METHOD FOR COOLING TOWERS MAINTENANCE POLICY SELECTION BASED ON RCM CONCEPTS

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Abstract. *In a thermal power station, the exhaust steam from the steam turbine flows thought a condenser in order to transfer heat to the a circulating cooling water system flow. The heat water is cooled in a cooling tower. In case of cooling tower failure the power plant must reduce its nominal output, reducing the plant efficiency, or even must face a forced shut down situation. Taking in view the great importance of the cooling tower for plant operation, its availability should be carefully evaluated.*
The availability of a system, such as the cooling tower, is strong associated with its parts reliability and maintenance policy. That policy not only has influence on the parts repair time but also on the parts reliability, affecting the system degradation and availability.
The Reliability Centered Maintenance (RCM) philosophy is one of the most popular maintenance optimization methods. The philosophy's key is the identification of the system critical components, which are defined in terms of the system functional performance degradation in case of component failure. In order to avoid the failure of the critical components, the maintenance efforts are focused on preventive or predictive tasks, aiming at reducing the frequency of failure. The scheduling of maintenance tasks for critical components reduces the downtime for corrective maintenance, increasing the system availability and reducing the maintenance costs.
This paper presents a method for cooling tower maintenance policy selection based on RCM concepts. This method has main steps: functional tree elaboration (defining the intending functional purpose of each cooling tower component and their performance criteria), development of Failure Mode and Effects Analysis (FMEA) – to describe the potential failure modes of each component and the consequences for the system functional operation, and maintenance policy selection for critical components, identified after the application of FMEA analysis, based on the RCM decision logic diagram.
The method for reliability evaluation is applied in a set of cooling towers installed in a 500MW combined cycle thermoelectric power plant. After defining the main failure modes for equipment, a reliability analysis is developed based on system reliability concepts. Considering the proposed maintenance policy selection method, a maintenance plan is proposed for the critical components in order to increase the cooling tower availability.

Keywords*: reliability, cooling towel and RCM.*

1. INTRODUCTION

The availability of the combined cycle thermal power plants depends on the perfect operation of all its systems (e.g. gas turbine, heat recovery steam generator, steam turbine and cooling system).The HRSG is the link between the gas turbine and the steam turbine process, the function of HRSG is to convert the exhaust gas energy of the gas turbine into steam, (Kehlhofer, 1999). In the cooling water system, heat is removed from the steam turbine exhaust is carried by the circulating water to the cooling tower, which rejects the heat to the atmosphere. Because of this direct path to the atmosphere, surrounding water bodies typically do not suffer adverse thermal effects. Cooling towers have been used for many years at power plants in locations where some water is available for cooling system use, but where once-through cooling is not viable. The recirculating cooling water system arrangement incorporates an evaporative cooling tower as show in the Fig. 1, (Black & Veatch, 1996).

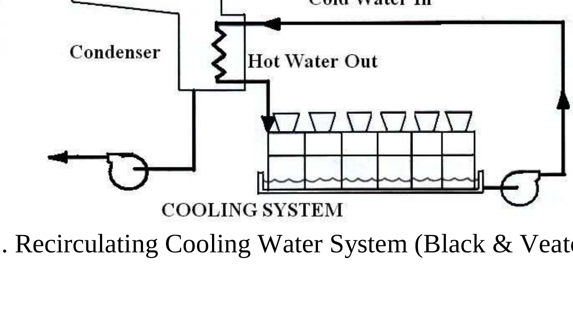

Figure 1. Recirculating Cooling Water System (Black & Veatch, 1996)

The efficiency of the cooling process depends on the ambient conditions and the heat rejection load within the tower must operate. Other factors that influence efficiency, and over which the cooling tower manufacturer has some measure of control, are the amount of heat transfer surface area, the time duration that the water surface is exposed to the airstream, and the ratio of airflow to water in the cooling tower. Those factors can be balanced in an array of combinations that produce the same end result of cooling the water to the design conditions. Besides these factors, to maintain the functional efficiency and availability of the cooling tower it is necessary to identify the critical components and to schedule maintenance tasks (preventive or predictive) to ensure high availability.

Bearing in mind the great importance of the cooling water system for steam cycle, and consequently for the plant operation, its availability should be carefully evaluated in order to foresee the performance – technical and economical - of the energy system. The availability of a complex system, such as the thermal power plant, is strongly associated with the parts reliability and maintenance policy. That policy not only has influence on the parts repair time but also on the parts reliability affecting the system degradation and availability.

This paper presents a system reliability-based method used to identify the most critical components in a cooling tower. The criticality is associated with the component failure effect on the cooling water system operation condition. The higher the criticality of the component more technical and economical resources should be used by the maintenance activities to keep the cooling tower available for operation. The reliability centered maintenance concepts are used as a guideline in ranking the maintenance policy priorities for the critical components aiming at the cooling tower operation availability.

2. RELIABILITY CENTERED MAINTENANCE

The Reliability Centered Maintenance RCM, as a procedure to identify preventive maintenance requirements of complex systems, has been recognized and accepted in many industrial fields, (Rausand, 1998); (Zio,2009). The RCM was introduced in the USA during the 1960's the first industry to confront these issues was the international civil aviation industry, (Richet et al. 1995). This experience generated the report that years later would be the pioneer work in presenting the RCM concepts, (Norwlan; Heap, 1978). RCM became more popular and it was applied in the thermo nuclear generation and in the armed forces, expanding to the gas and petroleum industry, (Rausand, 1998). The RCM was introduced in the Brazil in the late 1990's (Azevedo, 2004) and has been applied in the power generator Brazilian market in 2003, (Alkain, 2003) Raposo (2004), and in a combined cycle thermal power plant in 2006, (Carazas, 2006).

The RCM philosophy's main focus is on the identification of the functions of each one of the components of the system. This allows the application of the specified maintenance task for each one of the components considered critical, in order to guarantee the availability to operate, and the cut-back of maintenance costs. The criticality of a component is defined by the loss of operation performance of the system due to failure in the process, caused by a component failure. The greater the loss, the greater the criticality of the component. The RCM methodology is made up by a sequence of steps that allow its application in the various branches of the industry, which are as follows (Moubray, 1999); (Rausand, 1998):

a) Definition of the system and recollection of data and information;
b) Functional description - Elaboration of the Functional Tree;
c) Failure Mode and Effects Analysis (FMEA) - Determine the consequence of the functional faults;
d) Identification of the critical components;
e) Selection of the maintenance policies;
f) Evaluation of the Results.

3. METHOD DEVELOMENT

The method first step consists in the elaboration of the cooling tower functional tree that allows the definition of the functional links between the equipment subsystems. Although all cooling tower possess essentially the same subsystems, such as circulating water pumps, circulating water piping and fans, there are differences between the technologies used by the manufacturers; therefore the functional tree must be developed for each specific cooling tower model.

The next step is the development of the Failure Mode and Effects Analysis (FMEA) of each tower component in order to define the most critical components for cooling tower operation. This criticality is based on the evaluation of the component failure effect on the system operation, (Lewis, 1996). For the definition of the system degradation, the FMEA analysis uses a numerical code, usually varying between 1 and 10. The higher the number the higher is the criticality of the component that must be evaluated for each component failure mode. For the cooling tower analysis a criticality scale between 1 and 9 is proposed, (Carazas; Souza, 2007). Values between 1 and 3 express minor effects on the system operation and values between 4 and 6 express significant effects on the system operation. Failures that cause the combined cycle unavailability or environmental degradation are classified with criticality values between 7 and 9. These criticality values are shown on Table 1.

Table 1 Criticality Index Description for FMEA Analysis (Carazas; Souza, 2007)

Criticality Index	**Effects on the Turbine Operation**
7 (Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but does not cause damage to other equipment components, possibly affecting: - the equipment operation, once it must be stopped; - the environment in a severe manner; - the compliance with government requirements. The failure also causes the need of repair and/or replacement of the failed component. The plant is unavailable for short period of time.
8 (Very Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but do not cause damage to other equipment components, possibly affecting:- the equipment operation, once it must be stopped; - the environment in a severe manner; - the compliance with government requirements. The failure also causes the need of repair and/or replacement of the failed component. The plant is unavailable for long period of time.
9 (Hazardous Effects)	This severity ranking is given when a component potential failure mode can cause severe damage to other components and/or to the equipment, possibly affecting:- the equipment operation, once it must be stopped;- the environmental safety, including leakage of hazardous materials; - the safe power plant operation; - the compliance with government requirements. The failure also causes the need of repair and/or replacement of a great number of components. The plant is unavailable for long period of time.

The method third step involves a reliability analysis. The failures should be classified according to the subsystem presented on the functional tree. The reliability of each subsystem is calculated based on the failure data base and the system reliability is simulated through the use of block diagram. Considering the ‘time to repair’ data and the preventive maintenance tasks associated with the equipment, the cooling tower availability is evaluated using the block diagram.

Once the critical components are defined a maintenance policy can be proposed for those components, considering the RCM concepts. This maintenance policy philosophy has focus on the use of predictive or preventive maintenance tasks that aim at the reduction of unexpected failures during the component normal operation, (Smith and Hinchcliffe, 2003). For complex systems, the occurrence of unexpected components failures highly increases maintenance costs associated with corrective tasks not only for the direct corrective costs (spare parts, labour hours) but also for the system unavailability costs.

So, the use of predictive or preventive tasks allows the programming of maintenance tasks in advance and also reduces the component failure probability during a given operation period and consequently increasing the system availability.

The reliability block diagram analysis not only allows the evaluation of the actual maintenance policy but also allows the prediction of possible availability improvement considering the application of new maintenance procedures, expressed by the reduction of corrective maintenance repair time.

In Fig. 2 a flowchart is used to explain the method’s main steps (Carazas and Souza, 2007).

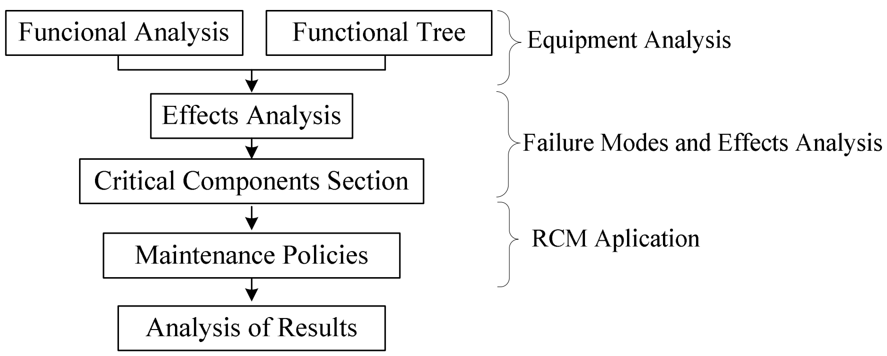

Figure 2. Flowchart for Complex System Availability Evaluation.

4. APPLICATION

The method is applied on the analysis of in a set of counterflow cooling towers installed in a 500MW combined cycle thermoelectric power plant located in South America.

4.1. Functional Tree

The functional tree for the counterflow cooling tower is show in Fig. 3. The equipment is divided in five main subsystems: recirculating water system, support, heat exchange system, water recovery system and drift eliminators. Those subsystems are divided in components, each one performing a specific function linked with the subsystem main function. A failure in a component at the bottom of the tree affects all subsystems above it, causing a possible degradation in the cooling water system operation, represented by any reduction in the heat exchange capacity or even environmental degradation. The tree was developed according to the operation manual furnished by the manufacturer.

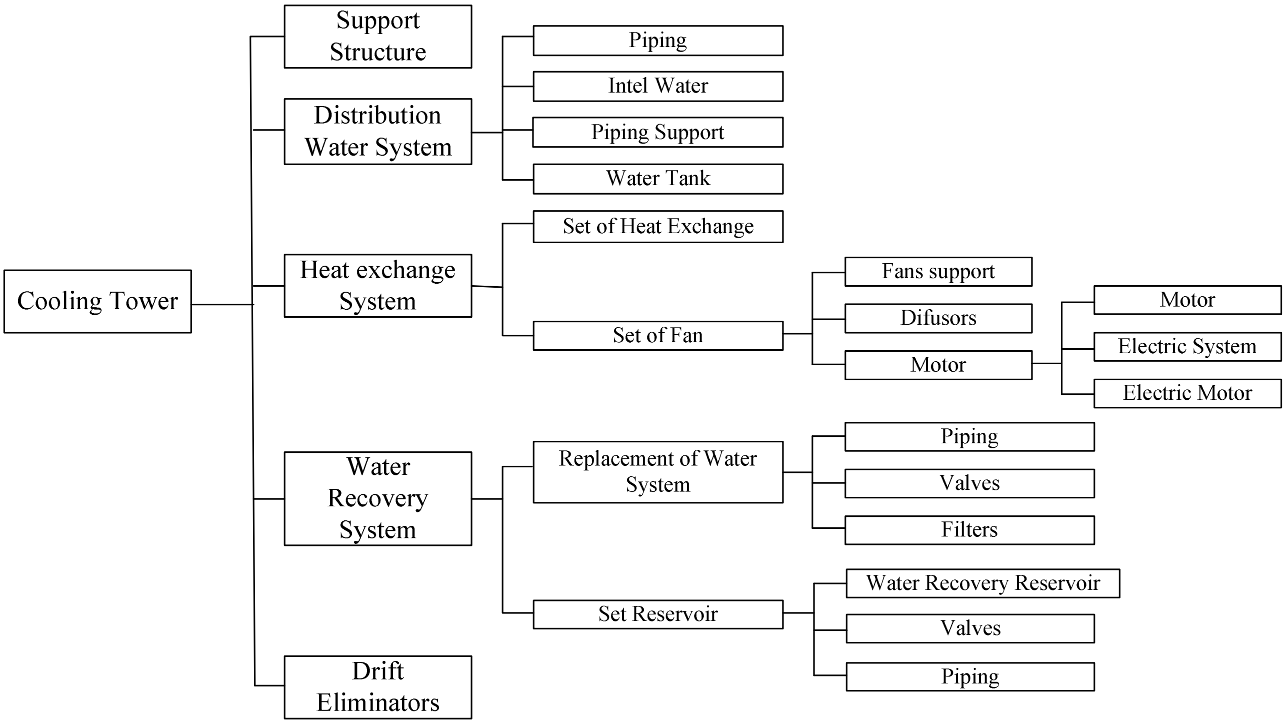

Figure 4. Cooling Tower Simplified Functional Tree

4.2. Failure Mode and Effects Analysis

Although there are many variants of FMEA, it is always based on a table, as shown in Table 2. In the left-hand column the component under analysis is listed; then in the next column the physical modes by which the component may fail are provided. This is followed, in the third column, by the possible causes of each of the failure modes.

The fourth column lists the effects of each failure mode that are classified according to the criticality scale, which expresses the degradation degree in the cooling water system operation.

The FMEA analysis was performed for each component listed in the end of a given branch of the functional tree. In Table 2 the analysis for the support structure is partially presented as an example. This component is critical because, - for example – on 21th August 2007, the Vermont Yankee nuclear plant was forced to reduce its power output after staff at the Vernon reactor detected problems with one of its two cooling towers: a cooling tower structure partially collapsed, (Boston Glove, 2009).

The FMEA analysis is used to enumerate the possible modes by which components may fail and for tracking through the characteristics and consequences of each mode of failure on the cooling water system as a whole.

Table 2 Failure Mode and Effects Analysis: Example – Support Structure

Function	Failure Mode	Failure Causes	Failure Effects	Critically
Structure Support	Achieve Ultimate limit state	Fatigue failure; fracture, Buckling; Overburden.	Loss of structural support; Loss of cooling water; Increase pressure in the HRSG, HRSG-TRIP, steam turbine TRIP.	9

The FMEA analysis pointed the most critical components for the cooling tower, which are listed in Table 3

Table 3 Results of the Application of Failure Mode and Effects Analysis in a Set of Cooling Towers

System	Subsystem	Component	Failure Mode	Critically
1.Cooling Tower	1.1. Structure Support		Achieve Ultimate limit state	9
	1.2. Distribution water system	1.2.1.Piping	Cross section Blockage	7
		1.2.2. Inlet water	Cross section Blockage	7
	1.3. Heat exchange System	1.3.1.Fans- Electric System	Incapacity to transmit electric energy	7
		1.3.2. Electric Motor	No electric power	7
		- Flexible shaft	Shaft cross section rupture	7
		- Gear Box	Gear tooth fatigue failure	7
			Shaft cross section rupture	7
		- Coupling	Linkage between coupling and electric motor failure	7
			Coupling failure	7
	1.4. Water Recovery System	1.4.1.Check Valve	Incapacity to open	6
		1.4.2. Water piping	Cross section Blockage	6

The failure modes for the components were developed according to manufacturer's information and failures analysis presented in literature, Kehlhofer *at al* (1999); Lora & Nascimento, (2004); Burgazzi, (2004), Black & Veatch(1996). A total of 32 FMEAs were developed and analyzed, (Carazas and Souza, 2006).

Once the critical components as for reliability analysis are identified the planning of maintenance activities is mainly focused on these components aiming at keeping cooling tower availability.

4.3. Reliability Analysis

Reliability can be defined as the probability that a system will perform properly for a specified period of time under a given set of operating conditions. Implied in this definition is a clear-cut criterion for failure, from which one may judge at what point the system is no longer functioning properly. Reliability can be calculated by equation (1).

$$R(t) = e^{-\lambda t} \quad (1)$$

where: *R(t)* is the reliability, *t* is a time period [h] and λ is a failure rate in [failures/hours].

The cooling tower block diagram, for normal operation condition, is a series system using all subsystems present in the first level of the functional tree. Once the reliability of each component is defined, based on statistical analysis of their failure data, the cooling tower reliability is equal to the product of the subsystem reliability, as show in the Fig. 5, and the system reliability is expressed by the equation (2).

$$R_{Ct} = R_{SS} \times R_{WS} \times R_{HE} \times R_{WR} \quad (2)$$

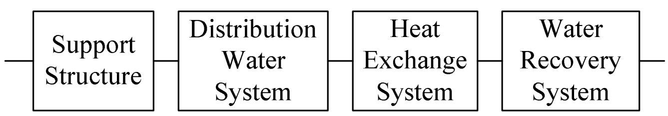

Figure 5 Cooling Tower Block Diagram

Where: R_{CT} is the Reliability of cooling tower, R_{SS} is the Reliability of support structure; R_{WS} is the reliability of distribution water system; R_{HE} is the reliability of Heat exchange system and R_{WR} is the reliability of water recovery system. Considering that each subsystems reliability can be modeled by an exponential distribution, the cooling tower reliability is also modeled by an exponential distribution which failure rate is calculated as:

$$\lambda_{CT} = \lambda_{SS} + \lambda_{WS} + \lambda_{HE} + \lambda_{WR} \quad (3)$$

Where: λ_{CT} is the cooling tower failure rate, λ_{SS} is the support structure failure rate; λ_{WS} is the distribution water system failure rate; λ_{HE} is the Heat exchange system failure rate and λ_{WR} is the water recovery system failure.

The reliability of those subsystems cam be estimated thought the following methods:

- Analysis of the historical failure database of the equipment.
- Analysis of the historical failure database of similar equipments.
- Analysis of prototypes reliability tests.
- Use of reliability prediction mathematical models based on commercial database.

For the present study, the selection of the most critical equipments as for reliability block diagram analysis is based on the failure database of the power plant. The critical equipments are those that present the greats frequency of failure.

Unfortunately, the failure database does not clearly register the time between two consecutive failures in given equipment that would support equipment reliability analysis. Thus, reliability estimate for the critical equipment is based on databook information.

The critical equipments are: support structure, electric motor, gear box and fans. The support structure is subjected to dynamic loading due to fan rotation. Electric motor and the box gear are subjected to an environment winy high humidity and subjected to dynamic loading due to fan rotation.

The simplified cooling tower diagram bock is show in the Fig. 6.

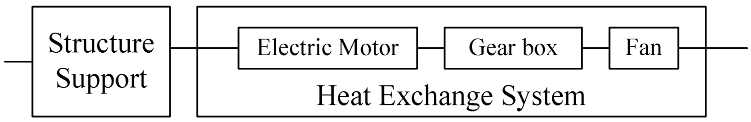

Figure 6 Critical Cooling Tower Block Diagram

Table 4 gives a list of the critical equipment that constitute cooling tower and the parameters of the reliability models, (MIL-HDBK-217F0, 1991); (Martone, 2009); (Krishnasamy, 2005);

Table 4. Failure Rate of Cooling Tower Critical Components

Subsystem	Component	Parameter
Structure Support	Structure	λ = 31,0x10^{-6} failures/hour
Heat Exchange System	Electric Motor	λ = 34,2x10^{-5} failures/hour
	Gear box	λ = 16,0x10^{-6} failures/hour
	Fan	λ = 1,20x10^{-6} failures/hour

The cooling tower failure rate is 390x10^{-6} failure per hour, and the *MTTF* (Mean Time to Failure) is:

$$MTTF_{CT} = \frac{1}{\lambda_{CT}} = 2564{,}10\ hours$$

The mean time to failure is close to four months of continuous operation. As for exponential reliability distribution, the main time to failure corresponds to a reliability of 36,8 %. This results means that there is a chance of 36,8% that the cooling tower will operate, without failure, for 2560 hours. The set cooling towers (eight units) reliability is 97,45%.

Aiming at increasing that reliability, maintenance tasks should be performed to detect the development of failures modes in the critical equipment. Those tasks must be executed in time intervals smaller than 2560hours to be effective.

4.4. RCM Maintenance Schedule for Cooling Towers

Component manufacturers and suppliers tend to recommend a very conservative and costly maintenance approach. Changes in the power system market has led to a shift from technical to economic driving factors, including the maintenance planning with the aim of the increase of the operational lifetime and reduce costs.

Modern engineering systems are ideally designed for profitable operation throughout their service life in compliance with given requirements and acceptance criteria typically related to the safety of the personnel and the risk posed to the public and the environment. For ensuring his, it is necessary to control the development of deterioration processes by appropriate planning and performing of inspections and predictive maintenance actions. The predictive maintenance aims to reduce or preventive maintenance tasks for critical components, this policy allows the reduction of unexpected failure occurrences that cause the system unavailability and are usually very expensive to repair.

The RCM philosophy recommended approaches maintenance tasks for critical components, in this way and based on the failure rates of these components, maintenance tasks are selected as shown in Table 5. The maintenance frequency is calculated to ensure a minimum reliability of 80% (for each critical components), by eq. 1. The result is displayed in the third column of Table 5.

Table 5 Maintenance Schedule for Counterflow Cooling Tower

Description	Comments	Maintenance Frequency
Overall visual inspection	Complete overall visual inspection to be sure all equipment is operating and safety systems are in place.	
Check tower structure	Check for loose fill, connections, leaks, etc./ inspect and readjust the unions in case they have lost the adjustment of product vibration. Inspect the presence of cracks or deformations in the structure.	Monthly/Bimonthly
Fan Electric motor condition	Check the condition of the fan motor through temperature or vibration analysis and compare to baseline values.	Monthly
Check fan blades	Check for excessive wear and secure fastening	Monthly
Flexible shaft	Check the condition of the flexible shaft fan through temperature or vibration analysis and compare to baseline values.	Monthly
Check motor supports	Check for excessive wear and secure fastening	Monthly
Motor alignment	Aligning the motor coupling allows for efficient torque transfer	Monthly
Check drift eliminators, louvers, and fill	Look for proper positioning and scale build up	Monthly
Inspect nozzles for clogging	Make sure water is flowing through nozzles in the hot well	Annually
Check bearings	Inspect bearings and drive belts for wear. Adjust, repair, or replace as necessary.	Annually
Motor condition	Checking the condition of the motor through temperature or vibration analysis assures long life.	Monthly
General recommendations for predictive and preventive maintenance.		
Vibration	Check for excessive vibration in motors, fans, and pumps	
Test water samples	Test for proper concentrations of dissolved solids, and chemistry. Adjust blowdown and chemicals as necessary.	
Check lubrication	Assure that all bearings are lubricated per the manufacture's recommendation.	
Clean tower	Remove all dust, scale, and algae from tower basin, fill, and spray nozzles.	
Piping	Checking the leaks or excessive corrosion. Monitor the pressure of operation of the system to avoid very high pressures, and inspect the filter system to prevent the entry of corrosive agents	
Thermographic Analysis	Check and monitoring motors, bearing and pumps	

5. CONCLUSIONS

The method for reliability analysis seems suitable for complex systems since it allows not only the identification of critical components for maintenance planning but also defines quantitatively the system's reliability.

The development of the system functional tree is fundamental for the understanding of the functional relation between system components. Based on this tree a reliability block diagram can be easily constructed, representing the information flow through the components in accordance with a pre-defined system performance level.

Based on the functional hierarchy, the FMEA analysis is performed considering the failure modes associated with the components listed at the end of each branch of the functional tree, identifying the effects of component failure on the system under analysis. Once the critical components are identified, based on the failure effects classification, a maintenance policy can be formulated to reduce their occurrence probabilities.

The maintenance policy aims to reduce the system unavailability through the use of predictive or preventive maintenance tasks for critical components. This policy allows the reduction of unexpected failure occurrences that cause the system unavailability and are usually very expensive to repair.

For cooling towers the use of predictive or preventive tasks seems feasible providing better maintenance practices for the complex heat exchange system. The most important results are show in Table 5, Maintenance Schedule for Counterflow Cooling Tower.

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