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An optimal preventive maintenance model to enhance availability and reliability of flexible manufacturing systems

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Abstract

General preventive maintenance model for the components of a system, which improves the reliability to 'as good as new,' was used to optimize the maintenance cost. The cost function of a maintenance policy was minimized under given availability constraint. On the other hand, in order to ensure appropriate reliability and availability, the development of the optimal maintenance policy is the one of the main issues in system to perform preventive maintenance (PM) in equipment. In this paper, maintenance characteristics of a typical flexible manufacturing system (FMS) have been determined. These characteristics can be used to understand and prevent the complex reality of failures and repairs. Also, an optimal model for the preventive maintenance management of a FMS has been presented based on preview literature in order to enhance availability and reliability of this system and to reduce the cost of maintenance tasks. Finally, proposed framework has been applied for a robot paint sprayer and its results shown in a form of the preventive maintenance plan, distribution fitting and Reliabilities' parameters for each component s of robot paint sprayer, and the maintenance scheduling timetable.

Keywords*:* Maintenance management, preventive maintenance, flexible manufacturing systems, availability, reliability, maintenance scheduling

1- Introduction

The literature is replete with examples of how computer controlled manufacturing technologies such as FMSs and computer integrated manufacturing (CIM) can be utilized to improve the strategic and competitive positions of firms. Significant improvements in inventory levels, space requirements, lead and cycle times, scrap and yield rates and other quality measures have been reported. In some cases, the benefits are truly impressive and border on orders of magnitude improvements. With increased global competition for manufacturing, many companies are seeking ways to gain competitive advantages with respect to cost, service, quality, and on-time deliveries. The role that effective maintenance management plays in contributing to overall organizational productivity has received increased attention (Luxhøj et al., 1997).

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As more and more factories employ the FMS technology, the subject of maintenance management is taking on a renewed importance. The failure of a single component can not only idle a very expensive piece of equipment but, due to reduced work-in process, the failure can quickly idle an entire production system. This is compounded in a just in time (JIT) environment where the flow of finished goods is disrupted, thus delaying customer shipments at the intangible but real cost of customer goodwill.

A second reason for the increased importance of maintenance management when using computer controlled manufacturing technology is the increased flexibility created by these programmable systems. Since an FMS is programmable it is expected to have a life expectancy greater than the single product or part family it was originally intended to produce. Companies are justifying these systems based on a longer expected life and the assumption they will not have future expenditures for replacement equipment (Fotsch, 1985). However, this is based on the assumption that the FMS's physical life will be longer than an organization's need for the system. These systems are not expected to achieve their potential effectiveness unless the ramp-up time is kept to a minimum (Nada et al., 2006). Therefore, maintenance policies capable of keeping these systems from physically deteriorating during their extended useful life will be required. The identification and implementation of such effective policies will enable managers to avoid premature replacement costs, maintain stable production capabilities, and prevent the devaluation of the system and its component parts.

During an FMS's extended useful life, it will experience a very different wear and tear history than a traditional machine tool operating during the same time period. It is estimated that an FMS will operate at 80% utilization or higher whereas a traditional machine tool would probably be utilized at only 20% (Meredith, 1988). This will result in the FMS incurring four times the wear during any given time period. It is not well known what the effect of such accelerated usage will be on the system, but it is generally agreed it will significantly increase the importance of maintenance and maintenance related activities.

Another reason for the increased importance of maintenance management for this technology is the synergistic benefits attributed to these systems. The linking of stand-alone systems into an FMS has created qualitative benefits such as faster response to customer requests, ability to customize products, improved quality, and better production control. These benefits are synergistic and make a significant additional contribution. Consequently, the cost of an isolated failure not only includes the loss of that piece of equipment, but also includes the loss of the significant contributions of synergy. Therefore, it will be important for maintenance management to consider not only the amount of time a machine is down for maintenance but also the timing of when it is down and the resulting synergistic costs (Koomsap et al., 2005).

Finally, these technologies are less reliant on skilled craftsmen for their day to day operations. The skills required for high precision machining have been embedded in the part and operating software, thus enabling the systems to be operated by fewer personnel with less traditional machining experience. However, the elimination of the skilled personnel has also removed a valuable maintenance management resource. The highly skilled machinist not only operated the machine but also continually monitored the machine for component wear or failure. Maintenance managers now realize these operators were performing preventive and minor corrective maintenance as well as reporting potential problems before they became major failures.

The above arguments point out the need for more research aimed at understanding maintenance management for advanced manufacturing technologies such as FMS. An essential element in maintenance management research will be knowledge of the failure and repair characteristics of FMSs.

The objectives of this paper are as follows:

- Enhance the availability and reliability measures of FMSs
- presenting the optimal preventive maintenance model for FMS, and calculating the interval of time between preventive maintenance actions for each component
- Minimizing the costs, and maximizing the total availabilities of system

- Helping the researchers and managers understand the complex reality of failures and repairs in a highly integrated advanced technological system such as an FMS and present schedule for conditional maintenance.

2- Maintenance characteristics of flexible manufacturing systems

An FMS is a combination of complex components integrated through computer systems. Each component of an FMS is a combination of many parts, where each part is itself complex and consists of many dissimilar interdependent components. The focus of general maintenance policies is on similar failure distributions for similar components. Whereas these policies in an FMS must consider a complex system consists of many dissimilar components. Mostly, the main components of an FMS include components such as mechanical, electronic, hydraulic, electro-mechanical, software, and human elements with considering different failure rate distributions. Therefore, because of the integrity of the components of FMSs, attention to the whole of system is necessary in their maintenance plan instead of individual parts or components (Cho and Parlar, 1991). Pintelon et al. (1995) also mention that the complexity and stochastic nature of maintenance requirements in such system make deciding on an appropriate maintenance policy a very difficult task. Many researchers have been done to develop appropriate maintenance plan for system or equipment with assumed failure characteristics (McCall, 1965; Lie et al., 1977; Sherif and Smith, 1981; Gits, 1986). It should be noted that it cannot provide the necessary data such as failure modes and failure data for each component of an integrated system with multi-component machines (Pintelon et al., 1995; Tsai et al., 2004). So, the obtaining and analysing of data to determine the actual failure distributions for the each component of a complex system would be an important research contribution.

Duarte et al. (2006) proposed an algorithm to solve the previous problem for equipment that exhibit linearly increasing hazard rate and constant repair rate. Based on this algorithm, they have developed another one to solve the problem of maintenance management of a series system based on preventive maintenance over the different system components. Zhou et al. (2007) have been presented an Integrated Reconfiguration and Age-Based Maintenance (IRABM) policy and applies it to a parallel-serial manufacturing system. In their research, the influences of the input parameters associated with reconfiguration, production, and reliability on the performance of IRABM policy have been studied. Also, Yang et al. (2007) has been introduced a method for optimizing system level effects of maintenance operations by coupling traditional maintenance operations of machine repair and replacement with changes in machine throughput settings. Consideration of multiple failure modes on each machines (or components), with the corresponding reliability characteristics and repair time distributions has been proposed from them for future work.

The above clearly shows that studies documenting and characterizing actual FMS failures and their distributions would make a contribution to the understanding of maintenance management for FMSs. Several authors have alluded to the lack of reliable maintenance data and its impact on maintenance decision making (Cho and Parlar, 1991; Pintelon et al, 1995). Further, Pintelon et al. (1995) note that a possible reason for the gap between maintenance theory and practice is the lack of reliable data on maintenance systems and this absence of reliable data could be attributed to inaccurate recording and inappropriate data aggregation. Also, it has been noted that until recently managers themselves did not consider maintenance data such as equipment failure history an asset.

3- Optimization of the preventive maintenance plan of a FMS

In this section, we will present a model for the preventive maintenance management of a FMS in order to enhance availability and reliability of this system and to reduce the cost of corrective and preventive maintenance tasks. The system is composed of a set of n components in series-parallel as figure 1 shows.

Let Tp_{ik} be the time unit between preventive maintenance tasks on i th component in the k th parallel subsystem (figure 2); assuming that these actions will restore periodically the components to the ‘as good as new' condition, they will have, therefore, consequences at the reliability and availability levels of the system.

Our goal is to calculate the vectors:

$[Tp_{11}, Tp_{21}, \dots, Tp_{n1,1}], [Tp_{12}, Tp_{22}, \dots, Tp_{n2,2}], \dots, [Tp_{1K}, Tp_{2K}, \dots, Tp_{nK,K}]$

(which $n = n_1 + n_2 + \cdots + n_K$)

In such a way that the total down time in a certain period of time does not exceed a predetermined value, that is to say, that it guarantees the specified service level and simultaneously minimizes the maintenance costs.

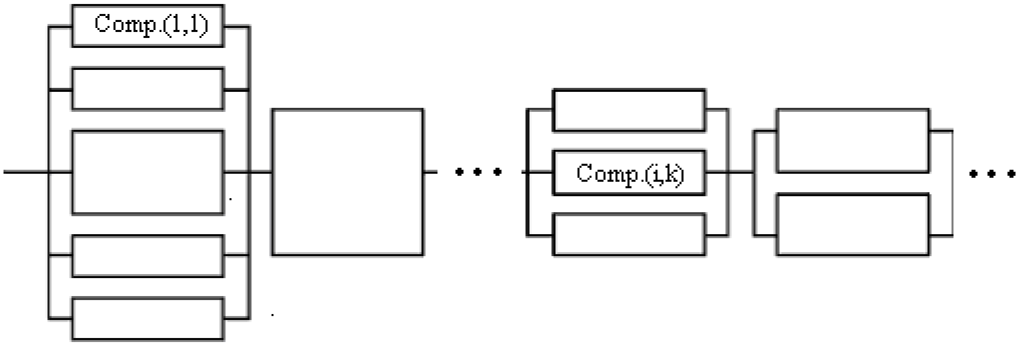


Fig 1. A FMS with *n* components

For every component under an age-based preventive maintenance (PM) policy there exist two types of maintenance actions: PM and corrective maintenance (CM). The mean time to failure (at which a CM must be carried out) and the PM interval together with their probabilities of occurrence are interrelated. Longer PM intervals result in greater mean times to failure. But at the same time the probability of occurrence of a failure at higher PM intervals is higher. These relationships can be used to define the optimal PM interval that minimizes the costs per unit time.

0	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}
$Tp_{1,1} = t_2$												
Component(1,1)		■		■		■		■		■		■
. . .							. . .					
$Tp_{n1,1} = t_4$												
Component(n_1,1)				■				■				■
. . .							. . .					
$Tp_{1,K} = t_3$												
Component(1,K)			■			■			■			■
. . .							. . .					
$Tp_{nK,K} = t_5$												
Component(n_K,K)					■					■		

Fig 2. A PM plan.

By adopting some authors ((Lhorente et al., 2004; Jardine, 1973; Bris et al., 2003; and Duarte et al., 2006), the following steps can be taken.

Defining:

$Cp\ (i, k)$	the cost of each preventive maintenance tasks
$C_f\ (i, k)$	the cost of each corrective maintenance tasks
T_p	PM Interval (operating hours)
$F(T_p)$	Probability of a failure occurring before reaching the PM interval T_p
$R(T_p)$	reliability, Survival probability; $R(T_p) = 1- F(T_p)$

Thus, within the age-based PM policy two different cycles can be distinguished: the component survives T_p and a PM is carried out incurring a cost C_p or the component fails beforehand and a CM must be carried out incurring a cost C_f. For this model the expected costs per unit time in function of T_p can be written as

$$C(Tp) = \frac{Cp \times R(T_p) + Cf \times F(T_p)}{T_p \times R(T_p) + M(T_p) \times F(T_p)} \tag{1}$$

where $M(T_p)$ represents the mean time to failure of an armature subject to corrective maintenance with a PM interval of T_p and,

$$F(T_p) = \int_0^{T_p} f(t)dt \tag{2}$$

$$M(T_p) = \frac{\int_0^{T_p} tf(t)dt}{F(T_p)} \tag{3}$$

where f(t) is the probability density function (p.d.f.) of the times to failure.

Whenever the p.d.f. of the times to failure of the component is known, the costs per unit time can be minimized over T_p; resulting in the optimal PM interval T_p^* .

Since, the availability of the system consisting of n components in series-parallel requires that all subsystems must be available (assuming that components' failures are independent), system availability A is:

$$A = \prod_{k=1}^{K} \left(1 - \prod_{i=1}^{n_k} \left(1 - A_{i,k} \right) \right)$$

where $A_{i,k}$ is the availability of *i*th component in the *k*th parallel subsystem.

Theorem. Let us assume a coherent system with randomly generated periods of inspection Tp(*i*, *k*). Apparently, the availability of the system at time *t* ($A_S(t)$) satisfies the following condition:

$A_S \geq WRV$.

Then the minimum value of system's availability (i.e. **min $A_S(t)$)**, converges for time going to infinity, to a value greater or equal then WRV, which is given as follows

$$\lim_{t \to \infty} \left[\min_{(0,t)} A_S(t) \right] \geq WRV.$$

WRV = *h*(A); A= (A_1, A_2, …, A_N), where

$$A_{i,k} = \exp\left[-\frac{Tp_{i,k}}{M(Tp_{i,k})} \right]$$

is the availability of the *j*th component at the end of its inspection period $Tp_{i,,k}$ ($i = 1, \ldots, n_k$ and $k = 1, \ldots, K$) (see proof of Theorem at Bris et al.(2003)).

The objective function (defined as a cost function per unit time) is

$$Min \quad C\left(A_{11}, \cdots, A_{n1,1}, \cdots, A_{1,K}, \cdots, A_{n_K,K}\right) = \sum_{k=1}^{K} \sum_{i=1}^{n_k} C\left(Tp_{i,k}\right)$$

$$subject\,to$$

$$\begin{cases} \prod_{k=1}^{K} \left(1 - \prod_{i=1}^{n_k} \left(1 - A_{i,k}\right) \right) \geq A, \\ 0 < A_{i,k} < 1; i = 1, \cdots, n_k, k = 1, \cdots, K \end{cases}$$

4- Failures that can be prevented

Failure modes, effects, and criticality analysis (FMECA) provides a method for determining which failures can be prevented. Necessary inputs all the frequency of occurrence for each problem and cause combination and what happens if a failure occurs. Criticality of the failure is considered for establishing priority of effort. FMECA is a bottom – up approach that looks at every component in the equipment and asked "Will it fail?" and if so, "how and why?" PM investigators are, of course, interested in how a component will fail so that the mechanism for failure can be reduced or eliminated. For example, heat is the most common cause of failure for electrical and mechanical components. Friction causes heat in assemblies moving relative to each other, often accompanied by material wear, and leads to many failures.

5- Numerical example

5-1- Robot paint sprayer

The case study selected in this work involves a robot paint sprayer. There are three parts:

a) The robot
b) The hydraulic system
c) The control cabinet

The robot positions the paint spray gun in space by the actions of six hydraulic jacks referred to as servos 1-6. The hydraulic system feeds oil under pressure to the robot, to provide the driving power. The control cabinet this houses the electronic system that controls the movements of the robot and holds the programs for the painting routines; it includes a control panel and connections to external equipment.

The electronic system comprises (figure 3):

- The hydraulic-power generation system
- The memory
- The servo system
- The AC supply
- The start-stop system
- The parity check system
- The digital control system
- The circuit-checking system

The functions of the various servos are as follows:

Servo 1 (linear motion): lateral movements of the robot arm
Servo 2 (linear): forward/backward movements of the robot arm.
Servo 3 (linear): up/down movements of the robot arm
Servo 4 (linear): positions the spray gun in the vertical plane
Servo 5 (linear): positions the spray gun in the horizontal plane

Servo 6 (rotary): rotates the spray gun

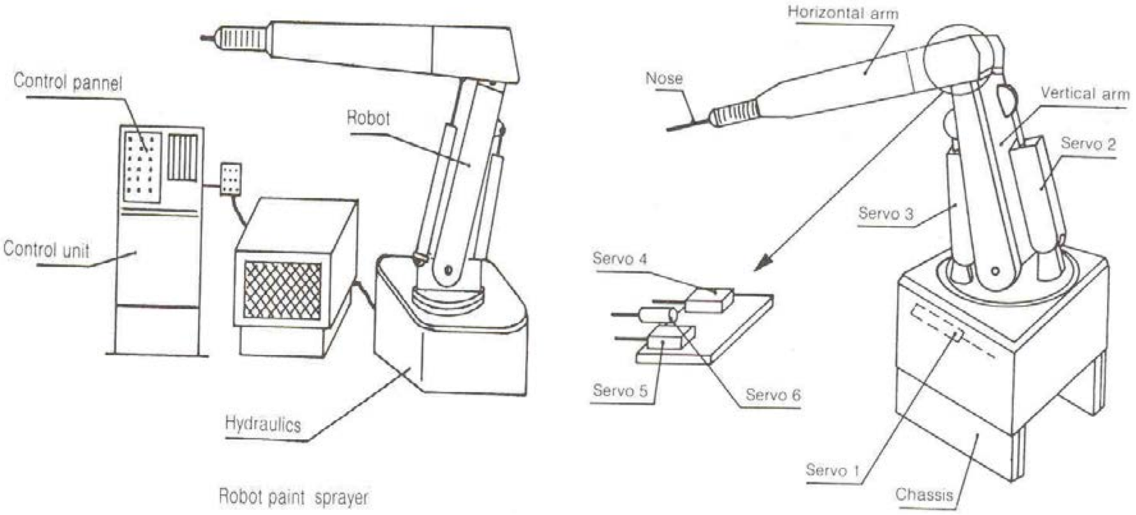


Fig 3: Robot paint sprayer - electronic system

5-2- Objective, data available

The ultimate aim is to reduce the number of breakdowns, by:

- Laying down a rationally planned program of preventive maintenance
- Introducing suitable technical improvements

The data on which to base this is a record of the failures of a similar machine installed on the same site, referred to as Robot 2; this gives:

- The data of each event
- The length of time out of service
- The nature of the fault and the repair/restoration work done
- A reference identifying the part of the equipment the failed.

Table 1. Robot paint sprayer: system components

Reference	Description
A	Gun electromagnetic valve
B	Jack
C	Horizontal arm
D	Control desk
E	Robot
F	Arm-movement detector
G	Oil pressure low/failed
H	Diskette
I	Circuit card DH
J	Servo circuit card(s)

5-3- The ABC analysis

Its aim is to identify the failures that cause the greatest amount of disruption. The results for this case are given in Table 1. The causes of the greatest disruptions are given in table 2. This shows that 76% of all lost time results from failures under E and D, and therefore most effort should be put into investigating these causes.

5-4-Distribution fitting

For the determination of the p.d.f. in this study, the Weibull distribution was chosen, due to its flexibility in representing components with constant, increasing and decreasing failure rates. To construct an optimum schedule for conditional maintenance we need to compute the Weibull models for the different types of failure; with the standard notation for this law.

$$R(t) = \exp(-(t-\gamma)/\alpha)^{\beta} \qquad (\gamma = 0) \tag{4}$$

Where β is the shape parameter and α is the scale factor or characteristic life.

5-5- The preventive maintenance plan

Records of the times between failures (TBF) for the different parts of the system are shown in the table 2 (all times presented in hours).

The cost of time lost is estimated at 4,650,000 Rials per minute; so the costs attributable to the most serious failures and operating records have been presented in table 3 and table 4, respectively.

Table 2. The times between failures for robot components

Robot components	First failure	TBF
Gun	160	100-150-30-45-170-195-200-250-340-60
Jack	800	250-400-430-670-1000-1500-1200-1050-480
Horizontal arm	-	No failures
Control desk	140	55-40-70-120-150-270-200-190
Robot	200	110-208-170-190-155-230-340-150-160-195-280-250
Arm-movement detector	50	45-60-72-68-95-12-18-40-49
Oil pressure	-	No failures
Diskette	-	No failures
Card DH	200	111-70-50-60-80-904-100-75-67-71-110
Servo card(s)	150	130-150-117-200-180-155-140-130-81-75

Table 3. The cost of time lost for some components

Robot components	Cost (Rials)
A	744,000,000
B	69,750,000
D	2,464,500,000
E	3,580,500,000
F	558,000,000
I	441,750,000
J	46,500,000

Table 4. Robot paint sprayer: operating records

Reference	**Description**	**Time lost (Mean Downtime)**	**Cumulative**	**Percentage**	**Availability**
E	Robot	770 min.	770	45%	0.9394
D	Control desk	530	1300	76	0.9394
A	Gun	160	1460	85	0.9830
F	Movement detector	120	1580	93	0.9623
I	Card DH	95	1675	98.5	0.9898
B	Jack	15	1690	99.4	0.9997
J	Servo card(s)	10	1700	100	0.9988

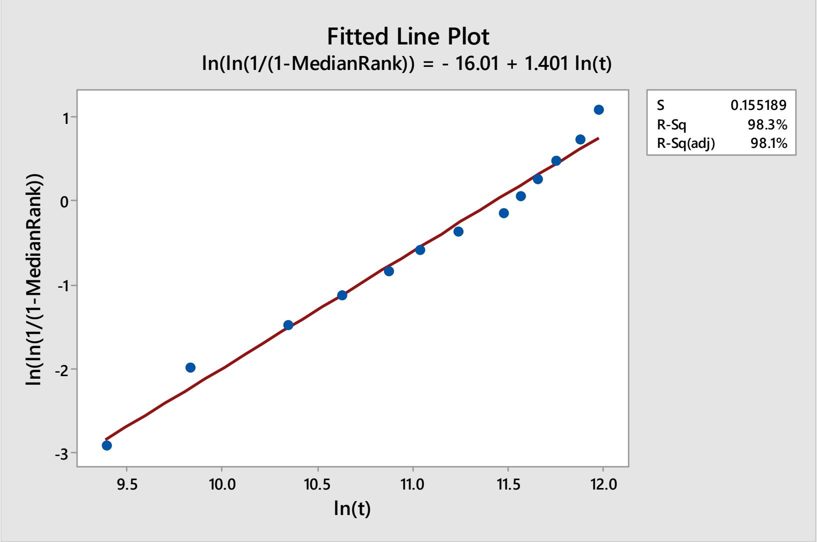
5-6- Results

The results related to η, β are summarized in table 5.

Table 5. Calculated values for availability measure

	A	B	D	E	F	I	J
η	180	905	161	227	61	89	153
β	1.24	1.80	1.39	3.25	1.42	3.92	3.12

The remaining item of information needed is the average cost of a preventive replacement: this is estimated as 7,750,000 Rials per item.

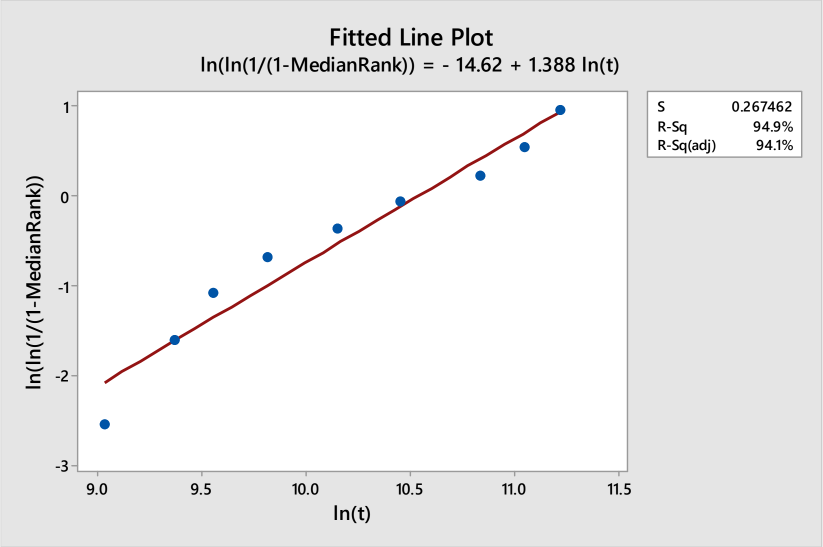


If $y = 0$ then $\gamma = 11.42755$
If $x = 0$ then $b = -16.01$
Line slope, $\beta = 1.401$

$$\alpha = e^{\left(-\frac{b}{\beta}\right)} \text{ then } \alpha = 91816.9086$$

$$R(t) = \exp\left(\frac{-(t - 11.42755)}{91816.9086}\right)^{1.401}$$

Fig 4. Distribution fitting and reliabilities' parameters for Robot component

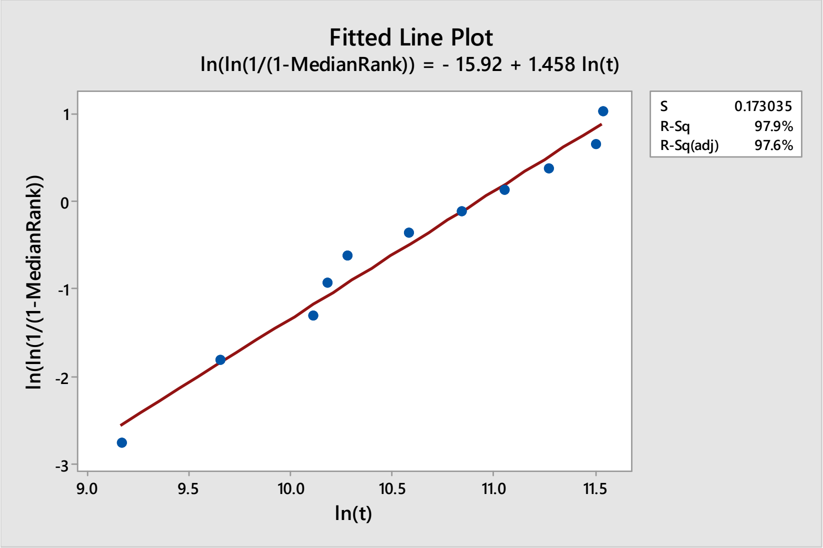


If $y = 0$ then $\gamma = 10.5331$
If $x = 0$ then $b = -14.62$
Line slope, $\beta = 1.388$

$$\alpha = e^{\left(-\frac{b}{\beta}\right)} \text{ then } \alpha = 37539.2079$$

$$R(t) = \exp\left(\frac{-(t - 10.5331)}{37539.2079}\right)^{1.388}$$

Fig 5. Distribution fitting and reliabilities' parameters for Control desk component

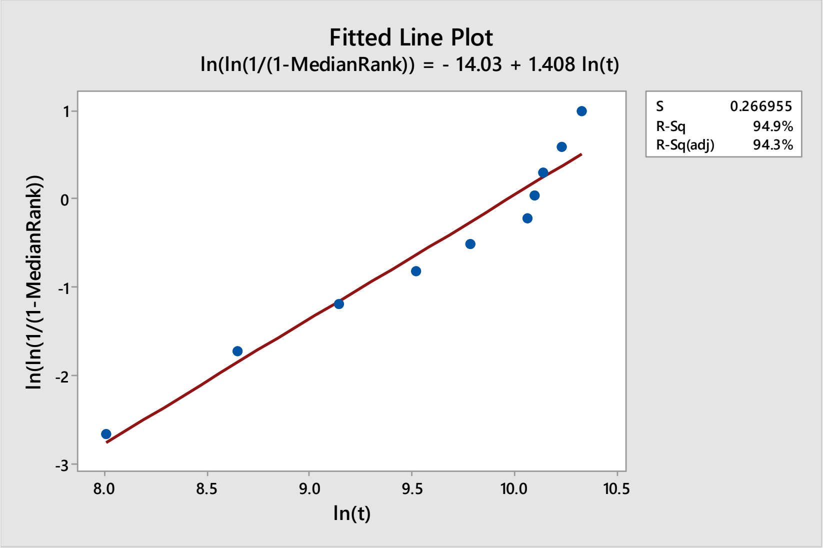


If $y = 0$ then $\gamma = 10.9191$
If $x = 0$ then $b = -15.92$
Line slope, $\beta = 1.458$

$$\boldsymbol{\alpha} = \boldsymbol{e}^{\left(-\frac{\boldsymbol{b}}{\boldsymbol{\beta}}\right)} \text{ then } \alpha = 55219.2672$$

$$R(t) = \exp\left(\frac{-(t-10.9191)}{55219.2672}\right)^{1.458}$$

Fig 6. Distribution fitting and Reliabilities' parameters for Gun component

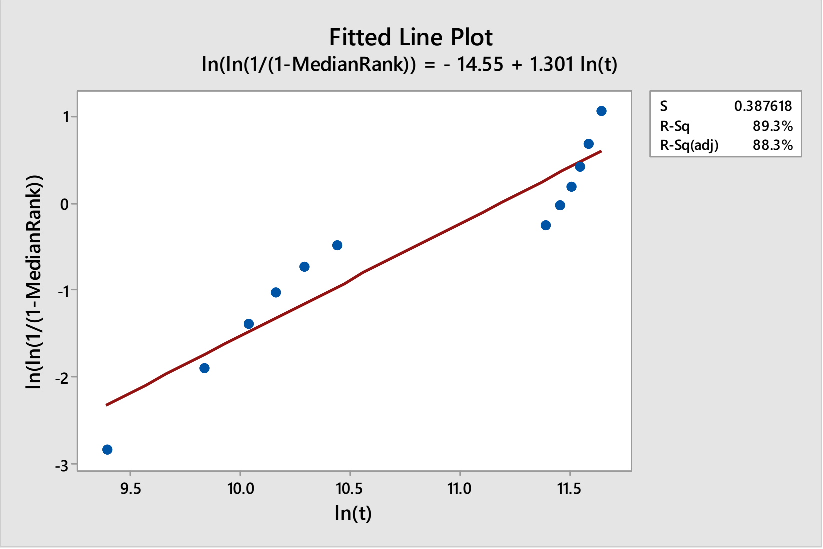


If $y = 0$ then $\gamma = 9.9645$
If $x = 0$ then $b = -14.03$
Line slope, $\beta = 1.408$

$$\boldsymbol{\alpha} = \boldsymbol{e}^{\left(-\frac{\boldsymbol{b}}{\boldsymbol{\beta}}\right)} \text{ then } \alpha = 21258.0013$$

$$R(t) = \exp\left(\frac{-(t-9.9645)}{21258.0013}\right)^{1.408}$$

Fig 7. Distribution fitting and Reliabilities' parameters for Arm-movement detector component

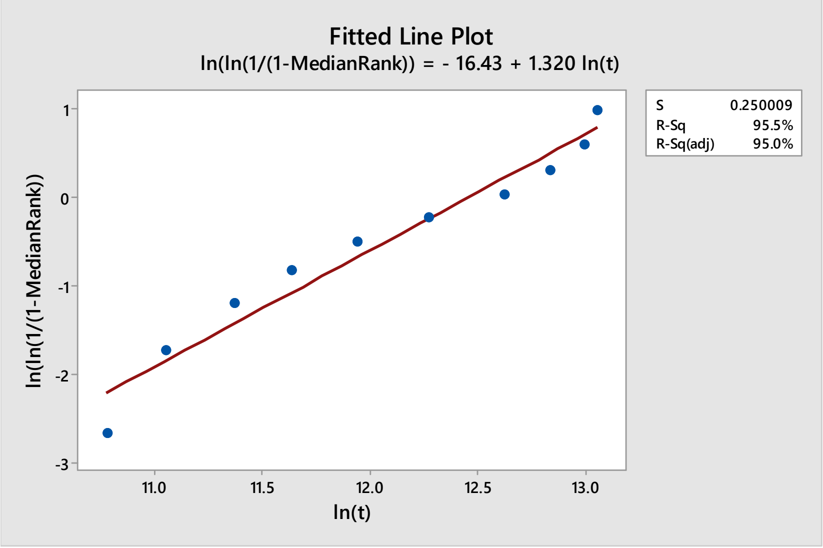


If $y = 0$ then $\gamma = 11.1837$
If $x = 0$ then $b = -14.55$
Line slope, $\beta = 1.301$

$$\boldsymbol{\alpha} = \boldsymbol{e}^{\left(-\frac{\boldsymbol{b}}{\boldsymbol{\beta}}\right)} \text{ then } \alpha = 71948.4265$$

$$R(t) = \exp\left(\frac{-(t-11.1837)}{71948.4265}\right)^{1.301}$$

Fig 8. Distribution fitting and Reliabilities' parameters for Card DH component

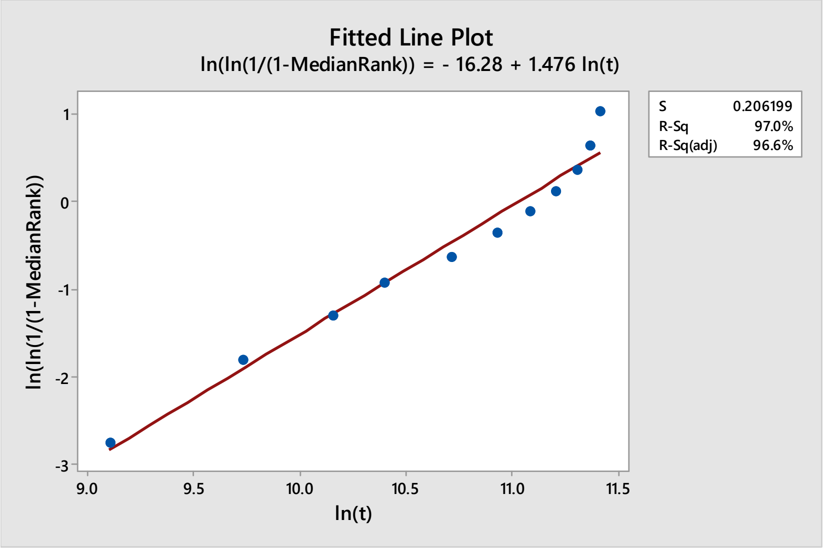


If $y = 0$ then $\gamma = 12.4470$
If $x = 0$ then $b = -16.43$
Line slope, $\beta = 1.32$

$$\boldsymbol{\alpha} = \boldsymbol{e}^{\left(-\frac{\boldsymbol{b}}{\boldsymbol{\beta}}\right)} \text{ then } \alpha = 254478.0076$$

$$R(t) = \exp\left(\frac{-(t-12.4470)}{254478.0076}\right)^{1.32}$$

Fig 9. Distribution fitting and Reliabilities' parameters for Jack component



If $y = 0$ then $\gamma = 11.0298$
If $x = 0$ then $b = -16.28$
Line slope, $\beta = 1.476$

$$\boldsymbol{\alpha} = \boldsymbol{e}^{\left(-\frac{b}{\beta}\right)} \text{ then } \alpha = 61685.8778$$

$$R(t) = \exp\left(\frac{-(t-11.0298)}{61685.8778}\right)^{1.476}$$

Fig 10. Distribution fitting and Reliabilities' parameters for Servo card(s) component

The optimum schedule (all time calculate in hours), between conditional maintenance examinations shown in table 6.

Table 6. The optimum schedule

Failure reference	Optimum time (hour)
A	18
B	corrective maintenance only
D	7
E	29
F	8
I	26
J	72

This leads to the following schedule for conditional maintenance that summarized in table 7. For example, every 8 hours the D and F components have been inspected, etc.

Table 7. Maintenance scheduling

Every .... hours	**Inspect**	**..........**
8		D, F
16		B, F, A
24		D, F
32		E, I, D, F, A
40		D, F
48		D, F, A
56		D, F
64		D, F, A, E, I, J

6 -Discussion and conclusion

This paper deals with a maintenance optimization problem for a flexible manufacturing system. First we have developed a model to determine the optimum frequency to perform preventive maintenance. Based on this model we have developed another one to optimize maintenance management of a FMS based on preventive maintenance over the different system components. In this paper, a cost function for maintenance tasks (preventive and corrective) has been used for the system. The model calculates the interval of time between preventive maintenance actions for each component, minimizing the costs, and maximizing the system's availability. The results have been shown in a form of the preventive maintenance plan, distribution fitting and Reliabilities' parameters for each component s of robot paint sprayer, and the maintenance scheduling timetable. The maintenance interval of each component depends on factors such as failure rate, repair and maintenance times of each component in the system. The results of model have been shown in figure 11.

0	8	16	24	32	40	48	56	64
T_A=16								
Component A		■		■		■		■
T_B = 16								
Component B		■		■		■		■
T_D = 8								
Component D	■	■	■	■	■	■	■	■
T_E = 32								
Component E				■				■
T_F = 8								
Component F	■	■	■	■	■	■	■	■
T_I = 32								
Component I				■				■
T_J = 64								
Component J								■

Fig 11. A PM plan for example

It should be noted that the main objective of this paper are as follows:

- Enhance the availability and reliability measures of FMSs,
- Presenting the optimal preventive maintenance model for FMS, and calculating the interval of time between preventive maintenance actions for each component,
- Minimizing the costs, and maximizing the total availabilities of system,
- Helping the researchers and managers understand the complex reality of failures and repairs in a highly integrated advanced technological system such as an FMS and present schedule for conditional maintenance.

In this paper, we have described maintenance characteristics of flexible manufacturing systems. Also, we have considered a case study (a robot paint sprayer) and presented schedule for conditional maintenance. The ultimate aim is to reduce the number of breakdowns, by:

- Laying down a rationally planned program of preventive maintenance
- Identifying appropriate technical improvements.

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