Considerations for Planning and Scheduling Part 3
Blending the Planned Maintenance Program and Reactive Maintenance Plan

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Introduction

When considering the overall planning and scheduling process, an idea of the amount of reactive maintenance time, or random failure time, must be determined as well as when they are most likely to occur by estimating equipment failure. There are a great many ways in which this may be determined, and most of those require a great deal of resources in order to come up with accurate measures. However, simple processes used in production/operations and finance referred to as forecasting can be used to provide a reasonably accurate idea of what and when issues may occur within a calculated error range.

The forecasting process is used in the WFC (Work-Flow Concept) and DFM (Design for Maintenance) methods in order to provide guidance to the planner/scheduler in identifying the most likely times that systems may fail and may be utilized on both critical and non-critical equipment in order to provide an additional layer to spares inventory and budgeting. In this paper, we are going to discuss forecasting, how it may be used to model a variety of concepts within the maintenance organization, then how it is used to determine resources and as a maintenance tool.

Forecasting for Random Failures

In a static maintenance environment, or one in which no new maintenance initiatives are being implemented, the concept of forecasting for random failures and reactive maintenance is straight forward and the time will usually be increasing. There are two methods that can be used for forecasting the maintenance process including the weighted moving average and linear regression. These are both measurement-based methods requiring that the user determine if they are going to base the forecast on a time-scale or production-scale. For instance, if the random failures seem to be more or less predictable regardless of production levels, then the user may wish to use a time-based system (ie: Failure Rate in Hours). If the random failures seem to follow increases and decreases in production levels, then the user may wish to use a production-based system (ie: Failure Rate in Units of Production).

There are several basic steps to the process that must be understood before actually applying the selected forecasting method:

1. What time-frame is the forecast being applied across? How far out is it going to be applied? This is important as the further you move out, in time or production, the greater the error will be.

2. Are there specific patterns to the random failure history? Are the patterns based upon the time of year? Time of day? Units of production? This information is used to determine the forecasting method in use.
3. There is an assumption that in a static system the total cost and resources to maintain the system will be increasing over time. Is this the case?

The first process that we will use will be the weighted moving average. For this process, a multiplier is used for history and applied via a formula, as follows:

Equation 1: Weighted Moving Average

$$F = 0.4(P4) + 0.3(P3) + 0.2(P2) + 0.1(P1)$$

Where F = the Forecast and P = the Period in Question

For example, if the forecast is being performed for the quarter, the history of the past four quarters is required. As in Table 1, the latest period is the highest number:

Table 1: Example of Hours of Random Failure Per Quarter

Quarter (Period)	Random Failure Hours
1	25
2	27
3	30
4	29

The weighted average for the next quarter would be:

Equation 2: Weighted Moving Average Applied (Example 1)

$$F = 0.4(29) + 0.3(30) + 0.2(27) + 0.1(25) = 28.5 hours$$

Based upon the moving weighted average, 28.5 hours should be forecast for the next quarter in reactive maintenance.

Now, let's see how a more dynamic example will apply:

Table 2: Example 2: Hours of Random Failure Per 1,000 Units Manufactured

1,000 of Units	Random Failure Hours
1	20
2	44
3	38
4	12

Equation 3: Weighted Moving Average Applied (Example 2)

$$F = 0.4(12) + 0.3(38) + 0.2(44) + 0.1(20) = 27 hours$$

As you can see, in the first example, the value given provides some level of accuracy that can have a specified error that would be acceptable. However, in the second example, you will notice that the value may not represent what may happen through random failures. The error has the potential of being too high. In this case, let us explore another level to the weighted average called 'exponential smoothing.'

Table 3: Example of Exponential Smoothing from Example 2

1,000 of Units	**Random Failure Hours**
1	20
2	44
3	38
4	12
5	42

In our original forecast for example 2, we came up with a value of 27 hours of reactive maintenance. Now, using exponential smoothing from Equation 4, we can use the error to predict the next random failure period.

Equation 4: Exponential Smoothing

$$F = F_{T-1} + \alpha(A_{T-1} - F_{T-1})$$

Where F is the forecast for the next period, F_{T-1} is the forecast for the last period
α is the smoothing constant and A_{T-1} is the actual failure for period T-1

The smoothing constant represents a percentage of the forecast error. For the third example, we will determine the exponentially smoothed forecast for the sixth batch of 1,000 units: The error was (27/42 = 0.643), so the next forecast will be: F = (27 + 0.643(42-27) = 36.6 hours. This method is then applied for the next period, and so on.

Another method of forecasting involves the use of simple linear regression in which a line is fixed to a set of points. The basic format for the simple linear regression technique is shown in Equation 5.

Equation 5: Simple Linear Regression Formula

$$y_c = a + bx$$

$$b = \frac{n(\sum xy) - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2}$$

$$a = \frac{\sum y - b\sum x}{n}$$

Where y_c is the estimated variable, x is the estimator, b is the slope of the Line and a is the value of y_c when x = 0 on a graph, n is number of paired observations.

The assumption for the linear regression is that points tend to develop around a straight line. So, with values such as those in Table 4, we can develop an analysis of forecast beyond the next period.

Table 4: Forecast of Reactive Maintenance Per Week

Week	Random Failure Hours
1	5
2	6
3	5
4	7
5	8
6	6
7	8
8	9
9	7
10	9

With this information, we can determine all of the X and Y needed for the formulae, as shown in Table 5.

Table 5: Linear Regression Calculations

x	y	xy	x^2	y^2
1	5	5	1	25
2	6	12	4	36
3	5	15	9	25
4	7	28	16	49
5	8	40	25	64
6	6	36	36	36
7	8	56	49	64
8	9	72	64	81
9	7	63	81	49
10	9	90	100	81
SUM =	SUM =	SUM =	SUM =	SUM =
55	70	417	385	510

These values can then be plugged in to the formulae in equation 5.

Equation 6: Solution for b (Example 3)

$$b = \frac{10(417) - (55)(70)}{10(385) - 55^2} = 0.388$$

Equation 7: Solution for a (Example 3)

$$a = \frac{70 - 0.388(55)}{10} = 4.87$$

Equation 8: Solution for Linear Regression (Example 3)

$$y_c = 4.87 + 0.388x$$

With this information, we can determine what is going to happen in the following weeks. For instance, if we were to estimate reactive maintenance hours for week 12, the answer would be $y_c = 4.87 + (0.388)(12) = 9.5$ hours. As you progress, you need to determine the actual hours and re-establish the linear regression to represent a more accurate view of conditions.

Forecasting Error

The use of forecasting error methods is to be able to evaluate the methods used and to compare them to other methods to see which one is the best process. The two common methods are MAD (Mean Absolute Deviation) and MSE (Mean Squared Error) where MAD is the average absolute error and MSE is the average of squared errors. For the purposes of this paper, we are going to work with the MAD method (Equation 9).

Table 6: Table of Errors Using Weighted Average (Example 4)

Week	Random Failure Hours (Actual)	Forecast (Weighted Average)	Error	[Error]
1	5			
2	6			
3	5			
4	7			
5	8	6	2	2
6	6	6.9	-0.9	0.9
7	8	6.7	1.3	1.3
8	9	7.3	1.7	1.7
9	7	8	-1	1
10	9	7.7	1.3	1.3
		SUM =	SUM =	SUM =
		42.6	4.4	8.2

Equation 9: MAD Forecasting Error Method

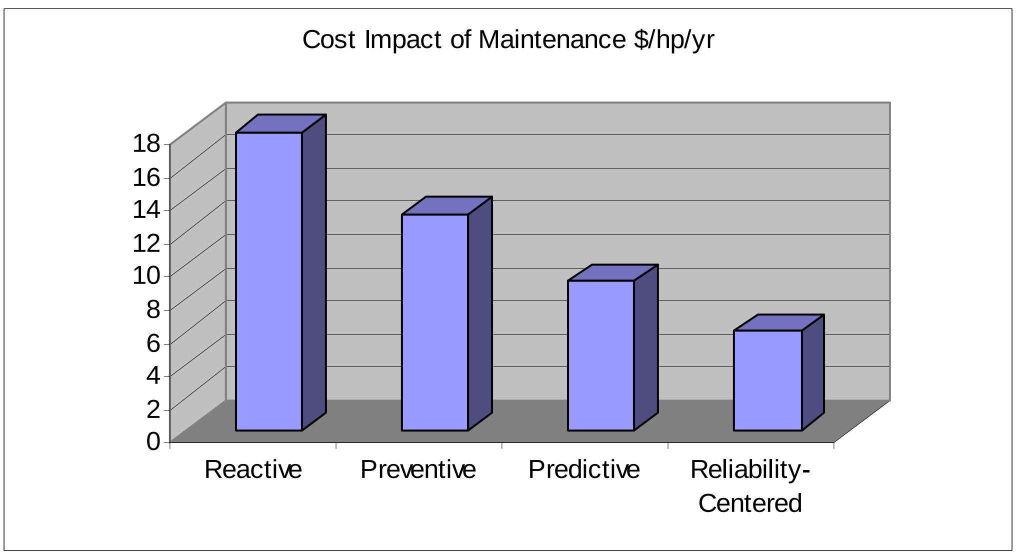
$$MAD = \frac{\sum |actual - forecast|}{n}$$

Using the MAD method for determining error, the error averages (4.4/6 = 0.73 hours) which is a pretty good forecast.

The Average Cost Impact of Maintenance Programs Multiplier

In previous papers and articles, we discussed the impact of different levels of maintenance in a cost($)/horsepower/year for a facility. These values, as shown in Figure 1, represent the potential impact of moving from one type of maintenance to the next. These values can be used in lieu of actual values, if you do not have a history of the impact of different programs.

Figure 1: Cost Impact of Maintenance Programs



The values are used as multipliers. For instance, if I am developing a predictive maintenance program from a reactive maintenance program, the impact would be (8/18)*100% or 44.4% times cost or hours.

Probability of Equipment Survival

In addition to the forecast of hours, there is a need to estimate the equipment that will be affected. For this part, history and some gut assumptions may have to be made. The more history and detail that is available, the more accurate your equipment forecasts will be. A few of the assumptions we will make in this article include:

- ☑ The equipment failure rate will, more or less, follow a normalized bell curve. This allows easy use of MTBF and MTTR values;

☑ The process will be a combination of series and parallel systems.

Using historical data, records, manufacturing data, etc., we need to determine the following:

1. Mean Time Between Failure (MTBF) or Mean Time To Repair (MTTR) by taking the total time of operation in hours, days, weeks or whatever your preference is, and divide by the number of failures;
2. Determine the Failure Rate, which is 1/MTBF or 1/MTTR;
3. Keep these values as high up the system as makes sense for modeling different maintenance practices; and,
4. Start by obtaining the extremes – Failure Rates for the systems if no maintenance is performed and the failure rates if all recommended maintenance is performed. Then any fine-tuning can be determined.

In the next step, make a block diagram of the system with identified failure rates for each part that is identified. We can now apply all of the data through a set of simple formulae known as the Reliability Function, The Series Reliability Function and the Parallel Reliability Functions.

Equation 10: The Reliability Function

$$R = e^{-t\lambda}$$

Where e is the natural log, t is the time of interest (must be the same as what was used to determine the failure rate), and λ is the failure rate.

The Reliability Function shown in Equation 10 is the chance of survival for the system at a particular time.

Equation 11: The Series Reliability Function

$$R_s = (R_a)(R_b)...(R_n)$$

Equation 12: Two-System Parallel Reliability

$$R_p = (R_a + R_b) - (R_a)(R_b)$$

Equation 13: The Parallel Reliability for Three or More Identical Systems

$$R_p = 1 - (1 - R)^n$$

Where n is the number of parallel systems.

When calculating through, determine the survivability of the parallel system first, then the series system. For instance, in a simple pump system, as follows:

There is a sump system where, if the level exceeds 10 feet, or the tank wall ruptures, it has failed. Because of the critical nature of the system, there are redundant submersible pumps. Both pumps are 'hard-piped' to a common outlet with backflow valves on each one. Both submersibles are fed by separate starters and float switches. The starters are fed from a common bus. It has been determined that maintenance practices and inspections will identify 90% of faults allowing for scheduled shutdowns.

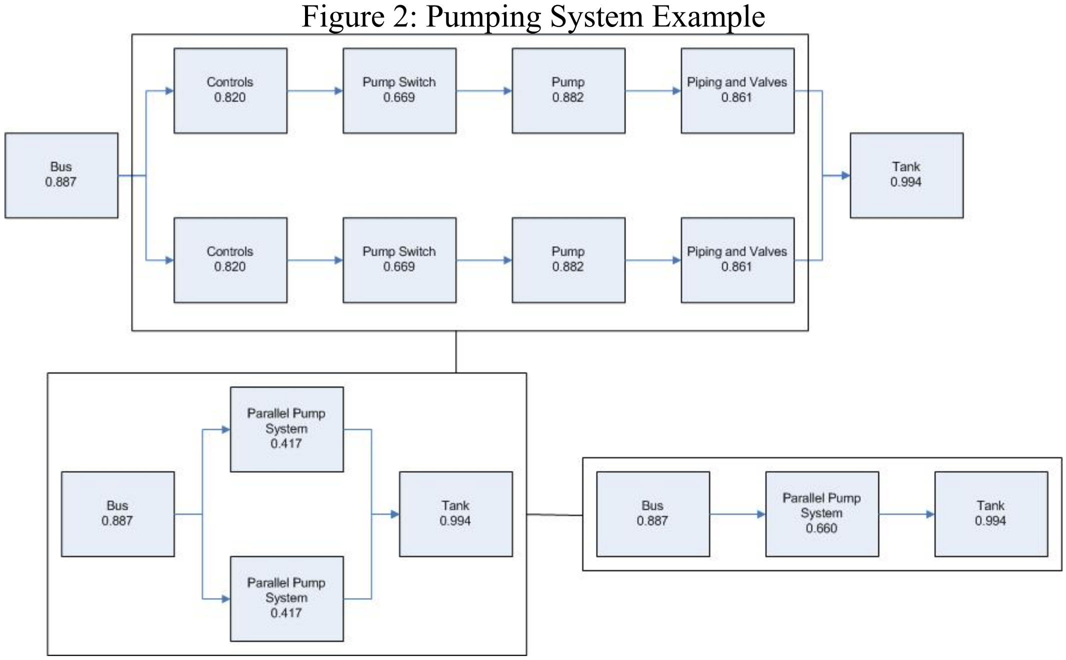
Breakdown of the system, the failure rate in hours and the availability of parts and time to repair are listed in Table 7.

Table 7: Breakdown of Components and Failure Rates

Component	Failure Rate (per hour)	Days for Repair
Bus	2.0×10^{-5}	5
Controls	3.3×10^{-5}	0.5
Float Switch System	6.7×10^{-5}	2
Pump	2.1×10^{-5}	5
Piping and Valves	2.5×10^{-5}	5
Tank	1.0×10^{-5}	20

The failure rates can also be presented in terms of what is being used for forecasting time, in order to make modeling scenarios similar. In this case, however, if we were to evaluate the system for 6,000 hours (3 shifts, 5 days per week), we would end up with a system as represented in Figure 2.

Figure 2: Pumping System Example



At the 6,000 hour point of operation, this system has a 58.2% chance of survival.

Modeling Systems for Accurate Planning and Scheduling

In the "Considerations for Planning and Scheduling Part 1" article, we discussed how to develop and improve wrench-time metrics for scheduled maintenance. In Part 2, we discussed how to develop a reactive maintenance plan for random equipment failure and systems that have been selected to 'run to failure.' In this article, we discussed methods for forecasting random failures and how to determine the survivability of systems.

With the above information we can begin to model scenarios for improving our planning and scheduling. Some of the additional information that we will need to determine include the lag times for the implementation of maintenance strategies. However, with the information provided in this paper, we can begin to look at our resource and manpower needs. The extent of such modeling can be as intense or as simple as is required.

For example, we will take a 4,000 hour per year production line. The process manufactures and packages cookies and consists of the following components:

1. Incoming electrical power;
2. Controls;
3. Measuring and Mixing machines;
4. A steam system;
5. An oven and conveyor system for cooking;
6. A cooling system;
7. A quality control system, pre-packaging;
8. Packaging;
9. A quality control system, post-packaging

Additionally, there are the following systems:

1. Storage and truck unloading;
2. Compressed air product transfer systems;
3. Building lighting systems;
4. HVAC systems;
5. Office systems and other systems will not be addressed at this time;
6. Facilities and cleaning systems;
7. Fire protection systems;
8. Other.

There are four industrial electricians (two per shift), four mechanical tradesmen and two general trades. Three of the four electricians are considered experienced and the fourth is new, with the same ratio for the four mechanical trades. The two general trades are considered laborers with a medium level of skill. A janitorial staff maintains the cleanliness of the building. While critical systems are automatically assigned planned and reactive maintenance programs, we cannot forget the run-to-failure systems.

Table 8: Reliability of Plant Systems

Component	Failure Rate (per hour)	Operating Hours (End of Week 11)	Critical?	Days for Repair
Transformer and Switchgear	1.3×10^{-5}	5,000	Y	1
MCC for each line	6.7×10^{-5}	2,500	Y	0.5
Controls (Measure and Mix)	6.7×10^{-5}	1,500	Y	1
Measure and Mix Equipment	4.0×10^{-5}	3,000	Y	2
Controls (Steam System)	1.3×10^{-4}	500	Y	1
Steam System (Boiler)	2.0×10^{-5}	3,300	Y	5
Oven and Cooking System	1.7×10^{-4}	0	Y	1
Chiller System	5.0×10^{-5}	1,000	Y	2
Refrigeration/Cooling	1.7×10^{-4}	6,000	Y	3
Quality Control Equipment	2.5×10^{-4}	100	Y	0.5
Packaging System	6.7×10^{-4}	800	Y	1
Storage and Truck Unloading	5.0×10^{-4}	1,000	Y	1
Compressed Air System	5.0×10^{-4}	100	Y	1.5
Building Lighting	1.0×10^{-2}	-	N	0
HVAC	5.0×10^{-4}	600	N	1

Table 9: Unscheduled Downtime By Trade-Type (80 hour week/ 2 x 40 hour shifts)

Week	**Random Failure Hours (Electrical)**	**Random Failure Hours (Mechanical)**
1	8	5
2	7	6
3	9	5
4	10	7
5	12	8
6	11	6
7	15	8
8	12	9
9	13	7
10	18	9

The complete system is on a planned maintenance program only.

The tradesmen have an estimated wrench-time of 6 hours per shift, or 30 hours per week, which is exceptional in that travel time and wait times are considered nil, for this model. The questions are:

1. What is the projected time of the 30 hours required for random failures for each tradesperson in week 11? The remaining time is the time that can be scheduled for general predictive maintenance.
2. What systems are projected to have the highest chance of random failure during that week? This allows the planner to rate the correct parts and vendor availability.

Through linear regression we are able to determine that mechanical has 9.14 hours and electrical has 16.9 hours. If spread across all four mechanicals, then (120 – 9.14)/4 = 27.7 PM hours in week 11 each and 25.8 PM hours in week 11 for the electricians.

The highest chance for failures are considered based upon the existing hours on Table 8, which are the end of the week on week 10 (Table 9). Week 11 includes the additional 80 hours. The order of potential failure is as follows:

Table 10: Survival Through Week 11 (Lowest to Highest)

Component	Failure Rate (per hour)	Operating Hours	Survival Week 11
Refrigeration/Cooling	1.7×10^{-4}	6,080	0.361
Packaging System	6.7×10^{-4}	880	0.555
Storage and Truck Unloading	5.0×10^{-4}	1,080	0.583
HVAC	5.0×10^{-4}	680	0.712
MCC for each line	6.7×10^{-5}	2,580	0.846
Measure and Mix Equipment	4.0×10^{-5}	3,080	0.887
Controls (Measure and Mix)	6.7×10^{-5}	1,580	0.904
Compressed Air System	5.0×10^{-4}	180	0.914
Controls (Steam System)	1.3×10^{-4}	580	0.927
Steam System (Boiler)	2.0×10^{-5}	3,380	0.934
Transformer and Switchgear	1.3×10^{-5}	5,080	0.936
Chiller System	5.0×10^{-5}	1,080	0.951
Quality Control Equipment	2.5×10^{-4}	180	0.975
Oven and Cooking System	1.7×10^{-4}	80	0.986

By taking each system down closer to the component level, the actual types of faults can be estimated.

Conclusion

The combined methods in parts 1 through 3 provide the planner/scheduler with the tools necessary to plan maintenance, improve maintenance and determine the potential impact of random equipment failure. The examples provided within the papers are simple in scope, but represent the potential should the user follow the system outlined. In Part 4 of this series, we will explore the use of the WFC/DFM method to determine the needs for spare parts and the ability to use the process to budget the maintenance department with a very low error margin.

About the Author

Howard W Penrose, Ph.D., CMRP, is the President of SUCCESS by DESIGN Reliability Services. SUCCESS by DESIGN specializes in corporate maintenance program development, motor management programs and maintenance and motor diagnostics training. For more information, or questions, see http://www.motordoc.net, contact info@motordoc.net or call 800 392-9025 (USA) or 860 577-8537 (World-Wide).