Table of survival probabilities with 95% confidence, it is found out that after one hour of operation the probability of properly functioning of the line lies between 0.9020 and 0.9203. After a shift (8 hours) of operation the probability of properly functioning of the line is between about 0.3677 and 0.4092, and after a working day (24 hours) the probability of the proper function of the line is between about 0.0344 and 0.0454. Therefore, the more the time

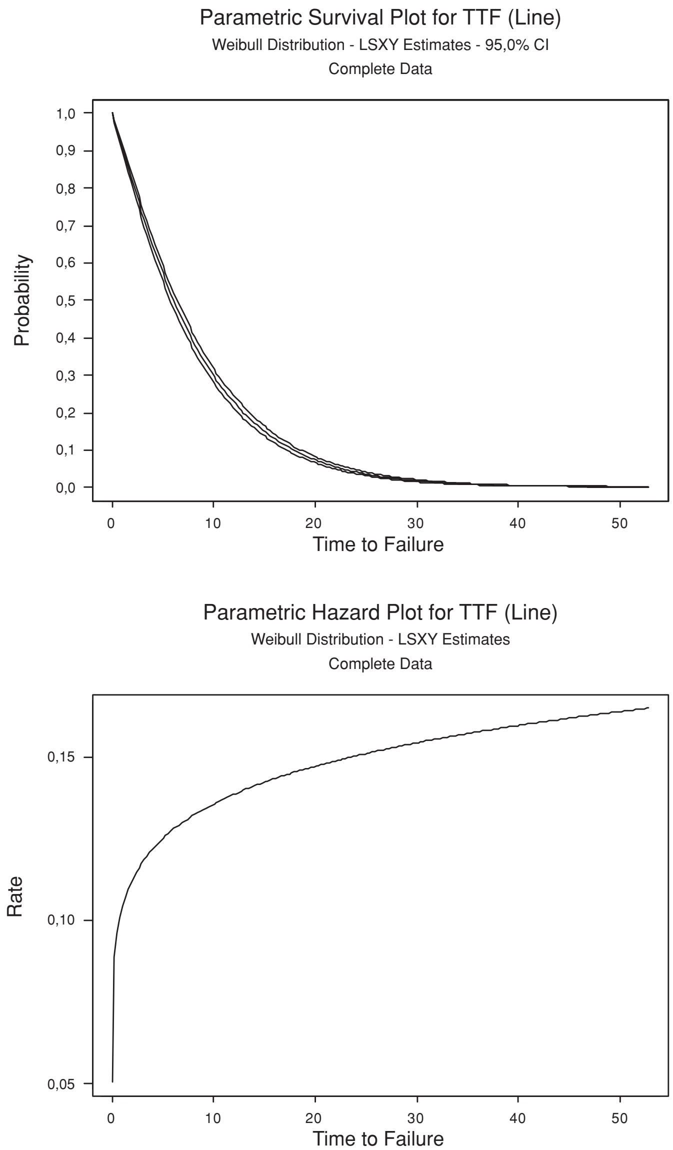


Figure 6 Survival function and Hazard function of TTF at line level.

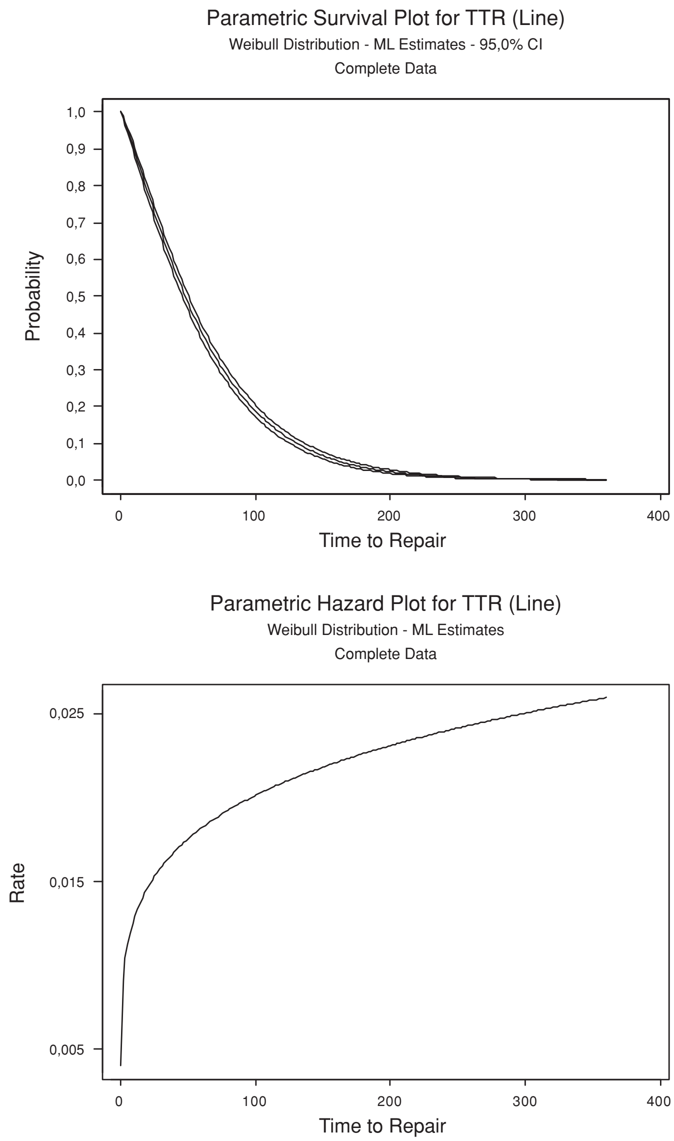


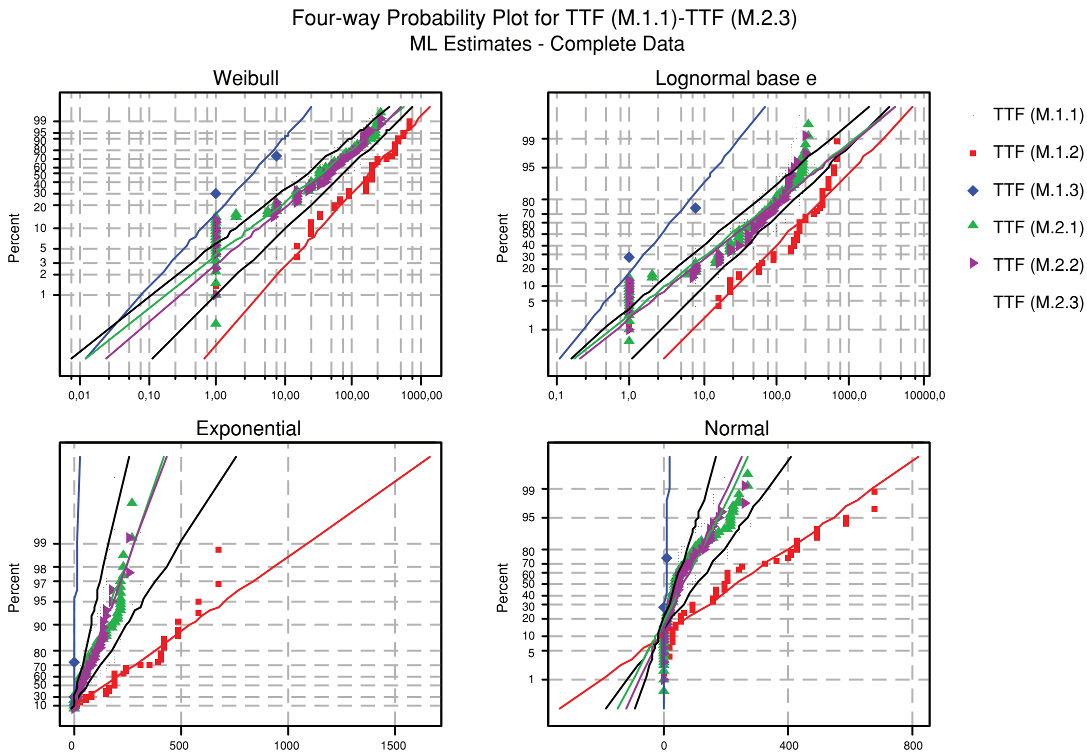
Figure 7 Survival function and Hazard function of TTR at line level.

passes in the line without a failure the lowest is the survival probability.

From Table 7, the following conclusions can be derived for TTR of the production line—(a) 25% of the failures will be repaired within 22.9785 minutes (first quartile), 50% of the failures will be repaired into 47.8462 minutes (second quartile), and 75% of the failures will be repaired into 85.2933 minutes (third quartile). (b) The scale parameter (θ) of the Weibull distribution indicates that the 2/3 of the failures will be repaired into 64.9540 minutes. (c) From the Table of percentiles with 95% confidence, one can perceive that 30% of the failures are repaired within time t which lies between about 25.7951 and 29.2977 minutes. (d) From the Table of survival probabilities with 95% confidence, the probability to repair the line before ten minutes is $1 - 0.8993 = 0.1007$. The probability to repair the line before thirty minutes is $1 - 0.6730 = 0.3270$, and the probability to repair the line before sixty minutes is $1 - 0.4028 = 0.5972$. Therefore, the more time passes in the line without completion of the repair, the higher the probability to restore it.

CONCLUSIONS

It was pointed out that (a) the availability of the bread production line is 90.74% and dropped to 86.76% because the equipment's failures cause an additional production gap in the line; some or all of the in-process material upstream of the failure will have to be scrapped due to quality deterioration during the stoppage. Although the mean TTR is 60.7110 minutes, the mean TLP is 94.1501 minutes for the line. (b) The 53.5% of all failures are revealed at the bread machine (M.2.3), the cooling tower machine (M.5.1), and the volumetric-divider machine (M.2.1). (c) The hazard rate functions over the entire line and in



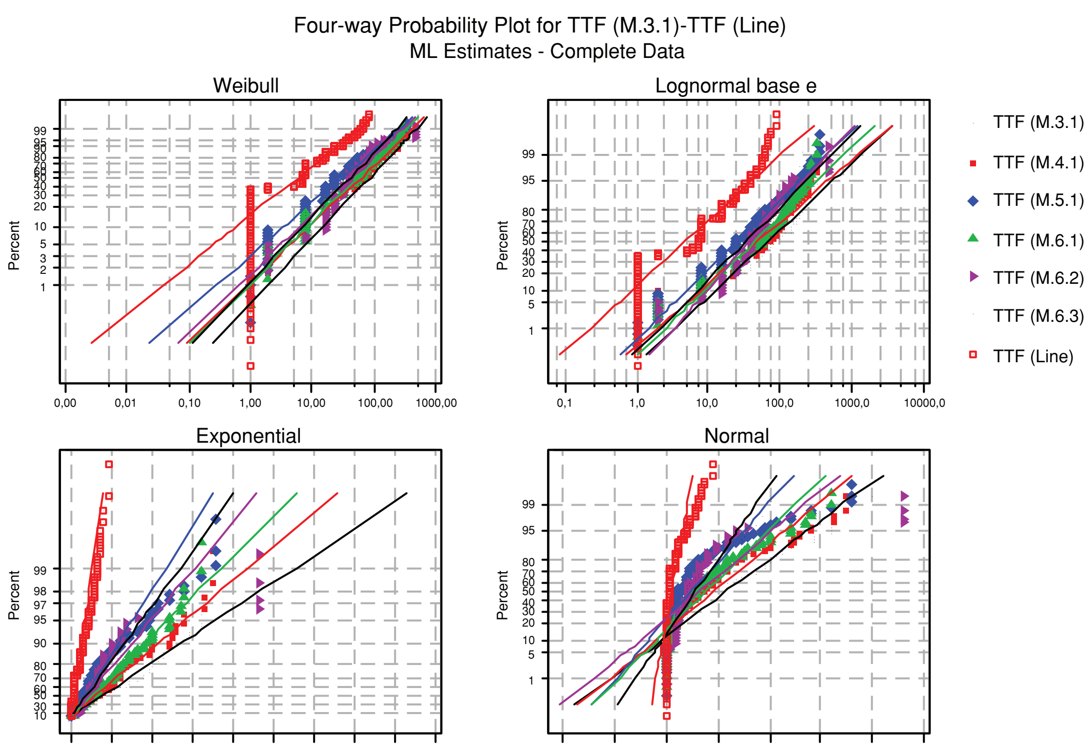
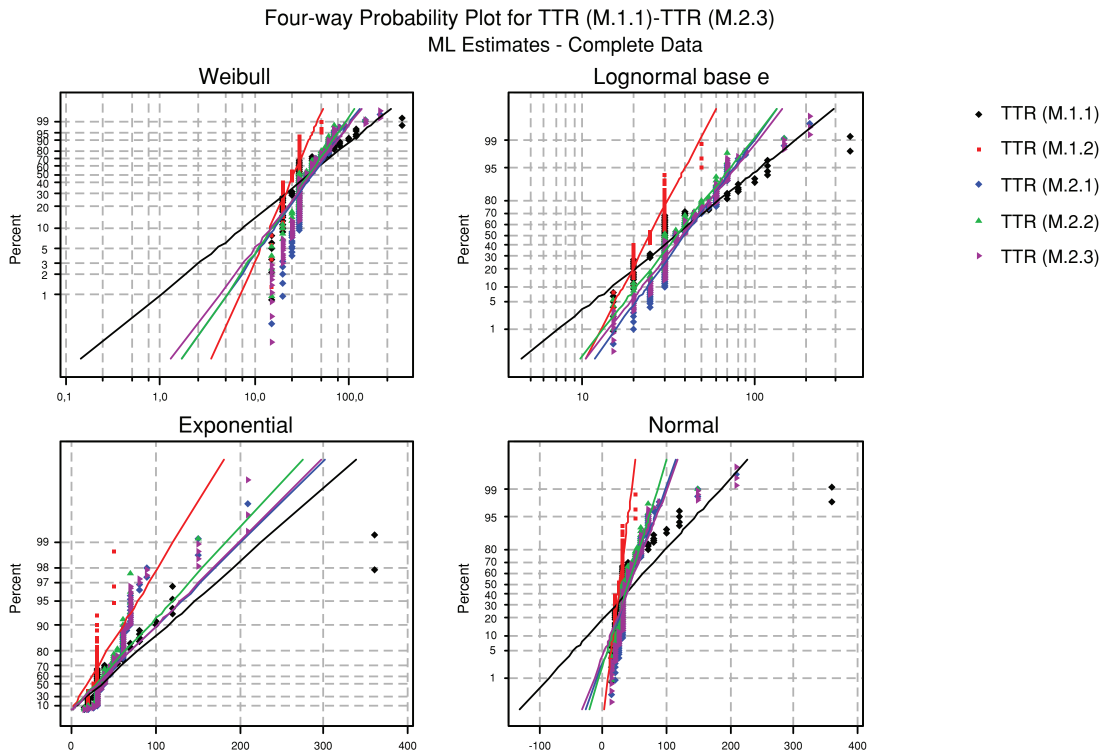


Figure 8 Identification of best fit of TTF and TTR for several theoretical distributions from failure data. *(Continued)*



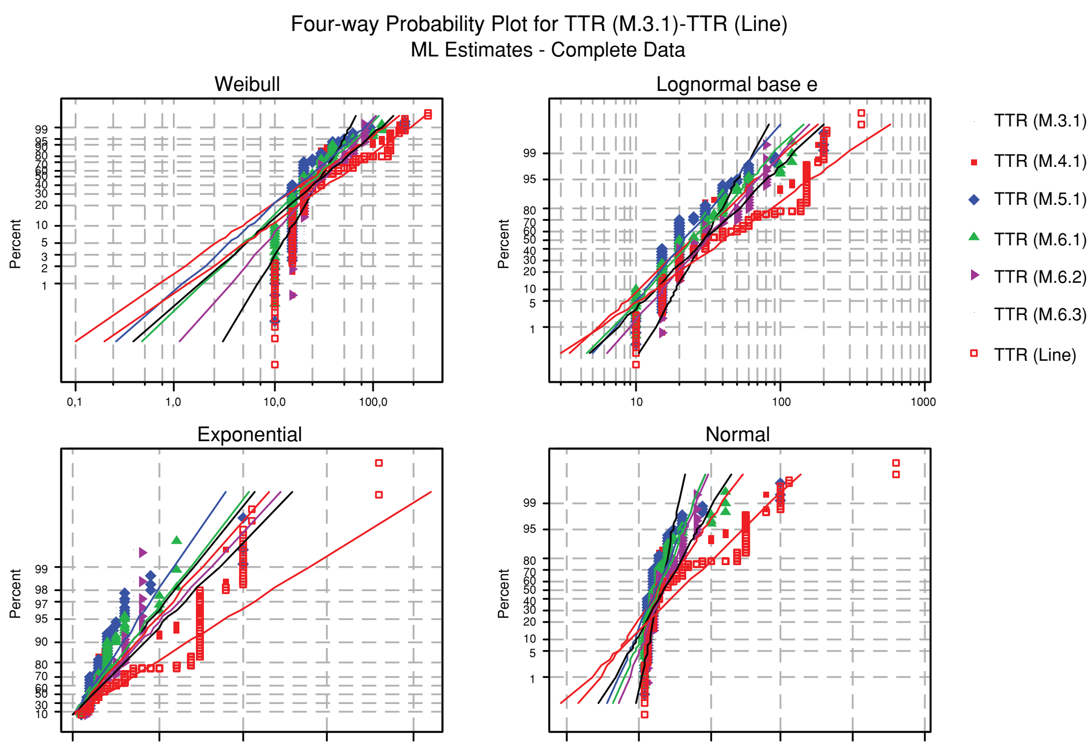


Figure 8 (Continued)

Table 6 Distribution analysis of TTF of bread production line at line level

Variable: TTF (Line)

Censoring Information	Count
Uncensored value	1512

Estimation Method: Least Squares (failure time (X) on rank (Y))
Distribution: Weibull
Parameter Estimates

Parameter	Estimate	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
Shape	1.11766	0.01538	1.08790	1.14822
Scale	8.4109	0.2131	8.0035	8.8391

Characteristics of Distribution

	Estimate	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
Mean(MTTF)	10.6118	0.1841	10.2591	10.9638
Standard Deviation	7.2363	0.1412	6.9648	7.5184
Median	6.0593	0.1723	5.7309	6.4066
First Quartile(Q1)	2.7588	0.1023	2.5654	2.9667
Third Quartile(Q3)	11.2659	0.2587	10.7700	11.7845
Interquartile Range(IQR)	8.5071	0.1730	8.1747	8.8531

Table of Percentiles

Percent	Percentile	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
1.00000	0.1372	0.01035	0.1183	0.1591
5.00000	0.5898	0.03319	0.5282	0.6586
10.00000	1.1231	0.05397	1.0221	1.2340
20.00000	2.1979	0.08743	2.0330	2.3761
30.00000	3.3439	0.1166	3.1230	3.5803
40.00000	4.6113	0.1443	4.3371	4.9029
50.00000	6.0593	0.1723	5.7309	6.4066
60.00000	7.7781	0.2025	7.3911	8.1853
70.00000	9.9305	0.2377	9.4755	10.4075
80.00000	12.8754	0.2838	12.3309	13.4439
90.00000	17.7390	0.3609	17.0455	18.4607
99.00000	32.9814	0.6474	31.7366	34.2749
99.95867	52.7954	1.1332	50.6204	55.0638

Table of Survival Probabilities

Time	Probability	95.0% Normal CI Lower	95.0% Normal CI Upper
0.1000	0.9930	0.9916	0.9941
1.000	0.9116	0.9020	0.9203
2.0000	0.8181	0.8028	0.8323
3.0000	0.7291	0.7104	0.7468
4.0000	0.6468	0.6261	0.6666
5.0000	0.5717	0.5501	0.5927
6.0000	0.5038	0.4820	0.5252
7.0000	0.4429	0.4214	0.4641
8.0000	0.3885	0.3677	0.4092
9.0000	0.3401	0.3202	0.3600
10.0000	0.2972	0.2784	0.3161
11.0000	0.2593	0.2417	0.2772
12.0000	0.2259	0.2095	0.2427
13.0000	0.1965	0.1814	0.2122
14.0000	0.1708	0.1568	0.1853
15.0000	0.1482	0.1354	0.1616
16.0000	0.1285	0.1168	0.1408
17.0000	0.1113	0.1006	0.1226
18.0000	0.0963	0.0866	0.1066
19.0000	0.0832	0.0744	0.0926
20.0000	0.0719	0.0639	0.0804
21.0000	0.0620	0.0548	0.0698
22.0000	0.0535	0.0470	0.0605
23.0000	0.0460	0.0402	0.0524
24.0000	0.0396	0.0344	0.0454

Table 7 Distribution analysis of TTR of bread production line at line level

Variable: TTR (Line)

Censoring Information	Count
Uncensored value	1512

Estimation Method: Maximum Likelihood
Distribution: Weibull
Parameter Estimates

Parameter	Estimate	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
Shape	1.19900	0.02333	1.15414	1.24560
Scale	64.954	1.479	62.118	67.919

Characteristics of Distribution

	Estimate	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
Mean(MTTF)	60.7122	1.3207	58.9778	63.2562
Standard Deviation	51.1858	1.3686	8.5724	53.9397
Median	47.8462	1.2154	45.5223	50.2887
First Quartile (Q1)	22.9785	0.8083	21.4476	24.6186
Third Quartile (Q3)	85.2933	1.8405	81.7612	88.9781
Interquartile Range (IQR)	62.3149	1.4069	59.6176	65.1342

Table of Percentiles

Percent	Percentile	Standard Error	95.0% Normal CI Lower	95.0% Normal CI Upper
1.00000	1.4008	0.1191	1.1857	1.6549
5.00000	5.4545	0.3264	4.8509	6.1332
10.00000	9.9423	0.4883	9.0300	10.9469
20.00000	18.5910	0.7162	17.2390	20.0492
30.00000	27.4907	0.8929	25.7951	29.2977
40.00000	37.0932	1.0522	35.0872	39.2139
50.00000	47.8462	1.2154	45.5223	50.2887
60.00000	60.3863	1.4065	57.6915	63.2069
70.00000	75.8298	1.6643	72.6371	79.1629
80.00000	96.5997	2.0720	92.6229	100.7473
90.00000	130.2273	2.8959	124.6733	136.0287
99.00000	232.1506	6.3706	219.9943	244.9787
99.95867	359.9440	12.0350	337.1121	384.3223

Table of Survival Probabilities

Time	Probability	95.0% Normal CI Lower	95.0% Normal CI Upper
5.0000	0.9548	0.9480	0.9608
10.0000	0.8993	0.8878	0.9098
15.0000	0.8415	0.8266	0.8553
20.0000	0.7838	0.7665	0.8000
25.0000	0.7274	0.7085	0.7453
30.0000	0.6730	0.6530	0.6921
35.0000	0.6210	0.6004	0.6409
40.0000	0.5717	0.5508	0.5920
45.0000	0.5252	0.5043	0.5457
50.0000	0.4816	0.4608	0.5020
55.0000	0.4408	0.4203	0.4611
60.0000	0.4028	0.3827	0.4229
70.0000	0.3349	0.3158	0.3542
80.0000	0.2770	0.2590	0.2953
90.0000	0.2280	0.2112	0.2452
100.0000	0.1868	0.1713	0.2029
110.0000	0.1525	0.1383	0.1674
120.0000	0.1240	0.1111	0.1377

the mixer (M.1.2), the cooling tower machine (M.5.1), the lifting machine (M.6.1), the wrapping machine (M.6.2), and the robot carton machine (M.6.3) are increasing. Therefore, the probability of failure is relatively high, for a quite extended period of time that covers twenty-five months. This means that the current maintenance policy is not adequate for those machines and for the entire line. (d) Both reliability and hazard rate models at workstations and entire line levels were calculated. Therefore, the prediction of the importance of this article lies in the best maintenance policy to keep the equipment operating at peak reliability, increasing the productivity and the efficiency of the line, and reducing the production cost.

REFERENCES

Barabady, J. (2005). Reliability and maintainability analysis of crushing plants in Jajarm Bauxite Mine of Iran. **In:** *Proceedings of the Annual Reliability and Maintainability Symposium*. Alexandria, Virginia, USA, 109–115.

Ben-Daya M. and Duffuaa S.O. (1995). Maintenance and quality: the missing link. *Journal of Quality in Maintenance Engineering* **1**(1): 20–26.

Buzacott, J. A. and Shanthikumar, J. G. (1993). *Stochastic Models of Manufacturing Systems*, Prentice Hall, Englewood Cliffs, NJ, pp 227–289.

Diallo, M., Perreval, H. and Quillot, A. (2001). Manufacturing cell design with flexible routing capability in presence of unreliable machines. *International Journal of Production Economics* **74**(1–3): 175–182.

Ebeling, C. E. (1997). *An Introduction to Reliability and Maintainability Engineering*. McGraw Hill, New York, NY., pp. 58–69.

Gershwin, S. B. (1994). *Manufacturing Systems Engineering*, Prentice Hall, Englewood Cliffs, NJ, pp. 132–143.

Groenevelt, H. A., Seidmann, A. and Pintelon, L. (1992). Production lot sizing with machine breakdown. *Management Science* **38**:104–123.

Jones J. A. and Hayes J. A. (1997). Use of failure field database for improvement of product reliability. *Reliability Engineering and System Safety* **55**:131–134.

Montgomery, D. C. (1985). Introduction to Statistical Control. John Wiley and Sons, Inc., New York, NY, pp. 69–85.

Inman, R. R. (1999). Empirical evaluation of exponential and independence assumptions in queuing models of manufacturing systems. *Production and Operations Management* **8**(4):409–432.

Hayter, J. A. (2002). Probability and statistics for engineers and scientists. (Second edition), CA, USA, pp. 859–879.

Liberopoulos, G. and Tsarouhas, P. (2002). Systems analysis speeds up Chipita's food processing line. *Interfaces* **32**(3):62–76.

Liberopoulos, G. and Tsarouhas, P. (2005). Reliability analysis of an automated pizza processing line. *Journal of Food Engineering* **69**(1):79–96.

Mobley R. K. (2002). *An introduction to predictive maintenance*. (Second edition), Butterworth - Heinemann, Woburn, MA, USA, pp. 99–112.

Seifoddini, S., and Djassemi, M. (2001). The effect of reliability consideration on the application of quality index. *Computers and Industrial Engineering* **40**(1–2):65–77.

Tsarouhas, P. (2009). Classification and Calculation of primary failure modes in bread production line. *Reliability Engineering and System Safety,* **24**:551–557.

Wang, Y., Jia, Y., Yu, J., and Yi, S. (1999). Failure probabilistic model of CNC lathes. *Reliability Engineering and System Safety* **65**(1):307–314.