Reliability Analysis of an Automated Pizza Production Line

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Abstract

We present a statistical analysis of failure data of an automated pizza production line, covering a period of four years. The analysis includes the computation of descriptive statistics of the failure data, the identification of the most important failures, the computation of the parameters of the theoretical distributions that best fit the failure data, and the investigation of the existence of autocorrelations and cross correlations in the failure data. The analysis is meant to guide food product machine manufacturers and bread & bakery products manufactures improve the design and operation of their production lines. It can also be valuable to reliability analysts and manufacturing systems analysts, who wish to model and analyze real manufacturing systems.

Keywords: bread & bakery products manufacturing, production line, reliability analysis, field failure data.

1 Introduction

The bread & bakery products manufacturing industry is one of the most stable industries of the food manufacturing sector. Most bread & bakery products in the developed world are manufactured industrially on specialized, automated, high-speed production lines. According to the annual survey of manufacturers for 2000, published by the U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau (2002), the total value of shipments in the bread & bakery products manufacturing industry in the U.S. was \$30.4 billion. Of this amount, only \$2.6 billion concerned retail bakeries, while the remaining

$27.8 billion concerned commercial bakeries ($24.9 billion) and frozen cakes, pies and other pastries manufacturing ($2.9 billion). The process of manufacturing bread & bakery products is similar for a wide range of different product types, such as breads, bagels, doughnuts, pastries, bread-type biscuits, toasts, cakes, crullers, croissants, pizzas, knishes, pies, rolls, buns, etc. Consequently, the production lines that make bread & bakery products are similar for most types of such products.

Bread & bakery products manufacturers often acquire entire automated production lines from a single food product machinery manufacturer. Such lines typically consist of several workstations in series integrated into one system by a common transfer mechanism and a common control system. Material moves between stations automatically by mechanical means, and no storage exists between stations other than that for material handling equipment (e.g., conveyors, pan handling equipment, bowl unloaders, etc.). Food product machinery manufacturers usually design all the workstations in a production line around the slowest station in the line, which determines the nominal production rate of the line. In bread & bakery products manufacturing, the slowest workstation is almost always the baking oven.

Food product machinery manufacturers worry more about the processing and engineering aspects of the lines that they manufacture than about their operations management aspects. An important managerial concern of bread & bakery products manufacturers operating such lines is to keep production running with minimum interruptions. Unfortunately, because of wear and tear on the individual machines of the production 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. Moreover, if the failure lasts long, it can cause an additional production gap upstream of the interruption, because some or all of the in-process material upstream of the interruption will have to be scrapped due to quality deterioration during the stoppage. As a result, the effective production rate of the line can be substantially less than the nominal production rate for which the line was designed.

The negative impact of failures on the effective production rate of automated production lines puts a pressure on bread & bakery products manufactures to assess and improve the reliability of their lines. This pressure is even 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 they manage so that they can take measures to reduce the frequency and downtime of failures. Such measures are primarily determined by good operating practices by the bread & bakery products manufactures who run the lines as well as good engineering practices by the food product machine manufactures who design the lines.

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 (Freeman, 1996), airplane tires (Sheikh, 1996), CNC lathes (Wang et al., 1999), offshore oil platform plants (Wang and Majid, 2000), and medical equipment (Baker, 2001). The literature on field failure data of production lines is scarce. Hanifin et al. (1975) used the downtime history recorded in a transfer line that machined transmission cases at Chrysler Corporation for seven days to run a simulation of the line. They compared the performance of the line to that obtained by an analytically tractable model of the line, which was based on the assumption that the downtimes of the machines are exponentially distributed. In another work, 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, interarrival times, cycles between failures, and times to repair. The literature on field failure data of production lines in the food industry is even scarcer. The only reference that we are aware of is Liberopoulos and Tsarouhas (2002), who presented a case study of speeding up a croissant production line by inserting an in-process buffer in the middle of the line to absorb some of the downtime, based on the simplifying 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 ten months of actual production data.

In this paper we perform a detailed statistical analysis on a set of field failure data, covering a period of four years and one month, obtained from a real automated pizza production line. Given the extensive length of the period covered, we hope that this paper will serve as a valid data source for food product machine manufacturers and bread & bakery products manufactures, who wish to improve the design and operation of the production lines they manufacture and run, respectively. It can also be valuable to reliability analysts and manufacturing systems analysts, who wish to model and analyze real manufacturing systems.

The rest of this paper is organized as follows. In Section 2, we describe the operation of a typical automated pizza production line, and in Section 3 we describe the collection of failure data from a real line. In section 4, we present the descriptive statistics for all the failures in the line, and in Section 5 we identify the most important failures. In Section 6, we identify the failure and repair time distributions, and in Section 7 we determine the degrees of autocorrelation and cross correlation in the failure data. Finally, we conclude in Section 8.

2 Description of an Automated Pizza Production Line

An automated pizza production 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. There are six distinct stages in making pizzas: kneading, forming, topping, baking, proofing, and wrapping. Each stage corresponds to a distinct workstation, as follows.

In workstation 1, flour from the silo and water are automatically fed into the removable bowl of the spiral kneading machine. Small quantities of additional ingredients 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 workstation.

In workstation 2, the dough fed into the lamination machine is laminated, folded, reduced in thickness by several multi-roller gauging stations to form a sheet. The sheet is then automatically fed into the pizza machine, which cuts it into any shape (usually a circle or a square) with a rotary cutting roller blade or guillotine. The entire process is fully automated. At the exit of the pizza machine, the pizzas are laid onto metal baking pans that are automatically fed to the next workstation.

In workstation 3, tomato sauce, grated cheese and other toppings, such as vegetables, ham, pepperoni cubes and sausage, are automatically placed on the pizza base by a target topping system leaving a rim free of topping. One of the reasons that the toppings are placed on the pizza base before the pizza is baked is to prevent the pizza base from rising.

In workstation 4, the baking pans are placed onto a metal conveyor which passes through the baking oven. The pans remain in the oven for a precise amount of time until the pizzas are partially or fully baked. Extra toppings are optionally placed on top of the pizzas at the exit of oven (usually for partially backed pizzas).

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

In workstation 6, the pizzas 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 pizza machine. The final products that exit from the pizza production line are loaded onto a conveyor. From there, they are hand-picked and put 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.

3 Collection of Field Failure Data

Production managers routinely record failure data for the systems they manage as they use these systems for their intended purposes and maintain them upon failure. We had access to such data from a pizza production line of a large tortilla and bread & bakery manufacturer. The line is identical to that described in the previous section. It consists of six workstations in series, where each workstation contains one or more machines, and each machine has several failure modes.

To take into account exogenous failures affecting the entire line, we define a seventh pseudo-workstation and call it “exogenous.” 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 7 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. Throughout the paper we use the following notation to distinguish the different levels of the production line:

WS.i = Workstation i,
M.$i.j$ = Machine j of workstation i,
F.$i.j.k$ = Failure mode k of machine j of workstation i.

Using the above notation, the workstations and machines of the pizza production line are shown in Table 1. The number of recorded failure modes at each machine is indicated inside a parenthesis next to the machine code. Also, the processing time per pizza at the machine or workstation level is indicated inside a parenthesis below the machine or workstation name.

Workstations	**Machines**			
WS.1 Kneading	M.1.1 (12[1]) Flour silo (3 min[2])	M.1.2 (9) Mixer (25 min)	M.1.3 (2) Elevator-tipping device (1 min)	
WS.2 Forming	M.2.1 (33) Lamination machine (30 min)	M.2.2 (19) Pizza machine (5 min)		
WS.3 Topping	M.3.1 (27) Topping machine (5 min)			
WS.4 Baking	M.4.1 (10) Baking oven (2 min)			
WS.5 Proofing (50 min)	M.5.1 (5) Load zone	M.5.2 (7) Transporter	M.5.3 (13) Pan cooling unit	M.5.4 (5) Unload zone
WS.6 Wrapping (8 min)	M.6.1 (22) Lifting machine	M.6.2 (28) Wrapping machine	M.6.3 (7) Carton machine	
WS.7 Exogenous	M.7.1 (1) Electric power	M.7.2 (1) Water supply	M.7.3 (1) Gas supply	M.7.4 (1) Air supply

[1] Number of recorded failure modes.
[2] Processing time per pizza in minutes.

Table 1: The workstations and machines of the pizza production line.

The failure data that we had access to covers a time period of 1491 days, i.e. four years and one month. During this period, the line operated for 24 hours a day, with three eight-hour shifts during each day, for a total of 883 working days. The data was extracted from the hand written records of failures that the maintenance personnel kept during each shift. The records included the failure mode or modes that had occurred during the shift, the action taken, the down (repair) time, but not the exact time of failure. This means that our accuracy in computing the *time between failures* (TBF) of a particular failure mode, machine, workstation, or of the entire line itself is in the order of number of eight-hour shifts rather than in the order of number of hours. The *time to repair* (TTR), on the other hand, was recorded in minutes. From the records, we counted a total of 1772 failures for the entire line, which were classified into 203 different failure modes that interrupted production. Besides these failure modes, there were 13 additional failure modes, which had no direct effect on production and were thus excluded from the data.

As we mentioned in Section 1, when a failure occurs, the part of the line upstream of the failure is forced to shut down, causing a gap in production downstream of the failure. If the failure takes place in the baking oven (M.4.1 or equivalently WS.4), the oven losses temperature during the failure; therefore, in addition to the TTR of the oven, denoted by TTR

M.4.1, an extra time to reheat the oven up to the specified operating temperature may be required. Specifically, if TTR M.4.1 is less than 5 minutes, then no extra time to reheat the oven is required. If TTR M.4.1 is greater than 5 minutes, however, the extra time to reheat the oven is proportional to TTR M.4.1, i.e. it is equal to TTR M.4.1 – 5. For any failure at any part of the line downstream of the flour silo (M.1.1), if the failure lasts long, an additional production gap may be created 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 deterioration during the stoppage. The most important type of quality deterioration in bread & bakery products manufacturing is the rise of dough. The maximum acceptable standstill time of dough (i.e. the time it can remain still without rising to an unacceptable level) is related to the proofing time of the yeast used in the dough. For products which use yeast with a long proofing time (over three hours), e.g. croissants, the maximum acceptable standstill time is approximately 45 minutes. For products which use yeast with a short proofing time (below one hour), such as pizzas, the maximum acceptable standstill time is shorter. For the pizza production line that we studied, the maximum acceptable standstill time was 25 minutes. With this in mind, the total gap in production caused by a failure is equal to the TTR of the failure plus the time to heat the oven, in case the failure is in the oven, plus the total processing time of the material that is scrapped upstream of the failure, if the TTR of the failure (plus the time to heat the oven, in case the failure is in the oven) is greater than 25 minutes. We refer to this total gap as the *effective time to repair* (TTRe). With this in mind, we computed the values of TTRe at various parts of the line according to the rules shown in Table 2.

IF	**THEN**
TTR M.1.2 > 25	TTRe M.1.2 = TTR M.1.2 + 25 (scrap material in M.1.2)
TTR M.1.3 > 25	TTRe M.1.3 = TTR M.1.3 + 25 (scrap material in M.1.2 and M.1.3)
TTR M.2.1 > 25	TTRe M.2.1 = TTR M.2.1 + 25 + 30 (scrap material in M.1.2- M.2.1)
TTR M.2.2 > 25	TTRe M.2.2 = TTR M.2.2 + 25 + 30 + 5 (scrap material in M.1.2-M.2.2)
TTR M.3.1 > 25	TTRe M.3.1 = TTR M.3.1 + 25 + 30 + 5 + 5 (scrap material in M.1.2-M.3.1)
5 < TTR M.4.1 < 15	TTRe M.4.1 = TTR M.4.1 + TTR M.4.1 – 5 (reheat oven)
TTR M.4.1 > 15	TTRe M.4.1 = TTR M.4.1 + TTR M.4.1 – 5 + 25 + 30 + 5 + 5 + 2 (reheat oven and scrap material in M.1.2-M.4.1)
TTR WS.5 > 25	TTRe WS.5 = TTR WS.5 + 25 + 30 + 5 + 5 + 2 (scrap material in WS.1-WS.4 and manually unload material after WS.4 in order not to block the line)
TTR WS.6 > 25	TTRe WS.6 = TTR WS.6 + 25 + 30 + 5 + 5 + 2 (scrap material in WS.1-WS.4 and manually unload material after WS.5 in order not to block the line)
TTR WS.7 > 25	TTRe WS.7 = TTR WS.7 + 25 + 30 + 5 + 5 + 2 (scrap material in WS.1-WS.4)
Otherwise	TTRe *X* = TTR *X*, where *X* is any workstation or machine.

Table 2: Computation of TTRe at different parts of the pizza production line.

To obtain a graphical representation of the frequency distribution of the failure data we constructed histograms of TBF, TTR and TTRe. To do this we grouped TBF, TTR and TTRe into classes and plotted the frequency of number of observations within each class versus the interval times of each class. Figure 1 shows the histograms of TBF, TTR and TTRe at the entire production line level. The histograms of TBF and TTR exhibit the typical skewed shape of the Weibull distribution function, whereas the histogram of the TTRe has a double peak because TTRe is equal to TTR plus an extra time which is added only in case material is scrapped.

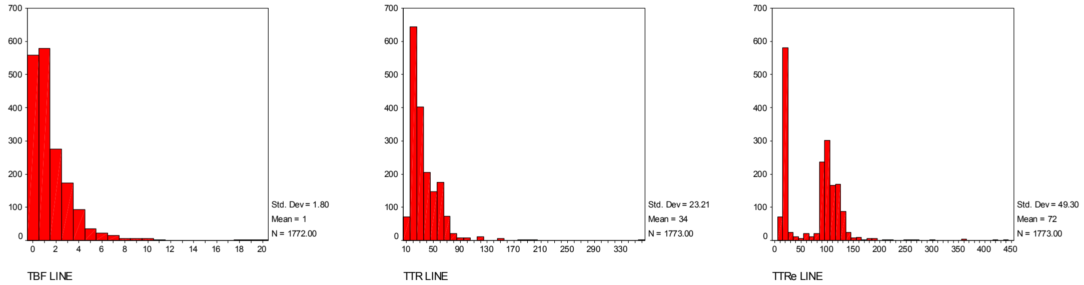


Figure 1: Histograms of TBF, TTR and TTRe for the pizza production line.

4 Computation of Descriptive Statistics from the Failure Data

Descriptive statistics computed from the failure data are very important for drawing conclusions about the data and may be useful in identifying important failures as well as identifying or eliminating candidate distributions for TBF, TTR and TTRe. From the records, we computed several important descriptive statistics of the failure data at the levels of the failure modes, the machines, the workstations, and finally the entire line. The sample size for computing the parameters of TBF is one less than the number of failures, whereas the sample size for computing the parameters of the TTR and TTRe is equal to the number of failures. Table 3 shows the descriptive statistics of the failure data and the resulting availability, at the machine, workstation and production line levels, where the availability is computed as the ratio of the mean TBF over the sum of the mean TBF plus the mean TTR or TTRe, depending on whether TTR or TTRe is used. The descriptive statistics of the failure data and the resulting availability at the failure mode level, for the most important failure modes, are shown in Section 5.

	N	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Std. Err.**	**Kurtosis**	**Std. Err.**	**Avail.**
TBF LINE	1772	0	20	1.4980	1.8007	2.9714	0.0581	17.9133	0.1162	-
TTR LINE	1773	10	360	34.2607	23.2094	3.4583	0.0581	28.9471	0.1162	0.9545
TTRe LINE	1773	10	442	72.0976	49.2956	0.8361	0.0581	4.1747	0.1162	0.9089

	N	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Std. Err.**	**Kurtosis**	**Std. Err.**
TBF WS.1	128	0	113	20.6250	24.2760	1.8326	0.2140	3.3523	0.4249
TBF WS.2	613	0	80	4.2104	6.2431	5.5424	0.0987	49.8426	0.1971
TBF WS.3	196	0	178	12.8469	21.2901	4.7375	0.1736	28.4641	0.3456
TBF WS.4	101	0	188	26.0693	34.1445	2.2878	0.2402	5.8895	0.4761

TBF WS.5	372	0	43	7.0806	7.6805	1.7105	0.1265	3.0416	0.2523
TBF WS.6	300	0	103	8.8033	11.2010	3.4419	0.1407	19.6181	0.2805
TBF WS.7	55	0	402	45.3636	80.2326	2.8643	0.3217	8.6605	0.6335

	N	Min	Max	Mean	Std. Dev.	Skewness	Std. Err.	Kurtosis	Std. Err.	Avail.
TTR WS.1	129	15	360	44.4574	35.8013	5.6823	0.2132	47.0364	0.4233	0.9955
TTR WS.2	614	10	200	43.1922	20.6281	1.5302	0.0986	7.1243	0.1969	0.9791
TTR WS.3	197	10	90	21.9036	12.9286	2.3349	0.1732	6.3000	0.3447	0.9965
TTR WS.4	102	15	190	31.2255	32.0229	3.5683	0.2391	13.0228	0.4738	0.9975
TTR WS.5	373	10	200	27.3324	16.4178	4.4770	0.1263	36.0492	0.2520	0.9920
TTR WS.6	301	10	150	27.6246	18.9672	2.2038	0.1405	7.6937	0.2801	0.9935
TTR WS.7	56	15	180	43.6607	31.7875	2.2610	0.3190	6.1013	0.6283	0.9980

	N	Min	Max	Mean	Std. Dev.	Skewness	Std. Err.	Kurtosis	Std. Err.	Avail.
TTRe WS.1	129	15	360	54.1473	36.7961	4.6368	0.2132	36.5768	0.4233	0.9946
TTRe WS.2	614	10	255	96.2622	30.5949	-0.8274	0.0986	3.4394	0.1969	0.9545
TTRe WS.3	197	10	155	37.0812	38.7197	1.3802	0.1732	0.2011	0.3447	0.9940
TTRe WS.4	102	92	442	124.4510	64.0457	3.5683	0.2391	13.0228	0.4738	0.9902
TTRe WS.5	373	10	267	59.8445	45.4010	0.4448	0.1263	-0.5571	0.2520	0.9827
TTRe WS.6	301	10	217	56.3389	48.8444	0.5329	0.1405	-1.1797	0.2801	0.9868
TTRe WS.7	56	15	247	96.3036	50.5669	0.0659	0.3190	0.6569	0.6283	0.9956

	N	Min	Max	Mean	Std. Dev.	Skewness	Std. Err.	Kurtosis	Std. Err.
TBF M.1.1	76	0	211	31.8289	44.6158	2.0994	0.2756	4.4646	0.5448
TBF M.1.2	49	1	267	49.4082	53.3307	2.3318	0.3398	6.2061	0.6681
TBF M.1.3	1	1	1	1.0000	-	-	-	-	-
TBF M.2.1	255	0	80	10.0471	11.6962	2.5448	0.1525	9.4400	0.3038
TBF M.2.2	357	0	249	7.2297	15.9776	10.5840	0.1291	149.6713	0.2575
TBF M.3.1	196	0	178	12.8469	21.2901	4.7375	0.1736	28.4641	0.3456
TBF M.4.1	101	0	188	26.0693	34.1445	2.2878	0.2402	5.8895	0.4761
TBF M.5.1	112	0	121	22.9821	24.5940	1.6990	0.2284	3.1713	0.4531
TBF M.5.2	85	0	169	30.9294	37.1204	1.8491	0.2612	3.4452	0.5168
TBF M.5.3	101	0	210	25.3960	35.2026	2.6864	0.2402	8.9454	0.4761
TBF M.5.4	71	0	292	35.2394	50.8279	2.8115	0.2848	9.5531	0.5625
TBF M.6.1	137	0	126	19.0292	24.1192	2.4024	0.2070	6.0820	0.4112
TBF M.6.2	99	0	211	26.6768	33.1979	2.6423	0.2426	9.8581	0.4806
TBF M.6.3	62	1	350	40.8226	69.0978	2.7933	0.3039	8.1477	0.5993
TBF M.7.1	50	0	402	49.8800	84.4122	2.6443	0.3366	7.1353	0.6619
TBF M.7.2	0	-	-	-	-	-	-	-	-
TBF M.7.3	1	9	9	9.0000	-	-	-	-	-
TBF M.7.4	1	27	27	27.0000	-	-	-	-	-

	N	Min	Max	Mean	Std. Dev.	Skewness	Std. Err.	Kurtosis	Std. Err.	Avail.
TTR M.1.1	77	15	360	47.7922	44.1550	4.9419	0.2739	32.8985	0.5415	0.9969
TTR M.1.2	50	15	80	40.3000	16.2697	0.3663	0.3366	-0.7078	0.6619	0.9983
TTR M.1.3	2	20	20	20.0000	0.0000	-	-	-	-	-
TTR M.2.1	256	15	200	47.9492	20.2918	2.4557	0.1522	14.3560	0.3033	0.9902
TTR M.2.2	358	10	150	39.7905	20.2166	1.0201	0.1289	2.0455	0.2571	0.9887
TTR M.3.1	197	10	90	21.9036	12.9286	2.3349	0.1732	6.3000	0.3447	0.9965
TTR M.4.1	102	15	190	31.2255	32.0229	3.5683	0.2391	13.0228	0.4738	0.9975

	N	Min	Max	Mean	Std. Dev.	Skewness	Std. Err.	Kurtosis	Std. Err.	Avail.
TTR M.5.1	113	10	50	20.7965	8.1165	1.5990	0.2274	2.4386	0.4512	0.9981
TTR M.5.2	86	15	200	37.9651	25.6490	3.2943	0.2597	17.9472	0.5139	0.9974
TTR M.5.3	102	20	120	29.9020	12.7811	3.9874	0.2391	24.5225	0.4738	0.9976
TTR M.5.4	72	15	40	21.2500	6.0369	1.3766	0.2829	2.0450	0.5588	0.9987
TTR M.6.1	138	10	120	27.5362	16.4699	2.5125	0.2063	9.7293	0.4098	0.9970
TTR M.6.2	100	15	150	37.0000	21.9619	1.7286	0.2414	5.6231	0.4783	0.9971
TTR M.6.3	63	10	20	12.9365	3.1921	0.6219	0.3016	-0.5425	0.5948	0.9993
TTR M.7.1	51	15	180	42.9412	32.8508	2.3100	0.3335	6.0477	0.6559	0.9982
TTR M.7.2	1	45	45	45.0000	-	-	-	-	-	-
TTR M.7.3	2	70	70	70.0000	0.0000	-	-	-	-	-
TTR M.7.4	2	30	40	35.0000	7.0711	-	-	-	-	-
TTRe M.1.1	77	15	360	47.7922	44.1550	4.9419	0.2739	32.8985	0.5415	0.9969
TTRe M.1.2	50	15	105	64.3000	18.4615	-0.3304	0.3366	0.5882	0.6619	0.9973
TTRe M.1.3	2	45	45	45.0000	0.0000	-	-	-	-	-
TTRe M.2.1	256	15	255	101.8750	23.2590	0.7582	0.1522	11.1921	0.3033	0.9793
TTRe M.2.2	358	10	210	92.2486	34.3819	-0.9810	0.1289	1.1475	0.2571	0.9741
TTRe M.3.1	197	10	155	37.0812	38.7197	1.3802	0.1732	0.2011	0.3447	0.9940
TTRe M.4.1	102	92	442	124.4510	64.0457	3.5683	0.2391	13.0228	0.4738	0.9902
TTRe M.5.1	113	10	117	39.7699	37.3021	1.0028	0.2274	-0.9256	0.4512	0.9964
TTRe M.5.2	86	15	267	83.9302	50.1899	0.0853	0.2597	0.5013	0.5139	0.9944
TTRe M.5.3	102	20	187	75.8824	39.4944	-0.4617	0.2391	-0.8686	0.4738	0.9938
TTRe M.5.4	72	15	107	39.8611	35.3790	1.0225	0.2829	-0.9286	0.5588	0.9976
TTRe M.6.1	138	10	187	58.6087	46.5424	0.3779	0.2063	-1.3433	0.4098	0.9936
TTRe M.6.2	100	15	217	80.5500	49.2699	-0.1986	0.2414	-1.1005	0.4783	0.9937
TTRe M.6.3	63	10	20	12.9365	3.1921	0.6219	0.3016	-0.5425	0.5948	0.9993
TTRe M.7.1	51	15	247	94.1765	52.2937	0.1725	0.3335	0.5354	0.6559	0.9961
TTRe M.7.2	1	112	112	112.0000	-	-	-	-	-	-
TTRe M.7.3	2	137	137	137.0000	0.0000	-	-	-	-	-
TTRe M.7.4	2	97	107	102.0000	7.0711	-	-	-	-	-

Table 3: Descriptive statistics of the failure data at the machine, workstation and production line levels.

From Table 3 we can make the following observations: (a) The sample size of failures at some machines is very small. Specifically, in the case of M.7.2 there was only one failure, so there are not enough data to compute TBF. In the cases of M.1.3, M.7.3 and M.7.4 there were only two failures, so the sample size is still too small to provide any reliable information about the data, especially TBF. (b) For all the workstations and nearly all the machines, the minimum TBF is zero. A zero TBF means that two consecutive failures occurred during the same shift. (c) The three workstations with the most frequent failures and lowest availabilities are WS.2, WS.5, and WS.6, in decreasing order of failure frequency and increasing order of availability. Indeed, the most failure-prone workstation, WS.2, is at the heart of the production process and consists of a very complex set of equipment with a total of 52 different failure modes (see Table 1). (d) The machines with the three most frequent failures are M.2.2, M.2.1, and M.3.1 in decreasing order of failure frequency. (e) The availability of the entire line is 95.45%, when it is computed based on the mean TTR. If it computed is based on the mean TTRe, however, its value drops to 90.89%.

In addition to the gap in production caused by TTRe, a twenty-minute break takes place at the turn of every eight-hour shift to allow workers to move in and out of the shift, causing an extra 4.16% drop in the production rate of the line. With this in mind, the ratio of the effective production rate to the nominal production rate becomes (90.89%)(100% – 4.16%) = 87.11%. This ratio agrees with the 87% output efficiency of the line, which was computed from the company's production output records that were collected independently of the failure data. The agreement between the two numbers validates the collection and analysis of the failure data.

5 Identification of the Most Important Failures

From the descriptive statistics of the failure data at the failure mode level, which were not included in Table 3 due to space considerations, we identified the most important failure modes according to several criteria. Table 4 lists the ten most important failure modes, among those failure modes which occurred more than eight times, i.e. relatively frequently, according to the following criteria: smallest mean TBF, smallest minimum TBF, largest CV of TBF, largest mean TTRe, largest minimum TTRe, largest CV of TTRe and AVAILe, where CV stands for the coefficient of variation, i.e. the ratio of the standard deviation over the mean, and AVAILe is the availability based on the mean TTRe.

Smallest Mean TBF	Smallest Min TBF	Largest CV of TBF	Largest Mean TTRe	Largest Min TTRe	Largest CV of TTRe	Smallest AVAILe
F.2.1.9	F.2.1.16	F.6.3.4	F.4.1.3	F.2.2.15	F.3.1.23	F.2.1.9
F.5.1.1	F.2.2.8	F.4.1.2	F.2.2.8	F.2.1.27	F.6.1.5	F.2.2.8
F.3.1.2	F.2.2.11	F.2.2.8	F.2.1.27	F.2.2.17	F.3.1.25	F.4.1.6
F.2.2.8	F.5.1.1	F.2.2.9	F.2.2.15	F.2.2.8	F.3.1.9	F.7.1.1
F.2.2.13	F.5.2.4	F.5.3.2	F.2.1.4	F.2.1.16	F.5.1.1	F.2.2.11
F.5.4.1	F.5.3.1	F.6.1.6	F.2.1.16	F.5.1.3	F.3.1.3	F.5.2.4
F.4.1.6	F.6.1.5	F.2.2.11	F.2.2.17	F.4.1.6	F.6.1.18	F.2.1.4
F.6.3.4	F.4.1.6	F.1.1.7	F.4.1.6	F.4.1.3	F.1.1.1	F.2.2.13
F.7.1.1	F.7.1.1	F.2.2.12	F.2.1.17	F.4.1.2	F.5.4.1	F.2.2.12
F.5.3.1	F.2.2.13	F.2.2.16	F.5.2.4	F.2.2.12	F.6.1.6	F.2.2.15

Table 4: Ten most important failure modes according to seven criteria.

The description of the failure modes that appear in Table 4 is given in Table 5. The descriptive statistics of the failure data at the failure mode level, for the most important failure modes in Table 4 are shown in Table 6.

Failure mode	**Description**
F.1.1.1	Blocking of air transport of flour at the flour silo
F.1.1.7	Failure at the electric power panel (fuse or relay)
F.2.1.4	Torn conveyor belt at the lamination machine
F.2.1.9	Broken double motion-chain in the extruder of the lamination machine
F.2.1.16	Failure of sensor at lamination machine
F.2.1.17	Blockage of the security casing at the lamination machine
F.2.1.27	Failure of motor inverter at the lamination machine
F.2.2.8	Motion-chain at the pizza machine is out-of-phase
F.2.2.9	Blocking of pans at the pizza machine
F.2.2.11	Torn conveyor belt at the pizza machine
F.2.2.12	Failure of the rotary cutting roller or guillotine
F.2.2.13	Realignment of laminated dough on the conveyor at the pizza machine
F.2.2.15	Blocking of mechanism that lays pizzas onto metal baking pans
F.2.2.16	Broken belt stretcher under pizza machine
F.2.2.17	Blockage of the security casing at the pizza machine
F.3.1.2	Failure of pneumatic system with pistons at the topping machine
F.3.1.3	Failure at the pan brake-system at the topping machine
F.3.1.9	Leaking gasket at the toping machine
F.3.1.23	Cleaning of malfunctioning nozzles of the topping machine
F.3.1.25	Cleaning of clogged nozzles at the topping machine
F.4.1.2	Broken motion-chain of metal conveyor
F.4.1.3	Blocking of pans in the oven
F.4.1.6	Failure of burner at the baking oven
F.5.1.1	Blocking of pans at the entrance of the load zone in the proofing section
F.5.1.3	Bending of pan guides at the load zone in the proofing section
F.5.2.4	Blocking of pans at the entrance (load zone) of the transporter in the proofing section
F.5.3.1	Clogged nozzles at the cooling unit of the proofing section
F.5.3.2	Cleaning of air filters at the transporter in the proofing section
F.5.4.1	Blocking of pans at the exit (unload zone) of the transporter in the proofing section
F.6.1.5	Failure of the forks that automatically lift pizzas from the baking pans
F.6.1.6	Blocking of pans at the pizza lifting machine
F.6.1.18	Alignment of head at the pizza lifting machine
F.6.3.4	Adjustment of carton sealing mechanism
F.7.1.1	Failure at the electric power generator

Table 5: Description of the failure modes of Table 4.

	N	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Std. Err.**	**Kurtosis**	**Std. Err.**
TBF F.2.1.4	33	2	432	75.4545	114.2738	2.1247	0.4086	3.7152	0.7984
TBF F.2.1.9	14	2	56	18.5000	18.5835	1.1272	0.5974	0.0308	1.1541
TBF F.2.1.16	25	0	506	101.9200	137.0812	2.0767	0.4637	4.0875	0.9017
TBF F.2.1.27	11	13	531	172.6364	184.9904	1.4201	0.6607	0.8098	1.2794
TBF F.2.2.8	74	0	531	34.5270	75.1676	5.0789	0.2792	29.0601	0.5517
TBF F.2.2.11	47	0	612	54.3830	108.1168	3.7018	0.3466	15.9266	0.6809
TBF F.2.2.12	30	1	798	78.5333	152.1784	3.9972	0.4269	18.0802	0.8327
TBF F.2.2.13	73	1	339	34.6849	56.6737	3.6570	0.2810	15.8229	0.5552
TBF F.2.2.15	23	2	697	104.8696	146.3332	3.2382	0.4813	12.6987	0.9348
TBF F.3.1.2	39	1	151	31.3846	31.7736	1.8748	0.3782	4.2639	0.7410
TBF F.3.1.23	15	7	637	149.0667	194.1261	1.4581	0.5801	1.3264	1.1209
TBF F.3.1.25	19	1	690	128.8421	192.3236	2.2057	0.5238	4.4051	1.0143
TBF F.4.1.2	12	3	1457	181.8333	408.2526	3.2724	0.6373	10.9948	1.2322
TBF F.4.1.3	16	3	739	132.0000	181.2196	2.7954	0.5643	8.9891	1.0908
TBF F.4.1.6	55	1	415	46.8182	77.4465	3.6167	0.3217	14.4374	0.6335
TBF F.5.1.1	92	0	153	27.6739	29.2350	1.8240	0.2513	3.9402	0.4977
TBF F.5.2.4	44	0	418	59.4545	86.0931	2.9634	0.3575	9.8865	0.7017

TBF F.5.3.1	43	0	424	53.2558	80.6722	2.9255	0.3614	10.3639	0.7090
TBF F.5.4.1	60	2	292	41.6500	54.8124	2.4138	0.3087	6.9604	0.6085
TBF F.6.1.5	27	0	420	88.5926	116.0926	1.9073	0.4479	2.9752	0.8721
TBF F.6.1.6	27	3	1015	94.5926	193.3533	4.4619	0.4479	21.5372	0.8721
TBF F.6.3.4	51	1	680	49.5686	111.6696	4.3632	0.3335	21.4851	0.6559
TBF F.7.1.1	50	0	402	49.8800	84.4122	2.6443	0.3366	7.1353	0.6619

	N	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Std. Err.**	**Kurtosis**	**Std. Err.**	**Avail.**
TTR F.2.1.4	34	50	70	61.9118	5.5068	0.3177	0.4031	-0.6005	0.7879	0.9983
TTR F.2.1.9	15	25	60	34.6667	8.3381	2.1467	0.5801	5.9239	1.1209	0.9961
TTR F.2.1.16	26	45	120	60.5769	17.5115	2.0868	0.4556	4.9122	0.8865	0.9988
TTR F.2.1.27	12	55	70	64.5833	5.4181	-0.3227	0.6373	-1.3813	1.2322	0.9992
TTR F.2.2.8	75	40	90	61.1333	9.8493	0.3830	0.2774	0.1905	0.5482	0.9963
TTR F.2.2.11	48	20	100	38.8542	16.7026	2.4170	0.3431	6.3178	0.6744	0.9985
TTR F.2.2.12	31	30	40	33.8710	4.4177	0.4764	0.4205	-1.5821	0.8208	0.9991
TTR F.2.2.13	74	10	30	17.7027	4.0704	1.3534	0.2792	1.7061	0.5517	0.9989
TTR F.2.2.15	24	50	80	59.5833	7.9286	0.7194	0.4723	0.4564	0.9178	0.9988
TTR F.3.1.2	40	10	30	17.7500	3.5716	0.4821	0.3738	2.4867	0.7326	0.9988
TTR F.3.1.23	16	10	60	19.3750	14.4770	1.9875	0.5643	3.4005	1.0908	0.9997
TTR F.3.1.25	20	10	40	19.7500	9.1010	1.3037	0.5121	0.9157	0.9924	0.9997
TTR F.4.1.2	13	15	30	19.6154	5.1887	1.2327	0.6163	0.9286	1.1909	0.9998
TTR F.4.1.3	17	15	60	30.2941	12.8051	1.0900	0.5497	0.4457	1.0632	0.9995
TTR F.4.1.6	56	15	60	23.3036	9.2085	1.8082	0.3190	4.1904	0.6283	0.9990
TTR F.5.1.1	93	10	50	18.5484	5.3963	2.4089	0.2500	11.4091	0.4952	0.9986
TTR F.5.2.4	45	20	90	42.1111	18.5402	1.2677	0.3537	0.8626	0.6945	0.9985
TTR F.5.3.1	44	20	40	24.7727	5.9995	1.1063	0.3575	0.5391	0.7017	0.9990
TTR F.5.4.1	61	15	40	20.0000	4.7434	1.5742	0.3063	4.3484	0.6038	0.9990
TTR F.6.1.5	28	10	30	16.2500	5.7130	0.7520	0.4405	0.4234	0.8583	0.9996
TTR F.6.1.6	28	10	40	22.1429	7.7494	0.5615	0.4405	-0.7367	0.8583	0.9995
TTR F.6.3.4	52	10	20	12.4038	2.8851	0.7143	0.3304	-0.4532	0.6501	0.9995
TTR F.7.1.1	51	15	180	42.9412	32.8508	2.3100	0.3335	6.0477	0.6559	0.9982

	N	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Std. Err.**	**Kurtosis**	**Std. Err.**	**Avail.**
TTRe F.2.1.4	34	105	125	116.9118	5.5068	0.3177	0.4031	-0.6005	0.7879	0.9968
TTRe F.2.1.9	15	80	115	89.6667	8.3381	2.1467	0.5801	5.9239	1.1209	0.9900
TTRe F.2.1.16	26	100	175	115.5769	17.5115	2.0868	0.4556	4.9122	0.8865	0.9976
TTRe F.2.1.27	12	110	125	119.5833	5.4181	-0.3227	0.6373	-1.3813	1.2322	0.9986
TTRe F.2.2.8	75	100	150	121.1333	9.8493	0.3830	0.2774	0.1905	0.5482	0.9927
TTRe F.2.2.11	48	80	160	98.8542	16.7026	2.4170	0.3431	6.3178	0.6744	0.9962
TTRe F.2.2.12	31	90	100	93.8710	4.4177	0.4764	0.4205	-1.5821	0.8208	0.9975
TTRe F.2.2.13	74	10	90	42.0270	33.1654	0.4056	0.2792	-1.8652	0.5517	0.9975
TTRe F.2.2.15	24	110	140	119.5833	7.9286	0.7194	0.4723	0.4564	0.9178	0.9976
TTRe F.3.1.2	40	10	95	19.3750	12.6180	5.7707	0.3738	35.3710	0.7326	0.9987
TTRe F.3.1.23	16	10	125	31.5625	40.0716	1.7986	0.5643	1.5527	1.0908	0.9996
TTRe F.3.1.25	20	10	105	36.0000	37.0135	1.2581	0.5121	-0.3713	0.9924	0.9994
TTRe F.4.1.2	13	92	122	101.2308	10.3775	1.2327	0.6163	0.9286	1.1909	0.9988
TTRe F.4.1.3	17	92	182	122.5882	25.6102	1.0900	0.5497	0.4457	1.0632	0.9981
TTRe F.4.1.6	56	92	182	108.6071	18.4171	1.8082	0.3190	4.1904	0.6283	0.9952
TTRe F.5.1.1	93	10	117	30.7957	30.2937	1.6747	0.2500	0.9476	0.4952	0.9977
TTRe F.5.2.4	45	20	157	104.6444	28.8343	-1.2466	0.3537	3.5712	0.6945	0.9963

TTRe F.5.3.1	44	20	107	56.7500	39.0391	0.1164	0.3575	-2.0488	0.7017	0.9978
TTRe F.5.4.1	61	15	107	33.1803	30.7357	1.5614	0.3063	0.5205	0.6038	0.9983
TTRe F.6.1.5	28	10	97	21.0357	21.8606	3.2952	0.4405	10.1569	0.8583	0.9995
TTRe F.6.1.6	28	10	107	46.0714	39.9156	0.6267	0.4405	-1.7030	0.8583	0.9990
TTRe F.6.3.4	52	10	20	12.4038	2.8851	0.7143	0.3304	-0.4532	0.6501	0.9995
TTRe F.7.1.1	51	15	247	94.1765	52.2937	0.1725	0.3335	0.5354	0.6559	0.9961

Table 6: Descriptive statistics of the failure data at the failure mode level for the most important failure modes of Table 4.

Tables 4-6 comprise a very valuable and informative guide for food product machine manufacturers and bread & bakery products manufactures who wish to improve the design and operation of the production lines they manufacture and run, respectively. A good staring point for making improvements would be for the designers and operators of the line to focus on the failure modes with the smallest AVAILe. If two failure modes have the same AVAILe, then the failure mode with the highest mean TTRe should be looked at first, given that a long infrequent failure create a larger disturbance than a short frequent failure.

From Table 6, the failure mode with the smallest AVAILe (99.00%) is the braking of the double motion-chain which is powered by a motor and turns the extruder cylinders of the lamination machine (F.2.1.9), so it should be looked at first. The availability of F.2.1.9 is so low because F.2.1.9 has a relatively high mean TTRe (89.6667 min) and a relatively small mean TTF (18.5 shifts). A more careful look at the data in Table 6, however, reveals that F.2.1.9 occurred only 15 times during the entire period of four years and one month (883 working days) examined. A simple division of the period examined, i.e. 883 days × 3 shifts per day, by the number of failures, i.e. 15 failures, yields an approximate mean TBF of 176.6 shifts instead of the 18.5 shifts listed in Table 6. Why is there such a difference between the two numbers? Looking back at the original records, we found that all the 15 occurrences of F.2.1.9 happened within a short period of three months rather than the entire period of four years, which explains the low mean TBF of 18.5 shifts listed in Table 6. It turns out that F.2.1.9 was a problem that troubled the line for three months but was ultimately fixed and never occurred again. Specifically, the chain kept breaking because of wear in the bearings of the extruder, which added an extra load on the chain. The wear of the bearings was detected after a few broken chains and was solved, and the chain never broke again. The failure modes with the second and third smallest AVAILe (99.27% and 99.52%), respectively, are F.2.2.8 and F.4.1.6, so they should be looked at next, followed by failure modes F.7.1.1, F.2.2.11, F.5.2.4. and F.2.1.4, with AVAILe equal to 99.61%, 99.62%, 99.63% and 99.68%, respectively, and so on.

From Tables 4-6 it can be seen that some failures occur very frequently but are not among the top ten failures according to the smallest AVAILe criterion, because they have very short repair times. A typical example is the blocking of pans at various parts of the line (e.g., F.5.1.1, F.5.2.4 and F.5.4.1). The blocking of pans is primarily due to the failure of the appropriate sensor to count the pans because they may be slightly deformed. When the problem becomes more acute, the deformed pans are either repaired or replaced. Other examples of frequent failures with fast repair times are the minor adjustment or cleaning of equipment (e.g., F.6.3.4 and F.5.3.1). From Tables 4-6, it can also be seen that some failures have very long repair times but are not among the top ten failures according to the smallest AVAILe criterion either, because they do not occur very frequently. A typical example is the blocking of pans in the oven (F.4.1.3), which occurs at a very difficult place to reach and requires shutting down and restarting the oven. Another example is the failure of an inverter in one the motors in the lamination machine, which requires disconnecting the failed inverter from the electric panel of the motor and connecting a new inverter.

As was mentioned above, Table 4 lists the ten most important failure modes, among those failure modes which occurred more than eight times. There were also several failure modes which occurred very infrequently, i.e. eight times or less, but which were nonetheless quite disruptive when they occurred. Table 7 shows the descriptive statistics of TTRe at the failure mode level, for the infrequent failure modes with the ten largest mean TTRe, where by infrequent failure modes we mean the failure modes which occurred at least four times but less than nine times. The description of the infrequent failure modes listed in Table 7 is shown in Table 8.

	N	**Min**	**Max**	**Mean**	**Std. Dev.**	**Skewness**	**Std. Err.**	**Kurtosis**	**Std. Err.**	**Avail.**
TTRe F.2.1.7	5	105	145	119.0000	16.7332	1.0885	0.9129	0.5357	2.0000	0.9994
TTRe F.2.2.4	5	110	130	121.0000	8.9443	-0.0524	0.9129	-2.3242	2.0000	0.9993
TTRe F.2.2.5	4	120	180	142.5000	26.2996	1.4431	1.0142	2.2349	2.6186	0.9989
TTRe F.3.1.13	8	115	135	124.3750	7.7632	0.2719	0.7521	-1.0011	1.4809	0.9986
TTRe F.4.1.1	4	362	442	397.0000	41.2311	0.1997	1.0142	-4.8581	2.6186	0.9990
TTRe F.5.2.7	7	112	137	119.8571	9.0633	1.3672	0.7937	1.2941	1.5875	0.9993
TTRe F.6.2.8	6	117	137	123.6667	8.1650	0.8573	0.8452	-0.3000	1.7408	0.9993
TTRe F.6.2.11	4	117	127	123.2500	4.7871	-0.8546	1.0142	-1.2893	2.6186	0.9993
TTRe F.6.2.20	4	127	147	139.5000	9.5743	-0.8546	1.0142	-1.2893	2.6186	0.9996
TTRe F.6.2.22	6	117	137	128.6667	7.5277	-0.3126	0.8452	-0.1038	1.7408	0.9993

Table 7: Descriptive statistics of TTRe at the failure mode level for the infrequent failure modes with the ten largest mean TTRe.

Failure mode	**Description**
F.2.1.7	Failure of the reduction gear at the lamination machine
F.2.2.4	Failure of photocell at the pizza machine

F.2.2.5	Failure of the clutch used to synchronize the laying of pizzas onto metal baking pans
F.3.1.13	Failure of the topping machine mandrel
F.4.1.1	Failure of the baking oven ventilator
F.5.2.7	Failure of the tray holders at the paternoster-type lifts.
F.6.2.8	Failed motor at the wrapping machine
F.6.2.11	Cut resistance jaw cables at the wrapping machine
F.6.2.20	Failure of the reduction gear at the wrapping machine
F.6.2.22	Short circuit at the wrapping machine

Table 8: Description of the infrequent failure modes of Table 7.

From Tables 7-8, it can be seen that the most disruptive infrequent failure is that of the baking oven ventilator (F.4.1.1), whose repair requires cooling down the oven, replacing the failed ventilator and reheating of the oven. The second and third most disruptive infrequent failures are the replacement of the clutch used to synchronize the laying of pizzas onto metal baking pans (F.2.2.5) and the replacement of the reduction gear at the wrapping machine (F.6.2.20). The repair of these failures requires disassembling and reassembling large pieces of equipment in the pizza machine and the wrapping machine, respectively.

6 Identification of failure and repair distributions

One of the main objectives of failure data analysis is to determine the distributions of the time between failures and the time to repair. Identifying candidate distributions is both an art and a science, as it requires an understanding of the failure process, knowledge of the characteristics of the theoretical distributions, and a statistical analysis of the data. From the failure data of the pizza production line, we set out to identify the distributions of TBF, TTR and TTRe at all levels of detail of the line, i.e. at the levels of the failure modes, machines, workstations and the entire line. To this end, we studied the histograms and descriptive statistics of the failure data and fitted several candidate theoretical distributions. Specifically, we used a least-squares fit for each candidate distribution, estimated its parameters and performed a goodness-of-fit test using the software package SPSS.

We found that the Weibull distribution best fitted the TBF and TTR data at the failure mode, machine, and workstation levels, as well as at the level of the entire line. For the TTRe data, on the other hand, no distribution with a single peak can provide a close fit, because the TTRe data exhibit a double peak (see Figure 1). Nonetheless, we fitted the Weibull distribution for the TTRe data as well. The parameters of the Weibull distribution are its shape and scale. The shape parameter, denoted by β, provides insight into the behaviour of the failure (and repair) process. A value of $\beta > 1$ signifies an increasing failure rate. More specifically, when $\beta > 2$, the failure rate is increasing and convex. In particular, when $3 \leq \beta \leq 4$, the Weibull distribution approaches the normal distribution, i.e. it is symmetrical. The scale parameter of the Weibull distribution, denoted by θ, influences both the mean and the spread of the distribution. As θ increases, the reliability at a given point in time increases, whereas the slope of the hazard rate decreases (Ebeling, 1997).

The parameters of the Weibull distribution for the TBF, TTR and TTRe of the most important failure modes listed in Table 6, all the machines and workstations, and the entire line are shown in Table 9, where 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. An index of fit below 1.2 indicates a very good fit. The scale and shape are estimated using the least square method.

Level	**TBF**			**TTR**			**TTRe**		
	Scale Parameter	**Shape Parameter**	**Index of fit**	**Scale Parameter**	**Shape Parameter**	**Index of fit**	**Scale Parameter**	**Shape Parameter**	**Index of fit**
F.2.1.4	57.3839	0.801	0.15	64.5289	11.7219	0.08	119.6431	21.9312	0.08
F.2.1.9	18.5960	0.974	0.1	37.7974	4.5725	0.15	93.6573	10.5217	0.15
F.2.1.16	85.7979	0.5217	0.08	66.8273	3.9456	0.15	123.3741	6.8589	0.15
F.2.1.27	172.0287	0.9698	0.12	67.2302	12.2948	0.04	112.2911	22.8926	0.04
F.2.2.11	33.9169	0.6546	0.1	43.5257	2.9967	0.15	106.2815	6.3293	0.2
F.2.2.12	58.1207	0.8441	0.12	35.9659	6.5005	0.05	96.1337	17.7732	0.06
F.2.2.13	27.7146	0.8628	0.12	19.1962	4.2657	0.05	46.6721	0.9791	0.12
F.2.2.15	92.5071	0.7362	0.07	63.035	7.7156	0.07	123.3028	15.2245	0.08
F.2.2.8	25.2622	0.7335	0.1	65.1783	7.1124	0.07	125.5371	14.0367	0.08
F.3.1.2	31.5374	1.0949	0.06	19.3309	4.9656	0.02	22.0853	2.49679	0.15
F.3.1.23	122.1201	0.7487	0.2	21.8211	1.5462	0.2	32.0388	0.8958	0.3
F.3.1.25	95.8984	0.6204	0.1	22.2270	2.4845	0.1	38.5918	1.0619	0.25
F.4.1.2	101.7323	0.6579	0.15	21.6387	3.6676	0.1	106.1751	8.9145	0.1
F.4.1.3	118.8987	0.8233	0.06	34.0465	2.6566	0.08	132.8122	5.1744	0.1
F.4.1.6	37.9855	0.8647	0.1	25.9707	2.8746	0.1	116.1886	6.1265	0.12
F.5.1.1	27.0231	0.9862	0.06	20.292	3.921	0.06	34.0377	1.183	0.25
F.5.2.4	50.4461	0.7604	0.08	47.1975	2.7505	0.15	125.4849	2.1474	0.2
F.5.3.1	200.0981	0.9623	0.1	17.2762	5.0629	0.002	17.2762	5.0629	0.002
F.5.4.1	37.0588	0.9857	0.15	21.7705	4.4028	0.05	37.4211	1.1833	0.15
F.6.1.5	80.9774	0.6852	0.1	18.2370	2.8036	0.030	23.3075	1.4519	0.2
F.6.1.6	71.9314	0.8452	0.1	24.7323	3.0627	0.1	50.9671	1.0707	0.2
F.6.3.4	31.3797	0.7869	0.15	13.6258	3.5941	0.002	13.6258	3.5941	0.002
F.7.1.1	32.7472	0.6014	0.08	47.3283	1.782	0.12	112.0088	1.2353	0.15
M.1.1	23.5973	0.6227	0.050	52.0758	1.8555	0.120	52.0758	1.8555	0.100
M.1.2	49.6005	1.0059	0.080	45.2911	2.7082	0.050	72.9497	3.0449	0.070
M.1.3	-	-	-	-	-	-	-	-	-
M.2.1	9.5125	0.6949	0.070	53.4389	3.0311	0.050	116.8008	3.2583	0.200
M.2.2	5.9382	0.6995	0.070	44.6892	2.2222	0.080	113.5097	1.5492	0.200
M.3.1	10.9148	0.6776	0.060	24.4637	2.2536	0.150	39.0400	1.1192	0.250
M.4.1	22.3624	0.7532	0.040	34.0459	1.5630	0.200	141.9052	2.4431	0.300
M.5.1	22.4771	0.6955	0.080	23.0723	2.9601	0.100	42.8935	1.0745	0.250
M.5.2	27.6181	0.6863	0.040	42.2034	1.9697	0.060	98.4084	1.1354	0.150
M.5.3	20.5398	0.5513	0.070	33.1680	2.9783	0.100	90.6266	1.2019	0.200

M.5.4	30.3546	0.7525	0.070	23.3516	3.7846	0.070	44.3798	1.1177	0.150
M.6.1	17.1183	0.7755	0.060	30.6924	2.2242	0.080	63.7904	1.0917	0.150
M.6.2	24.0122	0.6911	0.050	41.4618	1.9753	0.100	93.5395	1.1287	0.150
M.6.3	29.6937	0.8202	0.120	14.2368	3.5502	0.006	14.2368	3.5502	0.006
WS.1	18.4310	0.7801	0.040	48.9663	2.0909	0.100	60.2041	2.1178	0.040
WS.2	3.7535	0.6984	0.060	48.4866	2.4387	0.060	117.4583	1.8533	0.250
WS.3	10.9148	0.6776	0.060	24.4637	2.2536	0.150	39.0400	1.1192	0.250
WS.4	22.3624	0.7532	0.040	34.0459	1.5630	0.200	141.9052	2.4431	0.300
WS.5	6.7914	0.7099	0.040	30.3919	2.4196	0.100	66.3262	1.1042	0.150
WS.6	8.5246	0.7248	0.050	30.5721	1.8638	0.100	59.3088	1.0105	0.200
WS.7	28.5554	0.6085	0.070	48.2671	1.8481	0.150	115.4226	1.2791	0.150
LINE	1.4182	0.6941	0.050	37.9572	2.0142	0.080	81.1524	1.2081	0.200

Table 9: Weibull parameters for TBF, TTR and TTRe for several important failure modes, all the machines and workstations, and the production line.

Weibull plots of the cumulative proportions of the TBF, TTR and TTRe at the production line level against the cumulative proportions of the Weibull test distribution are shown in Figure 2. The expected distribution is calculated using Blom's formula ($r - 3/8$) / ($n + 1/4$), where n is the number of observations and r is the rank, ranging from 1 to n. Ties or multiple observations with the same value are resolved by assigning rank using the mean rank of the tied values.

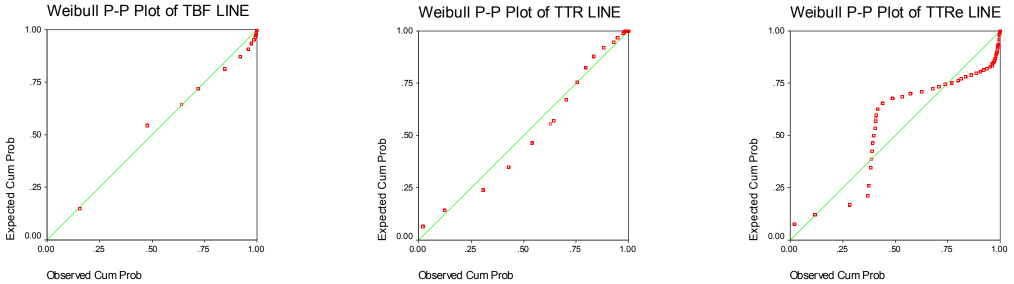


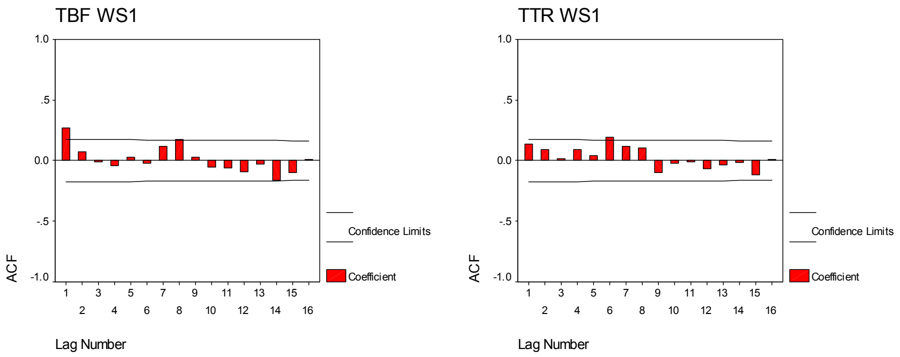
Figure 2: Weibull least-squares plots of TBF, TTR and TTRe at the production line level.

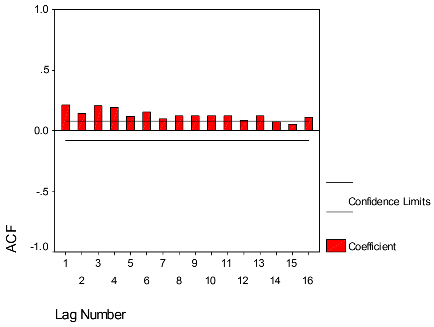
From Table 9 we can see that the shape parameter of the Weibull distribution of TBF is practically between 0.5 and 1 for all the failure modes, machines workstations and the entire line. This means that failures at the failure mode, machine, workstations and the entire line levels has a decreasing failure rate. This was somewhat surprising at the beginning, but it can be explained by the fact that the company which operates the line uses an effective condition-based maintenance policy. According to this policy, conditional maintenance tasks in the form of inspections are performed on a daily basis, identifying problems that are likely to occur in the near future and are reported to the maintenance personnel. The maintenance technicians take these reports into account during their routine maintenance operations, which take place approximately every other weekend. Thus, between two successive failures of the same type, it is likely that one or more condition-based maintenance operations may have been performed, reducing the effective age of the equipment and causing the failure rate of the particular failure type to be decreasing. From Table 9 we can also see that the shape parameter of the Weibull distribution of TTR and TTRe is greater than one for all the for all the failure modes, machines, workstations and the entire line. This implies that the repair rates are increasing. This is natural, because the longer the time since a repair started, the higher the probability that it will finish soon. In fact, in most cases the shape parameter is greater than two, which means that the repair rate is increasing and convex.

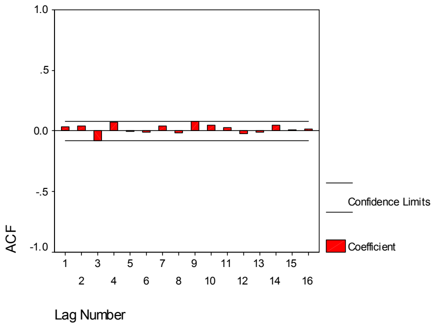
7 Determination of Degrees of Autocorrelation and Cross Correlation of the Failure Data

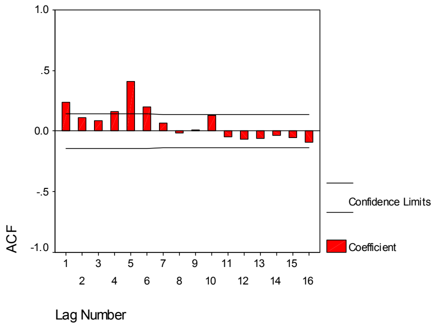
Many analytical models of transfer lines rely on the assumption that the TBF and TTR of the workstations are independent (e.g., see Buzacott and Shanthikumar, 1993, and Gershwin, 1994). Inman (1999) presented actual data from two automotive body-welding lines in order to assess among other things the validity of the independence assumptions for TBF and TTR. They found that while there is a somewhat statistically significant autocorrelation in TBF, it may not be practically significant and it does not seem to be of fundamental importance. Lack of autocorrelation is necessary but not sufficient to show that successive observations of a random variable are independent. For the purposes of manufacturing management, however, testing for autocorrelation should suffice as an indication of independence.

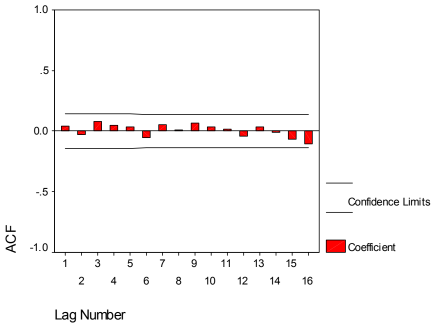
We assessed the significance of the lag – *r* autocorrelation coefficient for values of the lag number *r* ranging from 1 to 16, for the TBF and TTR, at the workstation level and at the entire line level. The results are shown graphically in Figure 3.

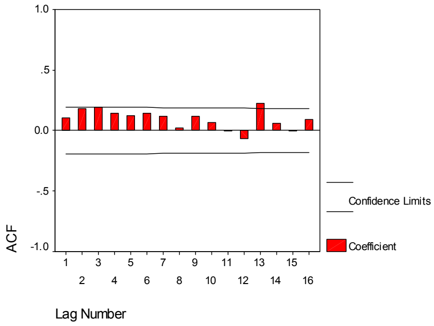


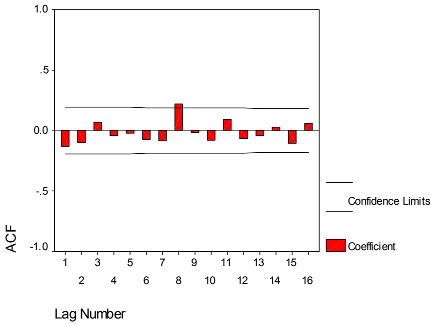

TBF WS2

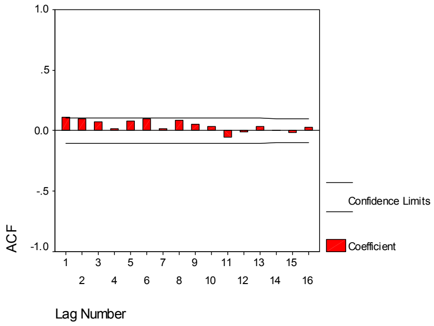

TTR WS2

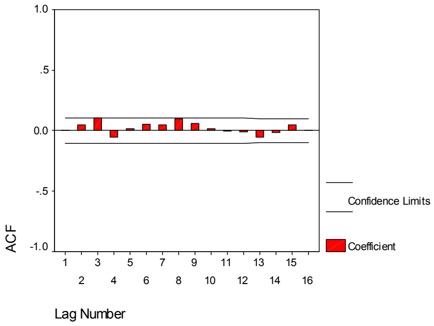

TBF WS3

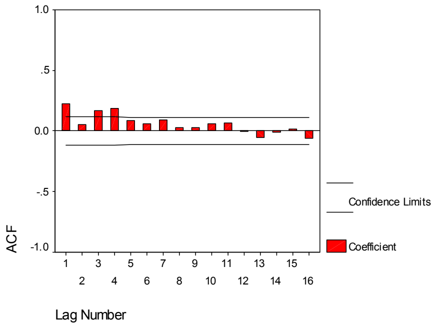

TTR WS3

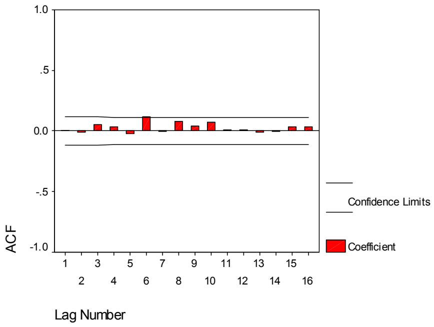

TBF WS4

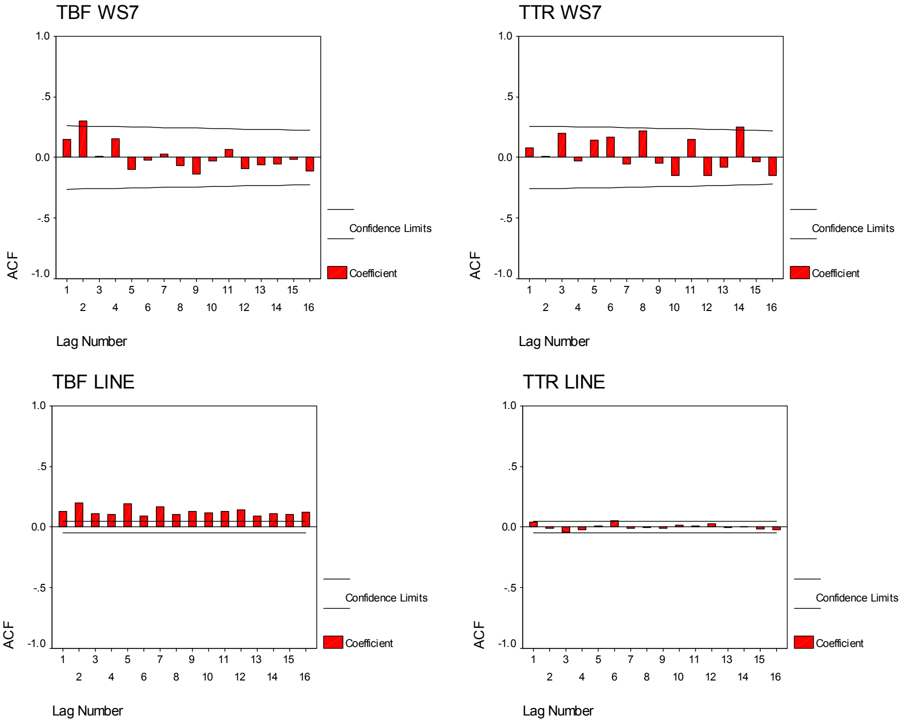

TTR WS4


TBF WS5


TTR WS5


TBF WS6


TTR WS6


TBF WS7

TTR WS7

TBF LINE

TTR LINE

Figure 3. Autocorrelation coefficient of TBF and TTR at the workstation and production line levels.

From the results in Figure 3 it appears that there is statistically significant positive autocorrelation in TBF at the workstation level for WS.1, WS.2, WS.3, WS.6 and WS.7 and at the entire line level, whereas there is no statistically significant autocorrelation in TBR neither at the workstation level nor at the entire line level. Table lists the largest autocorrelation coefficients of TBF and the respective standard errors for WS.1, WS.2, WS.3, WS.6, WS.7 and the entire line.

Level	Lag	Autocorrelation Coefficient	Std. Error
WS.1	Lag-1	0.273	0.087
WS.2	Lag-1	0.213	0.040
WS.3	Lag-5	0.410	0.07
WS.3	Lag-1	0.236	0.071
WS.6	Lag-1	0.228	0.057
WS.7	Lag-2	0.302	0.130
LINE	Lag-2	0.201	0.24

Table 10. Largest autocorrelation coefficients of TBF at the workstation and production line levels.

From Table 10, we can see that the largest autocorrelation coefficient is the lag-5 autocorrelation coefficient for WS.3 with 196 failures, which corresponds to a standard error of 0.07, whereas the next largest autocorrelation coefficients are below 0.31 and have relatively small standard errors as well. So while there is statistically significant autocorrelation in the TBF data, it may not be practically significant and does not seem to be of fundamental importance. Therefore, assuming independence appears valid for all practical purposes for both TBF and TTR. These results carry over to the TTRe data too, because TTRe is strongly positively correlated to TTR since it is equal to TTR plus an extra time which is added in case TTR is long.

In addition to autocorrelation, we calculated (1) the correlation between the time between failures n and $n + 1$, $\mathrm{TBF}_{n,n+1}$, and the time to repair of failure $n + 1$, TTR_{n+1}, and (2) the correlation between TTR_n and $\mathrm{TBF}_{n,n+1}$. Table 11 shows the Pearson correlation coefficient for the two cases and its two-tailed significance probability for the most important failure modes listed in Table 6, all the machines and workstations, and the entire line. The two-tailed significance probability is the probability of obtaining results as extreme as the one observed and in either direction when the null hypothesis (no correlation) is true. Pearson's correlation coefficient assumes that each pair of variables is bivariate normal. Correlation coefficients range in value from -1 (a perfect negative relationship) to +1 (a perfect positive relationship). A value of 0 indicates no linear relationship. A high level of correlation is implied by a correlation coefficient that is greater than 0.5 in absolute terms, i.e. greater than 0.5 or less than -0.5. A mid level of correlation is implied if the absolute value of the coefficient is greater than 0.2 but less that 0.5. A low level of correlation is implied if the absolute value of the coefficient is less than 0.2. The two-tailed test is checking whether the estimated coefficient can reliably be said to be above 0 (the first tail) or below 0 (the second tail).

	Correlation between $\mathrm{TBF}_{n,n+1}$ and TTR_{n+1}		**Correlation between TTR_n and $\mathrm{TBF}_{n,n+1}$**	
	Pearson Correlation Coefficient	**Two-tailed Significance probability**	**Pearson Correlation Coefficient**	**Two-tailed Significance probability**
F.2.1.4	-0.218	0.223	-0.201	0.262
F.2.1.9	-0.35	0.219	-0.093	0.743
F.2.1.16	0.298	0.148	-0.03	0.887
F.2.1.27	0.015	0.964	0.107	0.753
F.2.2.8	-0.116	0.323	-0.106	0.368
F.2.2.11	-0.049	0.744	-0.131	0.382
F.2.2.12	-0.189	0.318	0.253	0.177
F.2.2.13	-0.42	0.721	-0.103	0.385
F.2.2.15	0.232	0.286	0.205	0.348
F.4.1.2	0.575	0.051	0.061	0.851
F.4.1.3	-0.01	0.972	-0.407	0.118
F.4.1.6	-0.043	0.753	0.313[1]	0.02
F.3.1.2	0.163	0.321	-0.014	0.932
F.3.1.23	0.414	0.125	0.002	0.993
F.3.1.25	-0.135	0.581	-0.148	0.534
F.5.1.1	0.108	0.305	-0.02	0.85
F.5.2.4	-0.014	0.93	-0.071	0.645

F.5.3.1	-0.009	0.952	-0.136	0.383
F.5.4.1	0.027	0.837	-0.084	0.525
F.6.1.5	-0.056	0.783	-0.215	0.281
F.6.1.6	-0.257	0.195	0.116	0.564
F.6.3.4	-0.164	0.251	0.179	0.209
F.7.1.1	0.025	0.862	0.41[1]	0.003
M.1.1	0.026	0.822	-0.083	0.476
M.1.2	0.032	0.826	-0.135	0.354
M.1.3	--[3]	-	-	-
M.2.1	-0.058	0.354	-0.029	0.649
M.2.2	-0.04	0.455	0.043	0.422
M.3.1	-0.049	0.496	0.013	0.853
M.4.1	-0.082	0.412	-0.049	0.624
M.5.1	-0.105	0.268	0.004	0.968
M.5.2	0.044	0.692	-0.005	0.96
M.5.3	0.215[2]	0.031	0.252[2]	0.011
M.5.4	-0.073	0.544	0.011	0.928
M.6.1	-0.022	0.797	0.096	0.424
M.6.2	0.092	0.365	0.125	0.218
M.6.3	0.042	0.744	0.047	0.718
WS.1	0.016	0.854	-0.004	0.967
WS.2	0.073	0.071	0.015	0.708
WS.3	-0.049	0.496	0.013	0.853
WS.4	-0.082	0.412	-0.049	0.624
WS.5	0.024	0.649	-0.021	0.685
WS.6	-0.025	0.665	-0.069	0.234
WS.7	0.048	0.73	0.406[1]	0.002
LINE	0.049[2]	0.039	0.059[2]	0.013

[1] Correlation is significant at the 0.01 level (2-tailed).
[2] Correlation is significant at the 0.05 level (2-tailed).
[3] Cannot be computed because at least one of the variables is constant.

Table 11. Correlation between TBF and TTR.

From the results in Table 11, it can be seen that most of the correlation coefficients are so small that they are practically insignificant. At the failure mode level, the only failure modes that have a somewhat statistically significant correlation between TTR_n and $TBF_{n,n+1}$, at the two-tailed 0.01 significance level, i.e. with a 99 % degree of confidence, are the failure of burner at the baking oven (F.4.1.6) and the failure at the electric power generator (F.7.1.1). At the machine level, the only machine that has a slightly statistically significant correlation between $TBF_{n,n+1}$ and TTR_{n+1} and between TTR_n and $TBF_{n,n+1}$, at the two-tailed 0.05 significance level, is the pan cooling unit (M.5.3) in the proofing workstation. At the workstation level, the only workstation that has a somewhat statistically significant correlation between TTR_n and $TBF_{n,n+1}$, at the two-tailed 0.01 significance level, is the exogenous workstation (W.7), but this is linked to the fact that the vast majority of failures at W.7 are due to the failure at the electric power generator (F.7.1.1). Finally, at the entire production line level, there is a marginally statistically significant correlation between $TBF_{n,n+1}$ and TTR_{n+1} and between TTR_n and $TBF_{n,n+1}$, at the two-tailed 0.05 significance level.

In all the above cases, wherever there is a statistically significant correlation, this correlation is positive. This is reasonable in the following sense. A positive correlation coefficient between $TBF_{n,n+1}$ and TTR_{n+1} implies that the longer the time between two failures, the more problems accumulate, and therefore the longer the time it takes to repair the latter of the two failures. A positive correlation coefficient between TTR_n and $TBF_{n,n+1}$ implies that the more time one spends repairing a failure, the more careful job one does, and therefore the longer the time until the next failure is. Both implications are intuitively reasonable.

8 Conclusions

We presented a statistical analysis of failure data of an automated pizza production line, covering a period of four years. We computed descriptive statistics of the failure data and we identified the most important failures. We also computed the parameters of the Weibull distributions that best fit the failure data. We found that failures have a decreasing failure rate, because between of the condition-based maintenance policy used by the company operating the line, which means that between any two successive failures of the same type, it is likely that one or more condition-based maintenance operations may have been performed. Finally, we investigated the existence of autocorrelations and cross correlations in the failure data. We found that there is a statistically significant positive autocorrelation in TBF at the workstation level for WS.1, WS.2, WS.3, WS.6 and WS.7 and at the entire line level, whereas there is no statistically significant autocorrelation in TBR neither at the workstation level nor at the entire line level; however the statistically significant autocorrelation in the TBF data may not be practically significant and does not seem to be of fundamental importance. Therefore, assuming independence appears valid for all practical purposes for both TBF and TTR. We also found that at the entire line level, there is a marginally statistically significant, positive correlation between $TBF_{n,n+1}$ and TTR_{n+1} and between TTR_n and $TBF_{n,n+1}$, at the two-tailed 0.05 significance level. This implies that the longer the time between two failures, the more problems accumulate, and therefore the longer the time it takes to fix the latter failure. It also implies that the more time one spends fixing a failure, the more careful job one does, and therefore the longer the time until the next failure is.

References

Baker, R.D. (2001). Data-based modelling of the failure rate of repairable equipment. *Lifetime Data Analysis*, 7, 65-83.

Buzacott, J.A. and Shanthikumar, J.G. (1993). *Stochastic models of manufacturing systems*, Prentice Hall, Englewood Cliffs, NJ.

Coit, D.W. and Jin, T. (2000). Gamma distribution parameter estimation for field reliability data with missing failure times, *IIE Transactions*, 32, 1161-1166.

Edeling, C.E. (1997). *An Introduction to Reliability and Maintainability Engineering*. McGraw Hill, New York, NY.

Freeman, J.M. (1996). Analysing equipment failure rates. *International Journal of Quality & Reliability Management*, 13(4), 39-49.

Gershwin, S.B. (1994). *Manufacturing systems engineering*. Prentice Hall, Englewood Cliffs, NJ.

Hanifin, L.E., Buzacott, J.A. and Taraman, K.S. (1975). A comparison of analytical and simulation models of transfer lines. *Technical Paper EM75-374, Society of Manufacturing Engineers*.

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.

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

Sheikh, A.K., Al-Garni, A.Z. and Badar, M.A. (1996). Reliability analysis of aeroplane tyres. *International Journal of Quality & Reliability Management*. 13(8), 28-38.

U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau. (2002). *Statistics for Industry Groups and Industries: 2000: Annual Survey of Manufactures*.

Wang, Y., Jia, Y., Yu, J. and Yi, S. (1999). Field failure database of CNC lathes. *International Journal of Quality & Reliability Management*. 16(4), 330-340.

Wang, W. and Majid, H.B.A. (2000). Reliability data analysis and modelling of offshore oil platform plant. *Journal of Quality in Maintenance Engineering*, 6(4), 287-295.