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PRIMARY RESEARCH

Reliability and availability analysis of a manufacturing line system

Mehmet Savsar *

Department of Industrial & Management Systems Engineering, Kuwait University, Kuwait City, Kuwait

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Abstract— Today manufacturing systems are highly automated and consist of several interlinked machines. These automated lines are subject to frequent failures, which affect system reliability and availability, as well as its productivity. In operation of such lines, it is necessary to have enough information on failure and repair data in order to be able to analyze system reliability and availability so that exact output rates could be estimated. Reliability also depends on the preventive maintenance operations. Therefore, it is also desirable to have appropriate analysis in order to see the effects of preventive maintenances on system availability. This paper presents a procedure for collecting appropriate data, analyzing it, and determining system reliability, availability, and productivity of manufacturing lines. Furthermore, procedures and models are presented to study the effects of preventive maintenances on system availability. A special case example is used to illustrate the analysis in detail. The procedures and the models presented in this paper should be useful for operations engineers in order to improve the productivity of their manufacturing lines.

I. INTRODUCTION

Reliability is the probability that a system will adequately preform its intended function under stated environmental conditions for a specified interval of time, while maintenance is the process of maintaining an object at its proper condition. It is obvious that both are very important concepts in industrial sector. Reliability and maintenance planning have been extensively studied and discussed in the literature. Hundreds of research papers have been published related to reliability analysis of various systems. Similarly, manufacturing system reliability is studied and several papers have been presented.

In most of the continuous processes, including chemical and petrochemical industries, a storage tank, or an array of tanks, is provided between the production stages to decouple the stages in order to reduce the effects of production variation in one stage over the others. Without intermediate storage tanks, random equipment failures and variable operation times significantly reduce the process output rate and line efficiency. Since providing a large storage tank is costly, it is important to be able to determine the effect of a given tank size on production output rate. Different aspects of this problem have been considered in several previous studies with special emphasis being on discrete parts manufacturing systems. In the following paragraphs, related research literature is reviewed. [1] presented a model for estimating the productivity and operation uniformity of automatic lines with flexible links. [2] analyzed automated production flow lines with rigidly linked unreliable machines. [3] presented a model and formulation for determination of the availability of a system of two unreliable machines connected by an intermediate storage tank. [4] presented more advanced models for the analysis of three-stage transfer lines with unreliable machines and finite buffers. [5] developed a model for a two-stage production line with an intermediate storage and a single repair crew for two stages. [6] discussed the allocation of inter-stage buffer storage capacity in production lines.

*Corresponding author: Mehmet Savsar
†Email: msavsar@gmail.com

[7] presented a model for determination of optimal intermediate storage capacity. [8] estimated the throughput rate of multi-station unreliable production lines with storages. [9] discussed the optimal allocation of storage space in production line systems with variable processing times. [10] discussed buffer allocation in unbalanced three-station serial lines. [11] presented a stochastic model for an integrated pulp and paper factory with intermediate storage. Some researchers have used simulation and different heuristics in analyzing serial production lines. [12] studied buffer allocation in unreliable production lines using a knowledge-based system. [13] developed an integrated simulation-genetic algorithm model for buffer allocation in unreliable production lines. [14] presented an Integrated simulation-neural network meta model application in designing production flow lines. [15], [16] and [17] presented models and procedures for the analysis of unreliable multi-stage production lines with buffers and under various maintenance procedures. In this paper, we present a complete approach and a procedure for the analysis and modeling of a continuous manufacturing process, which consists of a set of machines connected in series with some intermediate storage tanks. In particular, two manufacturing lines at Kuwait Catalyst Company (KCC) are selected as a case example in order to illustrate the reliability and maintenance analysis procedure. Data are collected related to equipment failures over a one-year period. Collection of historical data was necessary in order to determine distributions related to time between failures and repair times. Furthermore, mean time between failures, mean repair times, corrective and preventive maintenance times, mean active maintenance times, availabilities, production lost times and related costs are estimated from data. As Kuwait Catalyst Company (KCC) is the only company that produces catalyst in the Middle East and it is fully automated, equipment reliability and availability are vital elements for productivity and company reputation. For this reason it is important to analyze reliability and availability of the system. Reliability analysis is based on data collected during the time frame from January 2015 to December 2015. Manufacturing system is operated 365 days per year and 24 hours per day, which results in 8760 hours of operation per year, during which data are collected.

II. SYSTEM DESCRIPTION

Kuwait catalyst is a company that produces catalysts which are substances used in the oil industry to purify the crude oil. The production of catalyst in KCC is done in two identical lines (Line A and Line B). The two lines are fully automated and identical with regard to the sequence and formation of the machines. The lines have similar production rates depending on the line's reliability at a certain time. Each line consists of two sections, the support section and the finishing section. The support section is the section that transfers the raw materials into the shape and size, and the properties of the catalyst are determined. The finishing section identifies catalyst type by introducing different chemicals.

The main concern of this study is to focus on reliability determination of manufacturing line at KCC and analysis of the effects of maintenance on system reliability, availability, and productivity. Maintenance is the act of preserving and protecting assets from failures. Maintenance is divided into two main categories: Preventive Maintenance is a scheduled maintenance action that is performed on a machine before it fails while Corrective Maintenance is an unscheduled maintenance action that is performed on a machine after a failure occurs. KCC maintenance department is responsible for keeping the production line in the best condition with the least cost. It has one senior maintenance engineer who's responsible for the management of the department. The maintenance department is divided into two sub-departments, mechanical and electrical departments. Mechanical department consists of seven workers: three mechanical workers; three skilled labor; and one welder. They work for six days per week in two shifts. Electrical and instrument department has one senior engineer and three technical workers, which work only one shift per day.

In KCC, corrective maintenance process begins with the failure occurrence. As a response, the maintenance staff is called to check the machine. Then, the machine is either directly fixed by the staff or the need for a spare part is determined. If a spare part is needed, a form must be prepared and sent to the spare parts warehouse. After receiving the spare parts the failure is fixed. The final step is the documentation of the failure. The production process at KCC starts from the two parallel hopper scales, which are scales that measure the raw material fed from the alumina silo and the chemicals tanks at desired weight, which is on average 500-600 kg/hr for each hopper scale. After the hopper scales come the two Kneaders that work in parallel for each line (Kneader 101 and Kneader 102 for line A) and (Kneader 103 and Kneader 104 for line B). A Kneader is a mixer that mixes the alumina powder and liquid chemicals into a dough. They are hung in a vertical manner to facil-

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itate the movement of the dough and its transportation to the Breakers. The breaker begins at the end of the kneader. The dough comes out of the kneader and pours into the breaker, which breaks it into smaller parts, and then the parts are transferred through the bucket conveys to the Extruder. The chunks of dough go through 180 die buttons in the extruder that can be changed depending on the catalyst type. The extruder cuts the dough by the die buttons and produces it in the shape of spaghettis. A horizontal conveyer attached to the extruder transfers its output to the next machine. Due to the chemicals added in the dough, it has a relatively high ratio of moisture that needs drying. The Drying process has to go through three stages because the material cannot withstand high temperatures at once. The company has three-stage drying mechanism, which is Pre dryer, Dryer, and Calciner. First is the pre dryer, which removes 52% of the moisture out of the catalyst. Then comes the dryer, which reduces the moisture level to 3-7%. The catalyst is then transferred to a storage tank which works as a buffer and holds up to 10000 kg. Next machine is Calciner, which is the final machine in the support section and in the drying process. It is a huge horizontal cylinder device that has a high temperature of 800 o¬¬C. The Calciner's function is to remove what ıs left of the moisture and produces a completely dry catalyst. Before the beginning of the finishing section, there is quality control check by a machine called Screens to remove any defects and abnormality in the production. The screens consist of two vibrating meshes that are on top of one another, the parts that are too big to pass the inspection are left on top of the first mesh and the ones which are too small are left in the bottom of the second mesh. That leaves the middle area between the two meshes for the non-defects. Another storage tank which also holds up to 10000 kg acts as a buffer before the beginning of the finishing section.

The finishing section starts wıth two parallel Impregnators. The impregnator is also a mixer; but it mixes the output from the support section with added chemicals that define the function and properties of the catalyst. After the impregnators comes the Soaker which keeps the catalyst in for two hours to assure total absorption of the chemicals by the catalyst. Then comes the drying process again, but in the finishing section it consists of only two stages, the dryer and the calciner. After drying all of the moisture from the catalyst, another quality control check is done by two parallel screens to assure optimal results. At last, comes the final Storage Bin at the end of the finishing section, which holds up to 10-12 metric tons of catalyst. The reason of the inclusion of two storage tanks in the support section and none in the finishing section is that the material flow rate in finishing section is higher than the one in the support section. The final step in this process is the Packing process, which is not fully automated, unlike the rest of the line. The packing of catalyst can be either in sacks or drums depending on the customer's request. Figure 1 shows the process flow diagram in the two manufacturing lines.

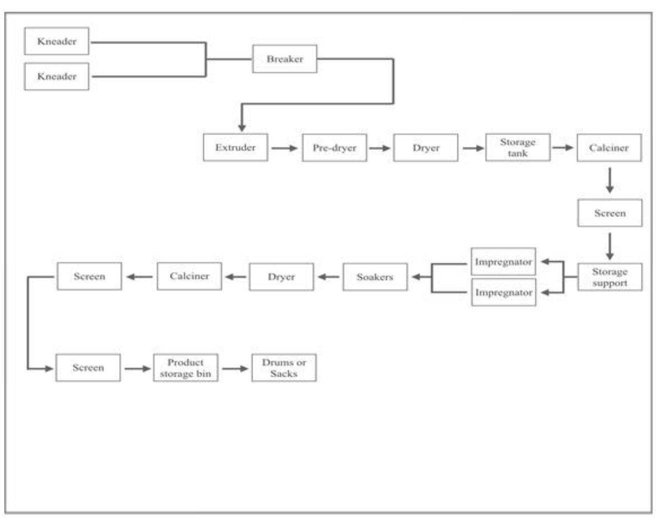

Fig. 1 . Machine sequence for manufacturing lines A and B

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A. Reliability Analysis of Equipment

Reliability of the system is defined as the probability that the system will adequately perform its intended function for a given period of time. There are several steps taken to calculate system reliability. In this section, we discuss the steps and procedures for system reliability calculations.

1. Data were collected on equipment failure dates and times during the year 2015.
2. Using the failure dates, time between failures (TBF) are obtained for each equipment on the line. It should be noted that time between failures is the difference between two subsequent failure times.
3. Time between failure data is entered into ARENA input analyzer software to obtain the failure distribution for each machine.
4. Using the time between failure distributions, reliability function is obtained for each machine. Reliability, R(t), is the probability that an equipment will not fail by time t. Therefore, R(t)=1-F(t), where F(t) is the cumulative failure distribution function. F(t) is the probability that failure time is less than t. Thus, 1-F(t) is the probability that failure time will be greater than t, which is the reliability of equipment by time t. As a case example, if the failure time is exponential, it has the exponential function as: $f(t) = \lambda e^{-\lambda t}$. The cumulative distribution function is $F(t)=1-e^{-\lambda t}$. Thus, the corresponding reliability function is R(t)=1-F(t) or $R(t)= e^{-\lambda t}$. Similarly, for other failure distribution functions, equipment reliabilities are obtained.

Since the reliability is a function of time, it is possible to determine equipment reliability for different time durations. Table 1 shows the list of equipment on manufacturing line A in the first column. The second column lists the failure distribution for the equipment; the third column shows the parameter(s) of the related distribution. The fourth column lists the reliability function for the equipment. The last two columns give the values of reliabilities for one day and for one week for each equipment. Similarly Table 2 shows the failure distribution functions, reliability functions, and reliability values for the machines on manufacturing line B. Note that the notation used in the analysis is as follows:

t = Study time period.

λ = 1/MTBF; the parameter of exponential distribution; failure rate. $f(t)=e^{-\lambda t}$.

MTBF= Mean Time Between Failures.

a, b = the parameters of the uniform distribution. UNIF(a, b). a=0 in reliability case.

θ, β = the parameters of the Weibull distribution. WEIB(θ, β).

It should be noted that Impregnator machine on line B did not have any failures during the study period of year 2015. Therefore, its reliability is assumed to be 1. In reliability calculations, one day was assumed to be 24 hours and one week was 7x24=168 hours.

As it can be seen from the calculations, reliabilities for one week are less than reliabilities for one day. This is expected since the longer the time duration, the higher is the probability of equipment failure. Also, when taking a closer look into the reliabilities of the machines of each line, the finishing dryer on line A appears to have the highest reliability, while Impregnator 202 on the same line has the lowest reliability. In case of line B, Impregnator 201 is the most reliable while the support dryer is the least reliable.

TABLE 1
RELIABILITY OF MACHINES ON LINE A

Machine	Distribution	Parameter (hr)	R(t)	Reliability (1 Day)	Reliability (1 Week)
Kneader 101	Exponential	278	$e^{-\lambda t}$	0.9173	0.5464
Kneader 102	Exponential	752	$e^{-\lambda t}$	0.9686	0.7998
Breaker	Exponential	896	$e^{-\lambda t}$	0.9736	0.8290
Extruder 101	Uniform	(564,1720)	1-t/b	0.9861	0.9023
Support dryer	Exponential	779	$e^{-\lambda t}$	0.9735	0.8285
Support Calciner	Exponential	779	$e^{-\lambda t}$	0.9697	0.8060
Impregnator 201	Uniform	(239,1240)	1-t/b	0.9806	0.8645
Impregnator 202	Weibull	(473,0.395)	$e^{-(t/\theta)^{\beta}}$	0.7349	0.5146
Finishing Dryer	Uniform	(177,2280)	1-t/b	0.9895	0.9263
Finishing Calciner	Uniform	(768,2250)	1-t/b	0.9893	0.9253

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TABLE 2
RELIABILITY OF MACHINES ON LINE B

Machine	Distribution	Parameter (hr)	R(t)	Reliability (1 Day)	Reliability (1 Week)
Kneader 103	Uniform	1679	1-t/b	0.9857	0.9
Kneader 104	Uniform	(456,3030)	1-t/b	0.9921	0.9445
Breaker	Exponential	1020	$e^{-\lambda t}$	0.9767	0.8481
Extruder 103	Exponential	616	$e^{-\lambda t}$	0.9618	0.7613
Support dryer	Exponential	472	$e^{-\lambda t}$	0.9504	0.7005
Support Calciner	Exponential	777	$e^{-\lambda t}$	0.9695	0.8056
Impregnator	201	-	-	- 1.00	1.00
Impregnator 202	Exponential	482	$e^{-\lambda t}$	0.9514	0.7057
Finishing Dryer	Uniform	(408,2580)	1-t/b	0.9907	0.9349
Finishing Calciner	Uniform	(264,1950)	1-t/b	0.9876	0.9138

B. Reliability Calculation of the Production Lines

After determining the reliability of individual equipment, manufacturing line reliability is estimated by considering the structure of the line. In particular, two aspects are considered. First, serial or parallel structure of machine operation is an important aspect in reliability calculation. Second, the position of intermediate storages, which decouple the line segments and help independent operation is incorporated into the reliability estimation. Thus, we estimate manufacturing line reliability for two cases: without considering intermediate storage buffers and with considering intermediate buffers. The machine sequences in each line are shown in Figure 1 for both lines A and B. Two basic formulations are used for the serial and parallel machine configuration and operations as follows:

$$R^{\text{sys}} = \prod_{i=1}^{n} R^{i} \tag{1}$$

$$R^{\text{sys}} = 1 - \prod_{i=1}^{n} (1 - R^{i}) \tag{2}$$

Considering the parallel and serial machine structures as given in Figure 1 and the machine reliabilities as given in Tables 1 and 2, system reliabilities are calculated for lines A and B and presented in the first column of Table 3.

After calculating the reliability of the system based on serial and parallel machine structures, it was necessary to look into intermediate storage buffers or storage tanks on the line. The existence of tanks is expected to increase the system reliability since they act as a storage area for the material that keeps the line in a steady flow even if there is a failure in one of subsequent sections; the sections that are before or after the storage tank. After researching for a similar case with two intermediate storage tanks in the literature, it was found that no exact study existed. Only some studies for two-stage lines were found. They have been mentioned in literature review. In order to analyze the system with two buffers and three stages, we have used an approximation approach. The system was divided into three subsystems according to the number of tanks. The first subsystem includes: Kneaders, Breaker, Extruder and Support Dryer. The second subsystem includes: Support Calciner. The third subsystem includes: Impregnators, Finishing Dryer and Finishing Calciner. Figure 2 illustrates the system as divided into three sections with two storages. Note that the machines included in the subsystems were the machines that have historical failures only.

The approach used to address this issue was the assumption of connecting the subsystems in parallel and series using the equations needed. This assumption was made on the basis that if the first subsystem fails, the second subsystem will not be affected as the tank already stores material which keeps the production line flowing steadily, so they were considered to be in parallel. Moreover, if the second subsystem fails, the third one will not be affected, so they were also considered to be in parallel. Then, the equivalent two reliabilities were considered to be in series, because the failure of the first two subsystems will cause the third one to fail. The previously mentioned series and parallel formulas were applied. The same procedure was done on both lines A and B for 1 day and 1 week. The reliability results are shown in the second column of Table 3. As it is seen in Table 3, line reliabilities are much higher in case of the inclusion of storage tanks as compared to without storage tanks.

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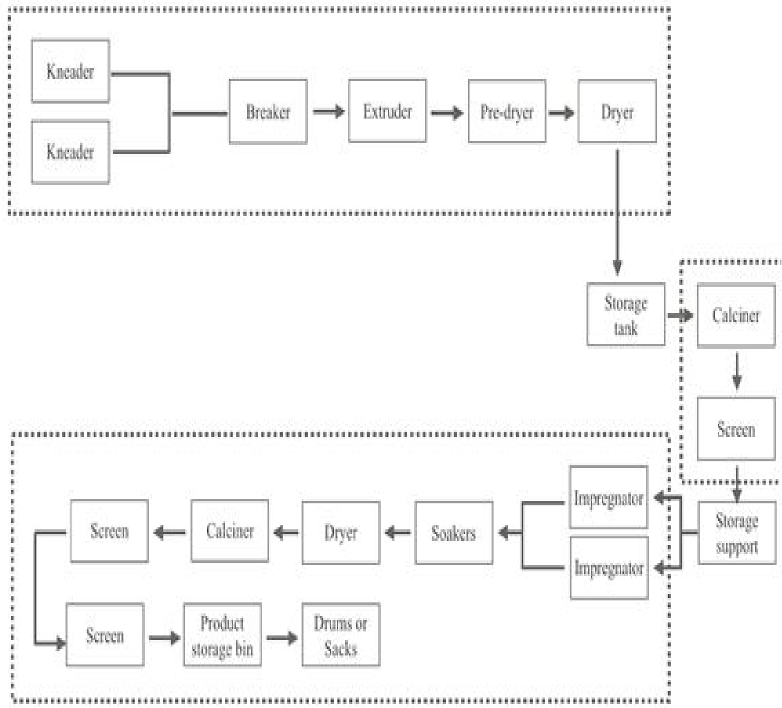

Fig. 2 . Division of line into three subsystems by storage tanks

TABLE 3
RELIABILITY OF MACHINES ON LINE A

		System reliability without tanks	System reliability with tanks
Line A	1 day	0.8118	0.9910
	1 week	0.3640	0.7458
Line B	1 day	0.8469	0.9948
	1 week	0.2186	0.8313

C. Maintenance Analysis

Maintenance is an essential activity in industry in order to keep the equipment in operation. In this section, we present maintenance related procedures and analysis that can guide engineers, who are dealing with the same problem. There are two types of basic maintenance actions: Corrective Maintenance (CM) and Preventive Maintenance (PM). Mean corrective maintenance time is the average value of unscheduled corrective maintenance time that is required to repair a failure on the line. It is calculated by finding the weighted average of the individual machine failures, Mct$_i$, by formula below. The mean corrective time is found to be 19.995 Hours/Repair, by equation (3).

$$M_{ct} = \frac{\sum_{i=1}^{n} \lambda_i M_{cti}}{\sum_{i=1}^{n} \lambda_i} \quad (3)$$

Where: M$_{ct}$= Overall Mean corrective maintenance time.
M$_{cti}$= Mean corrective maintenance time for the i$_{th}$ machine.
λi= Failure rate for the ith machine.

The average failure rate and mean corrective maintenance time of each machine are given in Table 4. These averages are based on the equipment downtime from the 2015 historical data. Also, the failure rates for each machine are the inverse of the mean time between failure for each machine.

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TABLE 4
FAILURE RATES AND MEAN CORRECTIVE TIME FOR EACH MACHINE

Machine	λ_i (Hours)=1/MTBF$_i$	M$_{cti}$ (Hours/Repair)
Kneader 101	0.000579	1.8
Kneader 102	0.000697	4.67
Kneader 103	0.000928	2
Kneader 104	0.000464	2.75
Breaker A	0.000813	4.29
Breaker B	0.000813	4.14
Extruder 101	0.000734	168
Extruder 102	0.000624	120
Predryer A	0.000232	3.5
Predryer B	0.000464	4.5
Support Dryer A	0.000817	11
Support Dryer B	0.001881	8.36
Finishing Dryer A	0.000695	1.5
Finishing Dryer B	0.000580	4.6
Support Calciner A	0.001047	4.67
Support Calciner B	0.000696	3.83
Finishing Calciner A	0.000464	5.25
Finishing Calciner B	0.000812	3.42
Impregnator 201 A	0.001212	2.54
Impregnator 202 A	0.000695	1.5
Impregnator 201 B	0.000000	0
Impregnator 202 B	0.000814	2.57

Mean preventive maintenance time represents the average time required to do a scheduled preventive maintenance action. It is calculated by the following formula:

$$M_{pt} = \frac{\sum_{i=1}^{n} M_{pt}}{n} \quad (4)$$

Where: M$_{pt}$= Overall Mean Preventive maintenance time.
M$_{pti}$= Preventive maintenance time for the i$_{th}$ machine.
n = number of preventive maintenances.

The preventive maintenance schedule and time spent on each preventive maintenance job for the year 2015 were taken from the company and shown in Table 5. Combined mean preventive time was found to be 41.67 hours by equation (5). After looking into the schedule it was noticed that PM was done in a random manner without a prior study.

TABLE 5
FAILURE RATES AND MEAN CORRECTIVE TIME FOR EACH MACHINE

Date	Description	Down Time (hours)
17/4/2015	Preventive maintenance was carried on the Impregnators	14
2/5/2015	Preventive maintenance was carried on the Support Dryer	13
11/7/2015	Preventive maintenance was carried out on Finishing Calciner	15
14/7/2015	Preventive maintenance was carried on Support Calciner	22
17/7/2015	Preventive maintenance was carried out on Finishing Dryer	19
20/7/2015	Preventive maintenance was carried on the Kneaders	19
12/8/2015	Preventive maintenance was carried on the Screens	17
17/8/2015	Preventive maintenance was carried on the Breakers	16
10/10/2015	Preventive maintenance was carried out in the Extruder	240

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The frequency of preventive maintenances is found to be 9/8760 = 0.001027 job per hour by using the following equation for line A.

$$f = \frac{\text{Number of preventive maintenance action in the study period}}{\text{Total operating hours of the study period}} \quad (5)$$

$$\bar{M} = \frac{(\lambda)(\bar{M}_{ct}) + (f)(\bar{M}_{pt})}{\lambda + f} \quad (6)$$

Mean active maintenance time is the mean elapsed time required to perform preventive (scheduled) maintenance or corrective (unscheduled) maintenance for the system. It excludes logistic delay time and administrative delay times required to provide spare parts and other. The mean active maintenance time was found using equation (6) below.

For line A: (0.0071 x21.25) + (0.001027 x41.67) / (0.0071x 0.001027) = 23.84 hr.

For line B: (0.0065 x 16.57) + (0.001027 x41.67) / (0.0065x 0.001027) = 20 hr.

This means that on average it takes 23.84 hours to perform a maintenance job on line A and 20 hours for line B, whether it is preventive maintenance or corrective maintenance. Maintenance Downtime is the mean elapsed time required to perform preventive (scheduled) maintenance and corrective (unscheduled) maintenance for the system, it includes Logistic Delay Time (LDT) and Administrative Delay Time (ADT). It is calculated by formula (7).

$$MDT = \bar{M} + LDT + ADT \quad (7)$$

For Line A: MDT = 23.84+ 0.167+ 0 = 24.007 hr.

Line B: MDT = 20.01+ .167+ 0 = 20.177 hr.

On average the maintenance downtime for either a corrective maintenance job or a preventive maintenance job equals 24 hours for line A and 20.2 hours for line B.

The mean time between combined maintenances (MTBM) represents the mean time between corrective maintenance or a preventive maintenance combined. It is given by equation (8).

$$MTBM = \frac{1}{\lambda + f} \quad (8)$$

For Line A: MTBM= 1/ (0.0071+ 0.001027) = 123.3 hr.

Line B: MTBM= 1/ (0.0065+ 0.001027) = 133.3 hr.

The mean time between maintenances is 123.3 hours for line A and 133.3 hours for line B as found from equation (8). This means that in every hour, a maintenance job takes place whether it is a corrective or a preventive maintenance.

D. Availability Calculations without Considering Storage Tanks

Availability is a measure of system readiness, which is the probability that the system will be ready or available when required. In this section, we present system availability calculations for both lines A and B assuming that intermediate storage buffers are not considered. Depending on calculation, there are three types of availabilities:

Inherent availability, Achieved availability, and Operational availability. These availabilities are calculated as follows:

Inherent availability is the probability that the system will work in an ideal way at any point in time assuming no preventive maintenances or scheduled maintenances, logistic delays and administrative delays are applied or exist in the system. It is calculated with the formula below:

$$A_i = \frac{MTBF}{MTBF + MTTR} \quad (9)$$

Inherent availabilities are calculated as Ai= 0.869 for line A and Ai= 0.903 for line B.

Line A: Ai= 141.18 / (141.18+ 21.25) =0.869.

Line B: Ai= 154.32 / (154.32+16.57) = 0.903.

Achieved availability is the probability that the system will work in an ideal way at any point in time assuming that preventive maintenance or scheduled maintenance are applied; however, no logistic or administrative delays exist. It is calculated as follows:

$$A_a = \frac{MTBM}{MTBM + \bar{M}} \quad (10)$$

The achieved availability is found by equation (10) for line A as 0.838 and for line B as 0.869. Detailed calculation is as follows:

Line A: Aa= 141.18 / (141.18 +23.84) = 0.838.

Line B: Aa= 154.32 / (154.32 +20) = 0.869.

Operational availability is the probability that the system will work in an ideal way at any point in time. It includes preventive maintenance or scheduled maintenance; possible logistic and administrative delays are included in the calculations.

$$A_o = \frac{MTBM}{MTBM + MDF} \quad (11)$$

The operational availability is found by equation (11) to be 0.837 for line A and 0.868 for line B. Detailed calculations are done as follows:

Line A: Ao=141.18/ (141.18+24) = 0.837.

Line B: Ao=154.32 / (154.32+20.16) = 0.868.

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E. Availability Study with Consideration of Storage Tanks

Previously calculated availability study was for the system as a whole without considering the effect of storage tanks. Since there were no study for analysis of lines with two or more intermediate storages, we have estimated the solution based on two different approaches; approach I and approach II. Approach I. Two intermediate storages divided the system into three subsystems as mentioned above. The production rate and the inherent availability were determined and then multiplied by the production rate for each subsystem individually. The least result was chosen as the system production per hour since it represented the bottleneck. The least was chosen because the three subsystems operate in series. The same procedure was done for both lines. Tables 6 and 7 show the calculations for lines A and B separately. Each line was divided into three subsystems; the availability of each was found by using Equation (9) and each subsystem had a different production rate Q. Multiplying the production rate by the availability gives the actual line production rate. The minimum is the bottleneck. Production rates are found as 398 kg/hr for line A and 397.8 kg/hr for line B.

TABLE 6
LINE A AVAILABILITY FOR APPROACH A

	Ai	Qi(K¬g/hr)	Qi(Ai) (Kg/hr)
Subsystem 1	0.876562	600	525.9372
Subsystem 2	0.995139	440	437.86116
Subsystem 3	0.99518	400	398.072

TABLE 7
LINE B AVAILABILITY FOR APPROACH A

	Ai	Qi (Kg/hr)	Qi (Ai) (Kg/hr)
Subsystem 1	0.90979	600	545.874
Subsystem 2	0.99734	440	438.8296
Subsystem 3	0.9945	400	397.8

Approach II. This method is based on a previous study done by [3] which presents a formulation for a serial line with a single buffer storage and two subsystems. The following rule is used to find the availability for two subsystems with respect to buffer storage tanks using the formulas below. The first and second subsystems availabilities were calculated by the given rule while neglecting the third one. Moreover, the second and the third subsystem availabilities were calculated while neglecting the first. Then, the whole system availability was calculated by multiplying the equivalent two availabilities by the least production rate for each subsystem. After that, the least resultant multiplication was chosen as the system availability. In the formulation below, c = Filling Rate/Emptying Rate of the storage tank = q/v. Tables 8 and 9 present the related calculations for availabilities and the production rates for the lines A and B. Note that Q12 represents minimum production rate of the first line subsystem consisting of two stages (stages 1 and 2), while Q23 represents minimum production rate of the second subsystem of the line consisting of two stages (stages 2 and 3). A_{12} and A_{23} represent the availabilities of subsystems 1,2 and 2,3 respectively.

TABLE 8
AVAILABILITY CALCULATIONS WITH RESPECT TO TANKS FOR APPROACH B

	C12	C23	K12	K23	A12	A23	Q12(min)	Q23(min)
Line A	1.3636	1.1	0.1218	0.00112	0.8733	0.9909	440	400
Line B	1.3636	1.1	0.16714	-0.05755	0.90793	0.9921	440	400

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TABLE 9
PRODUCTION RATES FOR APPROACH II

	Q12(min).A12	Q23(min).A23
Line A	384.252	396.36
Line B	399.4892	396.84

They are calculated by the formula (14) given for A(k). Note that k value corresponding to the subsystem consisting of stages 1 and 2 is given by k12 and k value for subsystem consisting of stages 2 and 3 is given by k23. λi and μi are failure and repair rates.

$$k = \frac{(\mu_1 + \mu_2 + \lambda_1 + \lambda_2)(\lambda_1\mu_2 - \lambda_2\mu_1)}{(\mu_1 + \mu_2)(\lambda_1 + \lambda_2)c} \tag{12}$$

$$p_i = \frac{\lambda_i}{\mu_i} \tag{13}$$

$$A(k) = \frac{(p_1 - p_2 e^{-k})A_1 A_2}{p_1 A_2 - p_2 A_1 e^{-k}} \tag{14}$$

III. CONCLUSION

Productivity is the main concern in manufacturing systems. In order to achieve higher productivity, equipment availability must be kept at higher percentage rates. Availability depends on system reliability. The higher the reliability, the higher is the availability. Equipment failures are unavoidable. No matter how reliable an equipment is, it can fail due to random chances and wear outs. Therefore, equipment must be continuously maintained by regular preventive maintenance activities in order to eliminate possible failures due to wear outs and system deterioration.

In analyzing operations of manufacturing systems, it is necessary to determine the reliability of the complete system so that system availability and productivity can be assessed. After the system reliability is assessed, appropriate maintenance policies are determined for the system under consideration. In this paper, we have considered a specific manufacturing system and developed several procedures, which could be used by operations and maintenance engineers, in order to determine system reliability and system availability under different operational conditions.

This study consisted of several phases: defining the system; analyzing it in detail; determining failure distributions; determining individual equipment reliabilities; calculating complete system reliability; finding various types of system availabilities; and determining system throughput rate under specified operational conditions. The procedures and models presented in this paper can be extremely useful for the operations engineers in analyzing their systems and improving their operations.

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— This article does not have any appendix. —