Chapter 8
Modeling Maintenance Productivity Measurement

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ABSTRACT

Modeling and simulation of industrial information communication systems and networks is one of the major concerns of productivity engineers for the establishment of productivity standards in virtually all functional areas of an industrial organization. Maintenance function is one of such areas that have always engaged the attention of engineering productivity practitioners. However, one of the basic problems is the difficulty in setting up integrated but easy and practical measurement schemes. Even where the measures are set up, the approaches to measurement sometimes are conflicting. Therefore the need for an integrated approach to optimize the basket of parameters measured remains.

In this chapter the author attempts to identify approaches in integrated and systematic maintenance productivity measurement and create models for optimising total productivity in maintenance systems. Visual yardstick, utility, queuing systems and simulations approaches for measurement of maintenance productivity are all discussed with a particular focus on markov chain approach for stochastic breakdowns in repairable systems.. The chapter also shows how understanding the impact of plant failure and repair/service distributions assists in providing measures for maintenance productivity using discrete event system simulation.

INTRODUCTION

Modeling and simulation of industrial information communication systems and networks is one of the major concerns of productivity engineers for the establishment of productivity standards in virtually all functional areas of an industrial organization. Maintenance function is one of such areas that have always engaged the attention of engineering productivity practitioners. However, the basic problem, and indeed the most important one, is the difficulty in setting up integrated but easy and practical measurement scheme. Even where the measures are set up, the approaches to

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measurement sometimes are conflicting. There is therefore the need to optimize the basket of parameters measured.

The overall objective of the maintenance function should be to support the operating department by keeping facilities in proper running condition at the lowest possible cost. In judging the productivity of the maintenance department one must consider not only the efficient use of manpower and material, but also how well production losses due to maintenance problems are controlled. The performance of the maintenance department is influenced by various factors such as business condition (e.g low and high profit times), maintenance philosophy (crises maintenance versus planned), extraneous factors (location, availability of skills and spare parts), and so forth.

This chapter discusses approaches in systematic maintenance productivity measurement and creating models for optimising productivity in maintenance systems. It discusses defects accumulation, the manual visual yardstick, queuing systems and simulations approaches and highlights markov chain approach solution for stochastic breakdowns in repairable systems. Also it shows how understanding the impact of plant failure and repair/service distributions assists in providing measures for maintenance productivity using the simulation approach.

APPROACHES TO MODELING MAINTENANCE PRODUCTIVITY

The word productivity is used in a variety of sense some of which are conflicting or very qualitative (namely, "efficiency", "overall effectiveness", etc). Similarly, the definition of "productivity" is varied. Productivity is often confused with "output" or "profitability". Whilst a good total productivity implies profitability, the converse does not hold. Profitability is affected by market prices and accounting practice. Productivity is defined simply as a relationship of output to input.

In sharp contrast to production, the performance of maintenance activity does not lend itself easily to expression in simple or unified figures. However, in the last two decades, the measurement of maintenance performance and productivity has engaged the attention of productivity engineers. (Priel, 1974) has written on maintenance organization particularly on performance ratios. He has identified twenty of such maintenance ratios. Some of the ratios are useful in establishing the basis for incentive scheme for maintenance personnel. (Hamlin, 1979) has shown various methods and (Alli, Ogunwolu, & Oke, 2011) applied same to measure maintenance productivity through their case studies. (Chan, Lau, Ip, Chan, & Kong, 2005), applying total productive maintenance approach to the electronics industry, (Eti, Ogaji, Probert, 2004 to the manufacturing industries in a developing country, (Lilly, Obiajulu, Ogaji, &Probert, 2007) to the petroleum-product marketing company and (Ahn & Abt, 2006), to the sawmills and planning mills industry provides examples of total productivity measurements in industry.

Another interesting point of view is provided by (Nanere, M, Fraser, I, Quazi, A, & D'Souza, C, 2007), who critically examines various methods for estimating productivity incorporating environmental effects and shows that adjusting for environmental impacts can result in higher and lower productivity depending on the assumed form of the damage. Although this was applies to the agriculture sector, this could be applicable to industrial environment, where work place hygiene and design could impact negatively or positively to productivity.

It can be seen that there are several ways of expressing maintenance productivity or performance. The problem is how to model a working

$$L = L_q + \frac{\lambda}{\mu} \qquad (11)$$

THE ERLANG MAINTENANCE SERVICE TIME

The *Erlang* distribution is a two-parameter family of distributions, which is a special case of the more general *gamma* distribution. It permits more latitude in selecting a service-time distribution than the one-parameter exponential distribution. In fact, the exponential service time and constant service-time situations are special cases of the Erlang service time. In practical situations, the exponential distribution is unduly restrictive because it assumes that small service times are more probable than large service time, which is unusual for manufacturing plants. On the other hand, the Erlang distribution permits the flexibility of approximating almost any realistic service-time distribution.

We consider two-parameter Erlang distribution

$$f\left(t;\mu,k\right) = \frac{(\mu k)^k t^{k-1} e^{-\mu k t}}{\left(k-1\right)!}$$

$t > 0;\ \mu > 0;\ k = 1,2,3,\ldots..$

$$E\left(T\right) = \frac{1}{\mu} \text{ for every } k = 1,2,3\ldots..$$

With $var\left(T\right) = \frac{1}{k\mu^2}$

For $k = 1,$ the Erlang reduces to the exponential distribution

The following queuing statistics can be derived:

Average numbers of breakdowns=

$$L = \left(\frac{k+1}{2k}\right)\left(\frac{\lambda^2}{\mu(\mu-\lambda)}\right) + \frac{\lambda}{\mu}\ for\, \lambda < \mu \qquad (12)$$

Average number of breakdowns in the queue=

$$L_q = \left(\frac{k+1}{2k}\right)\left(\frac{\lambda^2}{\mu(\mu-\lambda)}\right) for\, \lambda < \mu \qquad (13)$$

Average time a breakdown stays in the system=

$$W = \frac{L}{\lambda}\ for\, \lambda < \mu \qquad (14)$$

Average time a breakdown stays in the queue=

$$W_q = \frac{L_q}{\lambda}\ for\, \lambda < \mu \qquad (15)$$

WEIBULL DISTRIBUTION - MEAN TIME TO FAILURE

The Weibull distribution can be considered as a generalization of the exponential distribution

$$f\left(t\right) = \lambda\beta\left(\lambda t\right)^{\beta-1} e^{-\left(\lambda t\right)^\beta} \quad t > 0; \lambda, \beta > 0 \qquad \lambda$$

is on the scale parameter and β the shape factor.

When $\beta = 1$ this yields the exponential distribution.

Defects accumulation in some manufacturing systems approximates to the Weibull distributions.

GENERATION OF SIMULATION DATA

There are several approaches of generating the breakdown data for the system under consideration.

1. Actual data could be used to calculate the desired statistics.
2. Plot the histograms of the cumulative distribution of the breakdown times and the cumulative distribution of the service times and then generate sample breakdown and service times using these distributions.
3. Assume the actual data are values from certain theoretical distribution, and then

Example 1 (Analytical): Single Breakdown Queue and Single Maintenance Team-Poisson Failure Rate and Exponential Maintenance Service Distribution [Infinite Queue – Infinite Source]

Let $X =$ number of breakdowns or failures per week.

Then $f(x) = \frac{e^{-\lambda}\lambda^{x}}{x!} \quad x = 0,1,2\ldots; \quad \lambda > 0$ and mean $E(X) = \lambda.$

The parameter $\lambda,$ then is the mean time to failure.

Also, let $T = time\,to\,service\,a\,breakdown$

Then $g(t) = \mu e^{-\mu t} \quad t > 0; \mu > 0$ and $E(T) = \frac{1}{\mu}$. the parameter, μ, mean service time.

From Queuing theory, the following queuing equations can be derived:

Average numbers of breakdowns: $L = \frac{\lambda}{\mu - \lambda}$ (1)

Average number of breakdowns in the queue:

$$L_q = \frac{\lambda^2}{\mu(\mu - \lambda)} \tag{2}$$

Average number of breakdowns in nonempty queues: $L_w = \frac{\mu}{\mu - \lambda}$ (3)

Average time a breakdown stays in the system:

$$W = \frac{1}{\mu - \lambda} \tag{4}$$

Average time a breakdown stays in the queue:

$$W_q = \frac{\lambda}{\mu(\mu - \lambda)} \tag{5}$$

Probability of more than k breakdowns in the system: $P(n > k) = \left(\frac{\lambda}{\mu}\right)^{k+1}$ (6)

Probability of the time in the system is greater than t: $P(T > t) = e^{-\mu\left(1-\frac{\lambda}{\mu}\right)t}$ (7)

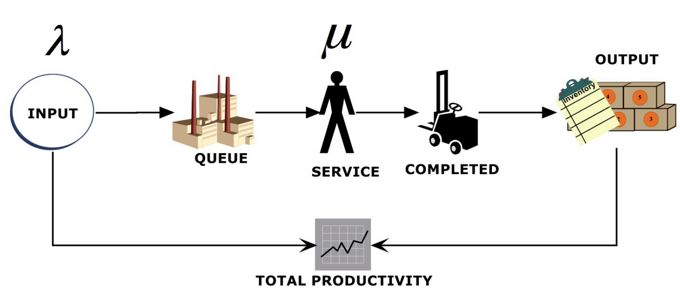
If any one of the quantities $L, L_q, W\, or\, W_q$ can be determined, then others can be determined from the relationships:

$$L = \lambda W \tag{8}$$

$$L_q = \lambda W_q \tag{9}$$

$$W = W_q + \frac{1}{\mu} \tag{10}$$

Figure 2. Single breakdown queue, single-server maintenance service team



$$Maintenance\ Cost\ Component, U_4 = \frac{Total\ Maintenance\ Cost}{Production\ Output}$$

$$Routine\ Service\ Workload, U_5 = \frac{Planned\ Maintenance\ Hour}{Total\ Maintenance\ Hour}$$

$$Cost\ Reduction\ Ratio, U_6 = \frac{Routine\ Service\ Workload}{Cost\ of\ Maintenance\ Hour}$$

The next step was to obtain the scaling factor, β_i, where $i = 1,2,\ldots 6$

The scaling factor is an index number obtained from the utility values from the plot of the performance measures over a period of years.

According to (Alli, et al, 2009) the utility values for each of the performance measures were derived as follows:

- Determining the best and worst values from the graph of each of the measures used,
- Normalising the values by assigning values of 1.00 and 0.00 for the best and the worst measure respectively,
- Taking five points between the best and the worst performance measure and assign values between 0.00 and 1.0,
- Using the intermediate points with the best and worst measures for each measure to plot a Utility Curve in order to determine the Utility values.

As an example from (Alli, et al, 2009) see Table 1.

This gives a Composite Maintenance Productivity of 63.2% for the period under study

THE QUEUING THEORY APPROACH

Maintenance queuing systems can be classified with the following queuing model characteristics:

1. Defects arrival or breakdowns, λ, which is the distribution of the numbers of defects occurring, the number of defects that exceeds the threshold for plant breakdown. It could also be the distribution of equipment breakdown.
2. The service process, μ, which include the distribution of the time to eliminate or service a defect, the number of maintenance service team, and the arrangement of the maintenance service process (in parallel, series, etc).
3. Queuing discipline such as first come first served (FIFO), last in first served (LIFO), random selection, etc.

Typical maintenance queuing systems are discussed in this chapter.

Table 1.

t	U_t	β_t	$\beta_t y_t$
1	0.66	0.191	0.125
2	0.58	0.181	0.105
3	0.28	0.171	0.048
4	0.89	0.162	0.144
5	0.85	0.152	0.129
6	0.56	0.143	0.081
Composite Number			0.632

Obviously, since accumulation of defects are observable, this thinking can be modeled as a waiting line or queuing system and some of the solution methodologies of queuing theory could be useful in deriving the maintenance productivity, depending on the occurrence pattern (or arrival process) of the defects, the maintenance team service process and queue discipline of the maintenance policy.

THE COMPOSITE APPROACH

This method is an extension of the work done by (Priel, 1974) which were discussed by (Onwugbolu et al, 1988) and (Parida et al, 2009). It starts with a number of performance measures as identified by (Priel, 1974) and then builds a composite number which is a weighted addition of the Utility values of all these performance measures. The approach can be stated as follows:

Let U_t be the utility value of the selected N performance measures, where $t = 1,2 \ldots\ldots N$

Let β_t be the scaling factors for the performance measures

Then the Maintenance Productivity is given by

$$Y_N = \sum_{1}^{N} \beta_t U_t$$

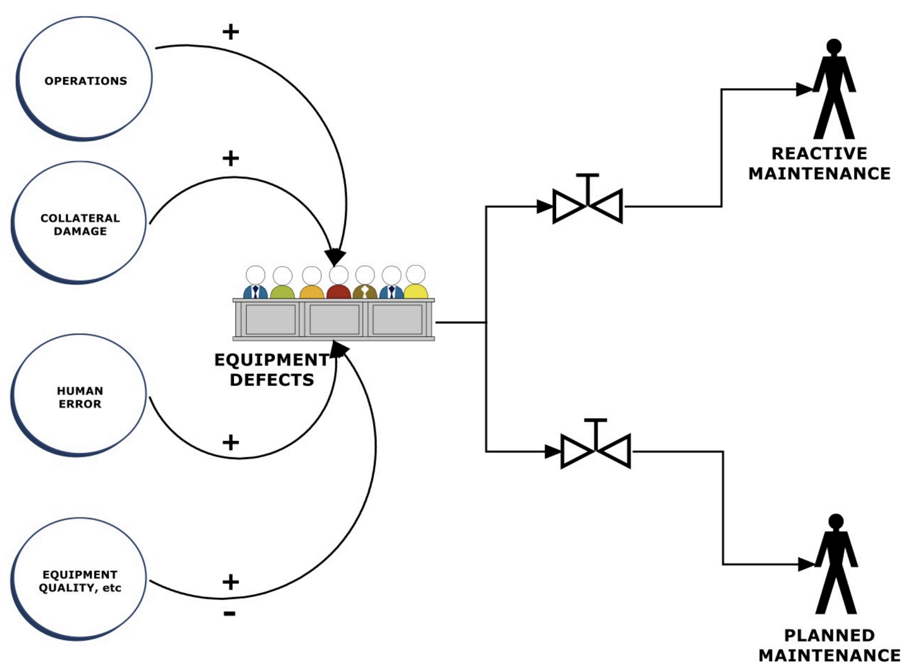
From the case study by (Alli et al, 2009), they selected the following six performance measures mentioned in (Priel, 1974):

$$Equipment\ Availability, U_1 = \frac{Downtime}{Downtime + Uptime} \times 100\%$$

$$Emergency\ Failure\ Intensity, U_2 = \frac{Downtime}{Uptime} \times 100\%$$

$$Cost\ of\ maintenance\ Hour, U_3 = \frac{Total\ Maintenance\ Cost}{Total\ Maintenance\ Hour}$$

Figure 1. System dynamics approach: defects accumulation



measurement scheme that gives good management information in areas critical to increasing productivity as well as being amenable to easy data collection.

GRAPHICAL APPROACH

(Priel, 1974) developed a graphical "instant yardstick" multi-variable chart for assessment of maintenance performance, which clearly identifies the inter-dependence of the various assessment indicators. He also discusses twenty maintenance performance ratios. These can be groups as follows:

1. Operation of the maintenance department determined by manpower utilization, work-order progress and departmental economy.
2. Assessment of the service determined by plant and equipment performance, degree of planning, the amount of service and cost of service provided.
3. Expense justification determined by cost reduction efforts, maintenance intensity and the overall rate of expenditure.

Operations of the maintenance department which deals with manpower efficiency, incentive coverage, utilization of craft hours, work order turnover, completion delays, cost of maintenance hour and department overhead largely affects the repairable systems service rates which impacts on the output side of total productivity measures. On the other hand assessment of the service which deals with downtime due to maintenance, breakdown frequency, routine service workload, breakdown workload, maintenance to production-hours ratio, maintenance mechanization and maintenance cost component largely relate to the input side of the total productivity measurement process.

SYSTEMS DYNAMICS APPROACH

According to (Sterman, 2000) Du Pont organization looked at the result of an in-house benchmarking study documenting a large gap between Du Pont's maintenance record and those of the best-practice companies in the global chemical industry and they developed an interesting defect creation and elimination model. Prior to the modeling work maintenance was largely seen as a process of defect correction (repair of failed equipment) and the maintenance function was viewed as a cost to be minimized. It shifted the views to defect prevention and defect elimination. The model centred on the physics of breakdown rather than cost minimization mentality.

The study postulates the following:

1. Equipment fails when a sufficient number of latent defects accumulate in it. Latent defects are any problem that might ultimately cause a failure. They include leaky oils seals in pumps, dirty equipment that causes bearing wear, pump and motor shaft that are out of alignment and cause vibration. The total number of latent defects in a plant's equipment is a stock (Figure 1).
2. The stock of defects is drained by two flows: reactive maintenance (repair of failed equipment and planned maintenance (proactive repair of operable equipment}. As defects accumulate the chance of breakdown increase. Breakdown leads to more reactive maintenance, and, after repair, the equipment is returned to service and the stock of defects is reduced. Similarly, scheduled maintenance or equipment monitoring may reveal the presence of latent defects. The equipment is then taken out of service and the defects are corrected before breakdown occurs.

Figure 9. SIMUL8 implementation - single breakdown queue, multiple maintenance job shops in series

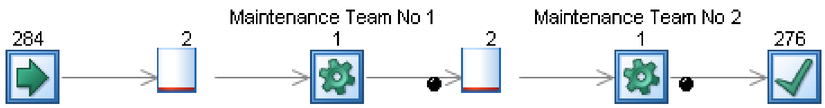


Figure 10. Multiple queues, multiple maintenance teams

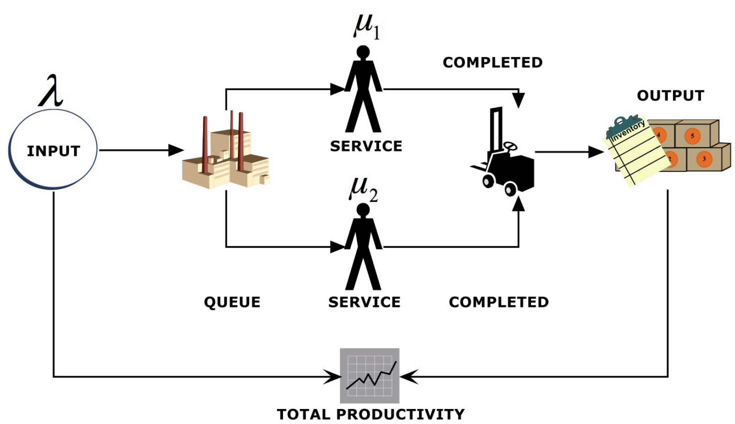


Figure 11. SIMUL8 implementation - multiple breakdown queue and multiple maintenance team

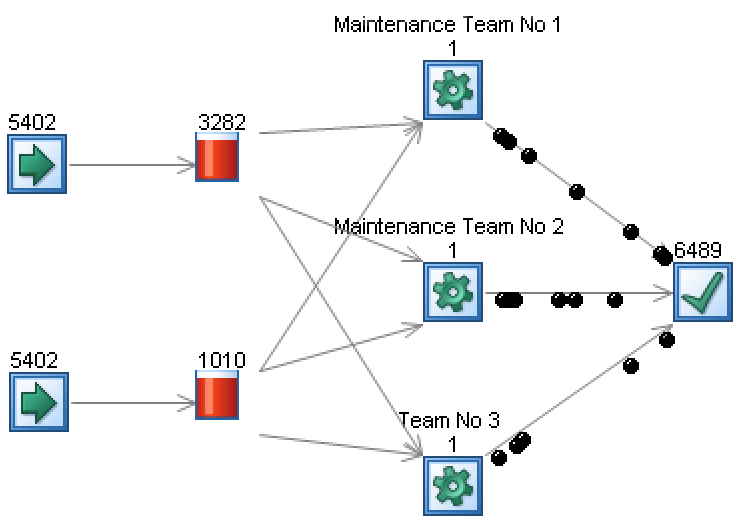


Figure 6. Single queue, multiple servers model

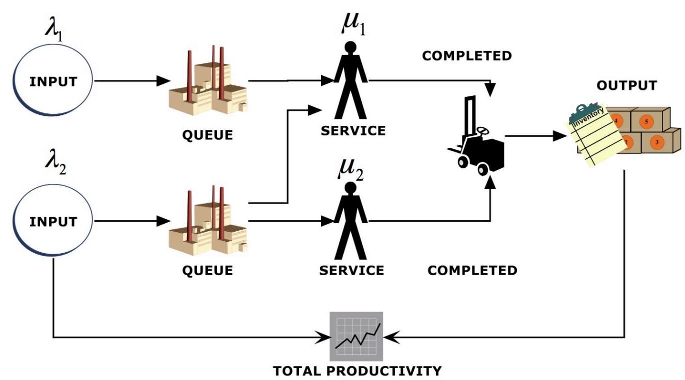


Figure 7. SIMUL8 implementation: single breakdown queue and multiple maintenance team

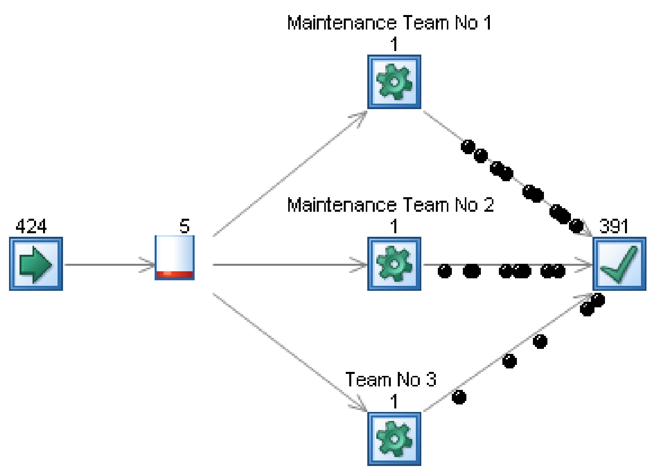


Figure 8. Single breakdown queue, multiple maintenance teams/job shops in series

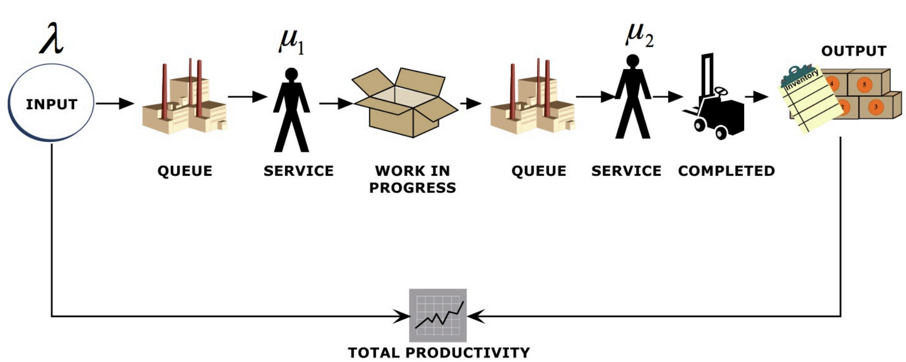


Figure 4. SIMUL8 result: single breakdown queue, single maintenance team

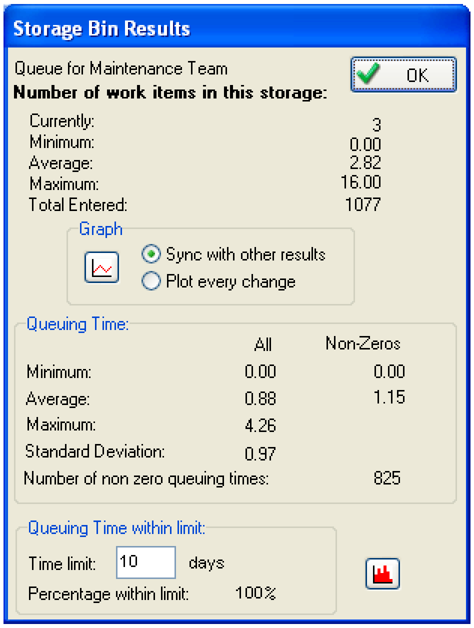
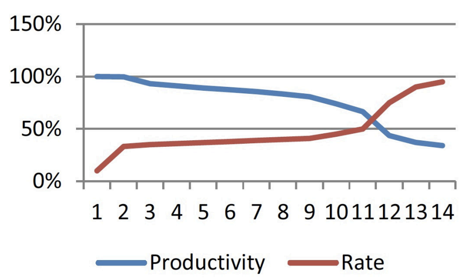


Figure 5. Maintenance productivity: single breakdown queue, single maintenance team



Average time a breakdown stays in the system:

$$W = \frac{L}{\lambda} \tag{28}$$

Average time a breakdown stays in the queue:

$$W_q = \frac{L_q}{\lambda} \tag{29}$$

Probability of the time in the system is greater than t:

$$P\left(T > t\right) = e^{-\mu t}\left\{1 + \frac{(\frac{\lambda}{\mu})^s P_0\left[1 - e^{-\mu t(s-1-\frac{\lambda}{\mu})}\right]}{s!\left(1 - \frac{\lambda}{\mu s}\right)(s - 1 - \frac{\lambda}{\mu})}\right\} \tag{30}$$

Also in practice, breakdowns queues cannot be infinite as this will definitely affect the total productivity of the production plant. When the capacity of the maintenance team is exceeded, service is procured from contract service team, of course, with the increased cost of maintenance and increased logistical effort.

Let

$s =$ number of servers

$M =$ maximum number of breakdowns that can be accommodated by the maintenance service teams

$$\lambda_n = \begin{cases} \lambda & for\, n = 0,1,\ldots\ldots M-1 \\ 0 & for\, n = M, M+1,\ldots\ldots. \end{cases}$$

Assume $1 < s < M$

$$\mu_n = \begin{cases} n\mu & for\, n = 0,1,\ldots\ldots s \\ s\mu & for\, n = s+1, s+2,\ldots\ldots. \end{cases}$$

Assume $1 < s < M$

Fraction of time that there is no breakdown in the system

$$P_0 = \frac{1}{\sum_{n=0}^{s}\left(\frac{1}{n!}\right)(\frac{\lambda}{\mu})^n + \left(\frac{1}{s!}\right)(\frac{\lambda}{\mu})^s \sum_{n=s+1}^{M}(\frac{\lambda}{\mu s})^{n-s}} \tag{31}$$

Fraction of time that there is nbreakdowns in the system

Average number of breakdowns in the queue:

$$L_q = L - (1 - P_0) \tag{20}$$

Example 3 (Simulation Using SIMUL8 Version 2010): Single Breakdown Queue and Single Maintenance Team

The data in Table 2 was used.

For productivity profile, the following data were used:

$$Productivity = \frac{Output}{Input} \tag{21}$$

For $\lambda = 0.33333$ and

$\mu = 0.1, 0.2, \ldots\ldots\ldots\ldots 0.95$

Optimal productivity profile can be obtained by varying breakdown rate, and "s"ervice rate μ.

SINGLE BREAKDOWN QUEUE AND MULTIPLE MAINTENANCE TEAM

We assume

1. *s maintenance teams*
2. Each maintenance team provides service at the same constant average rate μ
3. The average breakdown rate is constant, $\lambda_n = \lambda \, for \, all \, n$
4. $\lambda < s\mu$

With these assumptions, the following queuing equations can be derived.

$$P_n = \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n P_0 \quad n = 0, 1, \ldots.., s-1 \tag{22}$$

$$P_n = \frac{1}{s!\,s^{n-s}}\left(\frac{\lambda}{\mu}\right)^n P_0 \quad n \geq s \tag{23}$$

$P(n \geq s) = probability \, a \, breakdown \, has \, to \, wait \, for \, service$

= probability of at least $s \, breakdown \, in \, the \, system$

$= \sum_{n=s}^{\infty} P_n$

$$= \frac{(\frac{\lambda}{\mu})^s P_0}{s!(1 - \frac{\lambda}{\mu s})} \tag{24}$$

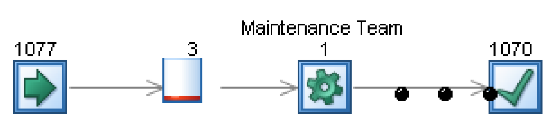
$$P_0 = \frac{1}{\left\{\left[\sum_{n=0}^{s-1} \frac{1}{n!}(\frac{\lambda}{\mu})^n\right] + \frac{1}{s!(1 - \frac{\lambda}{\mu s})}(\frac{\lambda}{\mu})^s\right\}} \tag{25}$$

Average number of breakdowns in the queue:

$$L_q = \frac{(\frac{\lambda}{\mu})^{s+1} P_0}{s.s!(1 - \frac{\lambda}{\mu s})^2} \tag{26}$$

Average numbers of breakdowns: $L = L_q + \frac{\lambda}{\mu}$ (27)

Figure 3. SIMUL8 implementation: single breakdown queue, single maintenance team



sample from the theoretical distribution. To determine a theoretical distribution that would be a good approximation of the actual data, several possible distributions could be considered as candidates, and then the chi-square and/or Kolmogorov-Smirnov test could be used to determine the best distribution to use.

These approaches were used in generating simulation data for the breakdown data from a four-hi Aluminium Rolling Mills collected over three years. Curve fitting was performed using MATLAB version 2011a Statistical Toolkit [3].

Example 2 (Analytical): Single Breakdown Queue and Single Maintenance Team-Poisson Failure Rate and Exponential Maintenance Service Distributions [Finite Queue –Infinite Source]

In practice, breakdowns queues cannot be infinite as this will definitely affect the total productivity of the production plant. When the capacity of the maintenance team is exceeded, service is procured from contract service team, of course, with the increased cost of maintenance and increased logistical effort.

Let $M =$ breakdowns that can be accommodated by the in-house maintenance team. For the case, λ need not be less than the mean service time since the breakdown queue cannot build up without bound.

We have that

$$\mu_n = \mu \qquad for\, n = 1,2,3,\ldots\ldots$$

$$\lambda_n = \begin{cases} \lambda & for\, n = 0,2,3,\ldots.M-1 \\ 0 & for\, n = M,\ M+1,\ldots. \end{cases}$$

We can derive the following queuing characteristics:

Fraction of time that there is no breakdown in the system

$$P_0 = \frac{1-\lambda/\mu}{1-(\frac{\lambda}{\mu})^{M+1}}\, for\, \lambda \neq \mu \qquad (16)$$

$$P_0 = \frac{1}{M+1}\, for\, \lambda = \mu \qquad (17)$$

Average numbers of breakdowns:

$$L = \frac{\left(M+1\right)(\frac{\lambda}{\mu})^{M+1}}{1-(\frac{\lambda}{\mu})^{M+1}}\, for\, \lambda \neq \mu \qquad (18)$$

$$L = M \,/\, 2\ \, for\, \lambda \neq \mu \qquad (19)$$

Table 2.

Mean Time Between Failure	0.333 Days
Breakdown Distribution	Poisson
Mean Service Time	0.25 days
Mean Service Time Distribution	Exponential
Run Period	365 Days, One Financial Year
Working Hours	00:00a.m to 24:00 hrs, 7 Days

$$P_n = \begin{cases} \frac{1}{n!}(\frac{\lambda}{\mu})^n P_0 & for\, n \le s \\ \frac{1}{s!s^{n-s}}(\frac{\lambda}{\mu})^n P_0 & for\, s < n \le M \\ 0 & for\, n > M \end{cases}$$

(32)

Average number of breakdowns in the queue

$$L_q = \frac{P_0 \left(\frac{\lambda}{\mu}\right)^s (\frac{\lambda}{\mu s})}{s!(1-\frac{\lambda}{\mu s})^2} \begin{bmatrix} 1-(\lambda / \mu s)^{M-s} - \\ \left(M-s\right)(\frac{\lambda}{\mu s})^{M-s}(1-\frac{\lambda}{\mu s}) \end{bmatrix}$$

(33)

Average numbers of breakdowns

$$L = L_q + s - \sum_{n=0}^{s-1} \left(s-n\right) P_n \quad (34)$$

Example 5 (Simulation): Single breakdown queue and multiple maintenance team (see Figure 7).

Example 6 (Simulation): Single breakdown queue and multiple maintenance team in series (see Figures 8 and 9).

Example 7 (Simulation): Multiple breakdown queue and multiple maintenance team (see Figures 10 and 11).

FUTURE RESEARCH DIRECTION

Formulation of Markov Chains

The service process can be considered for a stochastic process $\left\{X_i\right\}$ with a first order, finite-state *markovian* process, where the conditional probability distribution of X_{i+1} is independent on the states the system is in step 0, 1, 2, 3…., $i-1$ and is dependent only on the state of the system is at step i. It has a finite number of states, a set of stationery transition probabilities, and a set of initial probabilities, $P\left(X_0 = r\right),\ for\, all\, r.$

The probability of the state of the plant r to state s in n steps (for all states r and s) is given by

$$p_{rs}^{(n)} = P\left(X_{i+n} = s | X_i = r\right) = P(X_n = s \mid X_0 = r) \quad (34)$$

where

$$p_{rs}^{(n)} \ge 0 \quad for\, all\, states\, r\, and\, s; n = 1,2,\ldots\ldots \quad (35)$$

$$\sum_{s=0}^{N} p_{rs}^{(n)} = 1 \quad for\, all\, states\, r; n = 1,2,\ldots\ldots \quad (36)$$

A comparison of the various methods is shown in Table 3.

Table 3. Comparison of methods

Method	Visual Presentation (Priel, 1974)	System Dynamics (Sterman, 2000)	Utility (Alli, et al, 2009)	Queuing Simulation (Inclusive of Environmental Factor)
Ease of Determination	1	4	3	1
Integrated	3	2	3	1
Data Collection	1	4	3	3

1 = Excellent 2 = Good 3 = Fair 4 = Lot of work

CONCLUSION

This chapter attempts at identifying approaches in systematic maintenance productivity measurement and creating models for optimising productivity in maintenance systems. It looked at the following approaches:

1. **The graphical/visual approach:** Using the *'Instant yardstick'* from the ratio analysis maintenance data collected. It can be seen that Operations of the maintenance department which deals with manpower efficiency, incentive coverage, utilization of craft hours, work order turnover, completion delays, cost of maintenance hour and department overhead largely affects the repairable systems service rates which impacts on the output side of total productivity measures. On the other hand assessment of the service which deals with downtime due to maintenance, breakdown frequency, routine service workload, breakdown workload, maintenance to production-hours ratio, maintenance mechanization and maintenance cost component largely relate to the input side of the total productivity measurement process.
2. **The System dynamics approach:** Since accumulation of defects are observable, this thinking can be modeled as a waiting line or queuing system and some of the solution methodologies of queuing theory could be useful in deriving the maintenance productivity, depending on the occurrence pattern (or arrival process) of the defects, the maintenance team service process and queue discipline of the maintenance policy.
3. **The Queuing theory approach:** With adequate assumptions, some of simple industrial maintenance productivity can be estimated using analytical methods; this is impractical for most real life industrial problems. Discrete event simulation approach is very useful in measuring maintenance productivity for several breakdown distributions and maintenance team service distributions subject to maintenance team capacity constraints.
4. The states of the plant after maintenance activities can be incorporated as a *markovian* property of the production system.

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