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PETRI NET BASED RELIABILITY ANALYSIS OF THERMOELECTRIC PLANT COOLING TOWER

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Abstract. *The cooling tower plays a fundamental role in the operation of a coal-based thermoelectric plant, since it is one of the systems responsible for the thermodynamic balance of the plant. Therefore, for a proper maintenance plan to be developed for the cooling tower, it is necessary to carry out a qualitative and quantitative study of the reliability of this system. This paper proposes the development of a reliability analysis based on Stochastic Petri Nets for the Cooling Tower. Initially, a study of the system is done through the techniques of Functional Tree and Functional Description. Then, a qualitative analysis of the system reliability is performed through Failure Modes and Effects Analysis (FMEA). Finally, the quantitative analysis is done through Stochastic Petri nets, with the support of the Block Diagram technique. For this, the Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR) of each component of the system will be taken into account.*

Keywords: *Reliability Analysis, Petri Nets, Cooling Tower, Coal Fired Power Plant.*

1. INTRODUCTION

The reliability analysis is a set of studies that characterize the behaviour of a given system, with respect to the occurrence of failures (Liu, et al., 2015; Kececioglu, 1991). One of the ways to carry out such analysis is through the development of a model of the system being studied. Reliability models, such as block diagrams or fault trees, aim to evaluate the relationship between different system components, as well as the effect of their failure (Modarres, Kaminskiy, and Krivtsov, 2010; Smith and Hinchclife, 2004). The results obtained from the reliability analysis contribute to the decision making related to both the systems design and maintenance planning (Souza, Hidalgo and Silva, 2013; Souza, Hidalgo, Silva, and Martins, 2012).

Stochastic Petri Net (SPN) is a mathematical modelling language widely used in different areas of knowledge, especially when it is necessary to represent non-deterministic phenomena. SPN is currently being used for systems reliability, risk, availability, and performance analysis (Talebberrouane, Khan and Lounis, 2016; Vileiniskis and Remenyte-Prescott, 2017). This paper proposes the development of a reliability analysis based on Stochastic Petri Nets for the cooling tower of a coal-fired power plant. Other reliability analysis techniques are also used in order to support the Petri net model development.

2. COOLING TOWER BASICS

Cooling towers are an integral component of many refrigeration systems, providing comfort or process cooling across a broad range of applications. They are the point in the system where heat is dissipated to the atmosphere through the evaporative process, and they are common in industries such as oil refining, chemical processing, power plants, steel mills, and many different manufacturing processes that require cooled water (Kiran and Muthukumar, 2017).

Figure 1 shows a schematic arrangement of a cooling tower application in a coal fired power plant where it is used to condensate exhaust steam from the low-pressure turbine. The pump keeps the water re-circulating through the condenser where it picks up heat and distributes on the top of the twelve cells of the cooling tower.

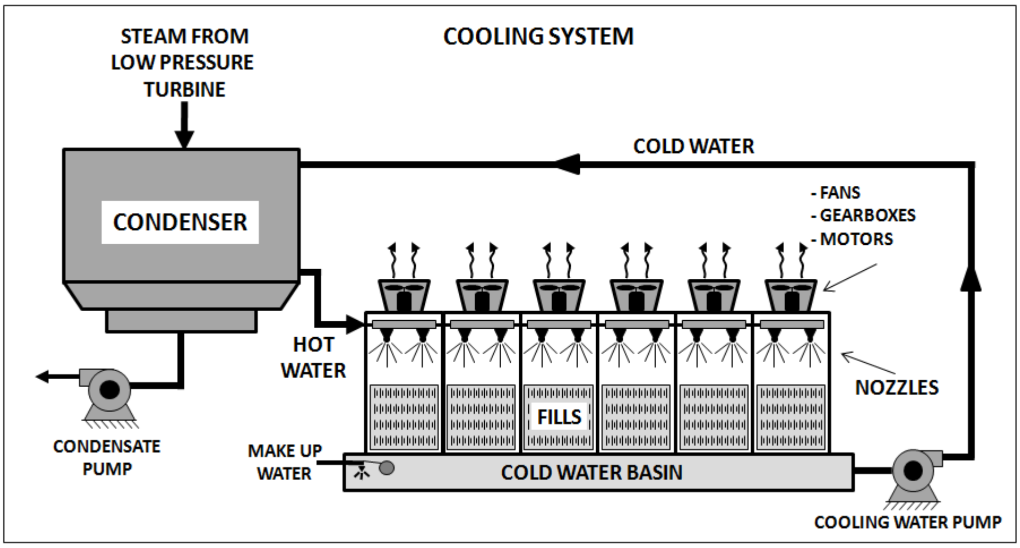

Figure 1. Cooling Tower System.

According to SPX Cooling Technologies (2017), each cell contains the basic components such as concrete structure or frame to support the exterior enclosures fan, motor, speed reducers. Most towers employ fills (made of plastic, wood or ceramic) to promote the heat transfer between air and water. The cold-water basin is located at the bottom of the tower and receives the cooled water that flows down through the tower and fills. Drift eliminators capture water droplets entrapped in the air stream so it will not be lost to the atmosphere. An air inlet area is where the air enters the tower. Nozzles spray the warm water through the fills uniformly, which is essential to achieve a good heat transfer. Fans are used to move large volumes of air efficiently and with minimum vibration. Speed reducers are used because optimum speed of a cooling tower fan seldom coincides with the most efficient of the driver (motor). Electric motors are used to drive the fans on cooling towers; they must be reliable under extremely adverse conditions.

The efficiency of cooling towers depends on the heat rejection load in which the tower must operate. During design phase, the manufacturer considers the heat transfer surface area, ambient wet bulb temperature, time in which the water is exposed to the airflow and the volume of airflow to the water (Carazas and Souza, 2009). During operation, the quality of the water is one very important factor the plant maintenance staff needs to have in mind. When water is evaporated or lost from the cooling tower, the solids and chemicals used to treat the water remain in the system. When water is bled from the system, chemicals lost through the bleed need to be replaced so the system remains protected. If the water is left unchecked, the system would lead to accumulation of solids would cause scale, corrosion, biological growth and sludge, not to mention loss of efficiency of the heat transfer.

3. THE PROPOSED METHOD

The main objective of the proposed method is to perform a reliability analysis of the cooling tower present in a coal-fired thermoelectric plant. Figure 2 shows each step to be performed for the method implementation.

Since the development of a reliability analysis requires a thorough knowledge of the system under study, the first step of the method is the construction of a Functional Tree. The objective of the Functional Tree is to structure, in a logical and hierarchical way, the interdependence between the different components of a system, in order to expose how it performs its functions. The functions of the equipments are listed in the Functional Description.

In the second step, the FMEA technique is implemented. Thus, in addition to knowing the components of the system and their respective functions, it will be possible to understand which faults they may present and how they affect the system as a whole. The FMEA must be performed for each component present in the Functional Tree.

The third step is the development of a block diagram of the system, which objective is to show which the relationships between the system components are. Finally, the obtained block diagram is used in the fourth step to support the construction of the Stochastic Petri Net. The system SPN model takes into account the mean time between failures (MTBF) and mean time to repair (MTTR) for reliability analysis.

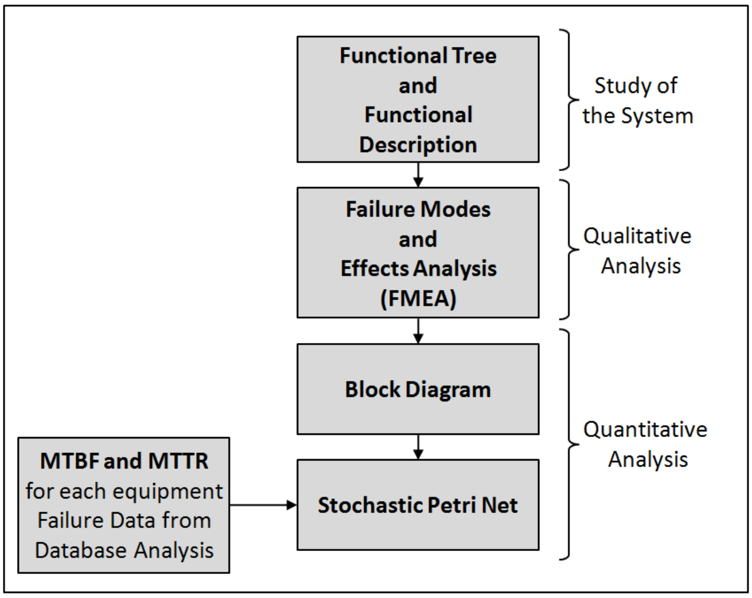

Figure 2. Proposed Method for Reliability Analysis.

4. RELIABILITY ANALYSIS OF THE COOLING TOWER

4.1 Functional Tree and Functional Description

The development of a maintenance program methodology for a given system requires a thorough knowledge of the functioning of all its components, for this reason the development of a Functional Tree is recommended. This cooling tower is divided into six main subsystems, as Fig. 3 shows.

Any failure at the bottom of the tree may affect a subsystem and then the heat exchange will not be as designed, causing the increase of pressure in the steam condenser (vacuum loss). The purpose of a Functional Tree (FT) is to structure, in a logical and hierarchical way, the interdependence among the different components of the system under study, in order to expose how each one performs its functions.

The next step is to have the Function Description (FD) for each one of these components. In FD, the main function of each component and subsystem are listed, according to the function tree. As an example, Fig. 4 shows the description of only one system: Air Circulating System.

4.2 Failure Mode and Effect Analysis (FMEA)

According to Almannai, Greenough, and Kay (2008), FMEA is an approach used to identify potential failures of a product (root causes) and then determine the frequency and impact of this particular failure in the system performance. This analysis must be performed by a team of experts on each field; some information can also be acquired on publications on the subject. FMEA can be understood as the most commonly used and well known qualitative reliability method in the area of reliability methodology. It is a dynamic preventive reliability method used in the modification of systems during early design cycle for modification of components. The overall goal is to analyze and modify components to achieve a better reliability assessment. One of the key factors in properly performing a failure analysis is keeping an open mind while examining and analyzing the evidence to create a clear picture of the failure.

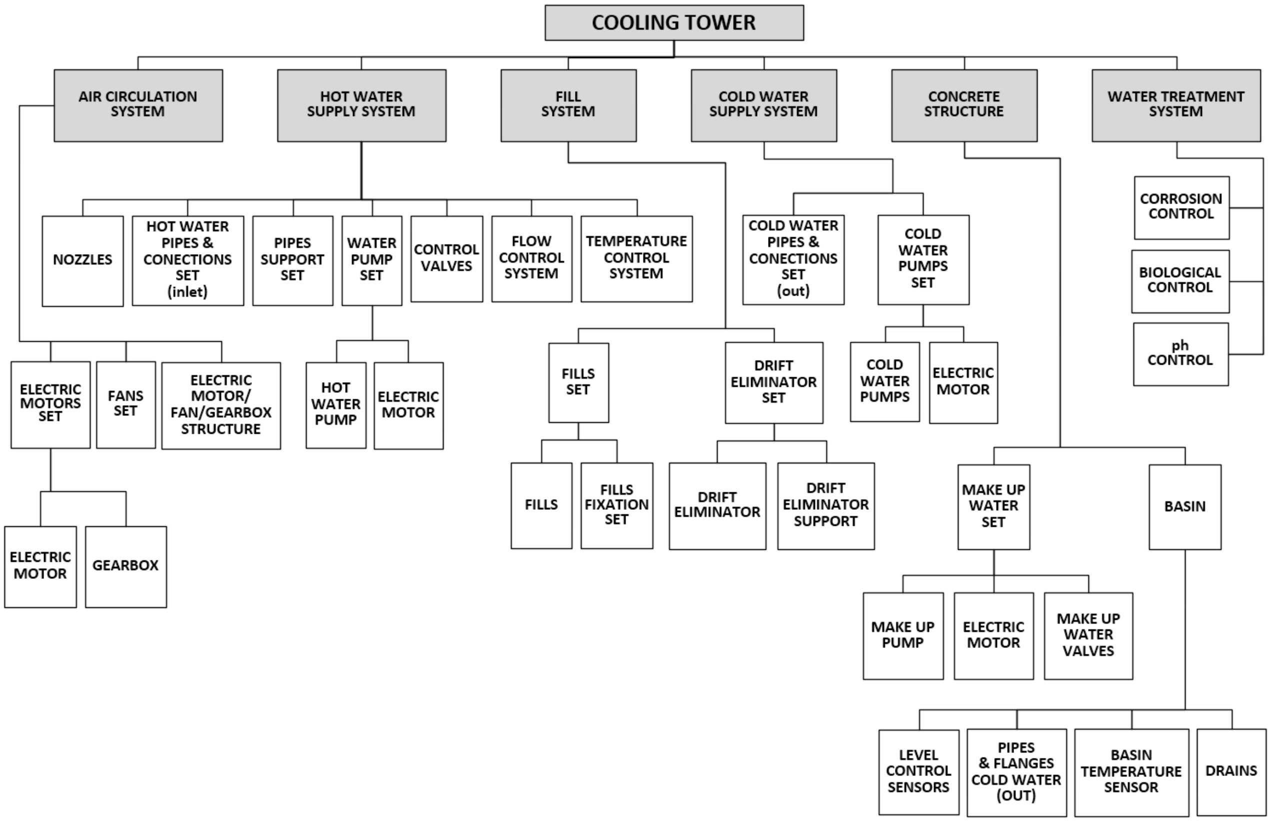

Figure 3. Cooling Tower - Function Tree.

System / Subsystem / Component	Primary Function
Cooling Tower	Cool the water for the condenser
Air Circulating System	Force air circulation through the cooling tower
Electric Motor Set	Provide power to drive the fan
Electric Motor	Provide power to drive the fan
Gearbox	Reduce motor rotation speed to drive the fan
Fan Set	Force air circulation through the cooling tower
Electric Motor / Fan / Gearbox Structure	Fix motor / fan / gearbox to the cooling tower

Figure 4. Function Description of the Air Circulating System.

Collaboration with experts in other areas is required to make an accurate analysis with a quantitative understanding of the design, manufacture, and service history of the failed component or system. Figure 5 shows an example, the FMEA analysis in some components of the cooling tower.

After finishing the FMEA analysis, critical components or systems can be identified and maintenance plan can start for these items. By setting up from high to low the critical items and planning their corrective actions, the cooling tower availability will increase. Reliability and maintenance are very important for plants availability. The better the reliability and maintainability the better the availability of a plant is.

Component	Function	Failure Mode	Causes	Potential Failure Effect
Nozzles	Distribute hot water evenly over the fills	Loose	1. Clamp corrosion 2. Loose Fasteners	Increased average water temperature, affecting overall plant efficiency
		Clogged or Obstructed	1. Excess of biological material 2. Uncalibrated 3. Solid particles in the water	
Flow control valves	Balance hot water flow that enters all sections of the cooling tower	Failed open	1. Blocked moving parts 2. Worn out moving parts 3. Actuator fail	1. Reduction of cooled water mass, affecting overall plant efficiency 2.Increased average water temperature, affecting overall plant efficiency
		Failed partially open	1. Blocked moving parts 2. Worn out moving parts 3. Actuator fail	
		Failed closed	1. Blocked moving parts 2. Worn out moving parts 3. Actuator failure	
		Valve leakage	1. Worn out seals 2. Expansion/contraction 3. Housing cracks	
Circulating cooling water pump	Supplies cooled water to the condenser	Abnormal or unstable flow	1. Cavitation 2. Pump bearing failure 4. Excessive internal leakage 4. Pump electric motor failure 5. Clogged suction line	Cooling tower out of work
		External leakage	1. Worn out seals 2. Expansion/contraction 3. Housing cracks	Cooling tower loss of efficiency
		No flow	1. Irregular stator wear 2. Misaligned axle 3. Bearing failure 4. Pump motor failure 5. Clogged suction line	Cooling tower out of work

Figure 5. Failure Mode and Effect Analysis: Some components from the cooling tower.

4.3 Reliability Block Diagram

Before starting any reliability analysis on a system, one must have a good knowledge of the operational relationships between the elements that form the system under study. The reliability of a system cannot be improved or even evaluated unless there is a clear understanding of how each one of its elements function and how these functions affect system availability. A Reliability Block Diagram (RBD) provides a method of representing this information in an easy way to comprehend, since it is simple and has visual impact. Reliability is defined as the probability that a system will perform its function properly for a specified period of time under a given operating condition. One way to express reliability is by exponential distribution, Eq. (1):

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

Where: R (t) = Reliability, t = Time Period (hours) and λ = Failure Rate (failure per hour)

Figure 6 shows the cooling tower block diagram according to the Functional Tree. Reliability of the cooling tower can be obtained after analyzing the failure data from the coal-fired power plant for each subsystem and component. Reliability of the cooling tower is the product of the reliability of each subsystem; it is expressed by the Eq. (2).

$$R_{\ (cooling\ tower)} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6 \tag{2}$$

It is important to note that each block of Figure 6 represents the reliability of a subsystem of the cooling tower, and for the calculation of this reliability, these blocks could be subdivided into others that would represent the components of the subsystem in question. However, for systems involving complex interactions between its components, construction of the RBD can be very difficult (O'Connor and Kleyner, 2012). The Air Circulating System, for example, consists of twelve cells, each containing a fan, but if only ten of these fans are working, the heat exchange in the tower is sufficient.

This means that the tower would no longer perform its function only if three or more fans failed or were unavailable at the same time. This type of relationship cannot be modeled in the RBD and this is why the SPN was used in this work.

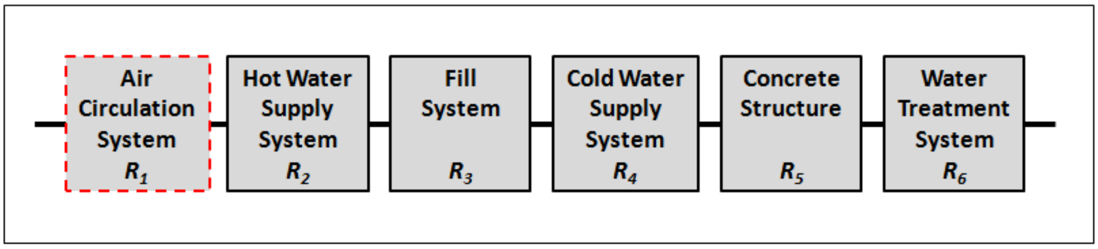

Figure 6. Cooling Tower Block Diagram.

4.4 Stochastic Petri Net (SPN)

This study presents a failure analysis based on Petri net (PN) models, first introduced by Carl Adam Petri in 1962 (Liu and Chiou, 1997). A Petri net is a modeling method that can show a system's structure and dynamic behavior in a graphical way. It is a tool for describing the relationships between conditions and events (O'Connor and Kleyner, 2012). When it was introduced, it did not include the concept of time, but in the late 1970s a "timed" PN called Stochastic Petri Nets (SPN) was presented (Haas, 2002). It uses some basic symbols for describing relations between conditions and events. Both PN and SPN can represent and analyze the behavior of a variety of systems, like manufacturing, computer and hardware. PN have some basic symbols called Places, Transitions, Arcs and Tokens. The basic symbols are described on Fig. 7.

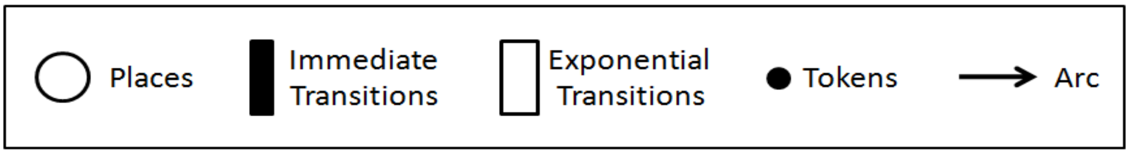

Figure 7. Basic Petri Net Symbols

Bringing these symbols into reliability analysis, *Places* correspond to the state of the system or condition in the process, *Transitions* correspond to events causing the system state to change, such as component faults, maintenance, etc., *Arcs* connect *Places* to *Transitions*, and it is the relationship of state and event. The system current state is represented by a *Token*. The system model should include elements of the marking states and those causing the states to change. A simple Petri net of a system is given as an example on Fig. 8. It shows the system operating (Place with the Token), then when the system fails, the system goes to the state of Failure (the Token moves from system Operating place to the System in Failure place), and then if the system is repaired, it goes back to System Operating state again (the Token moves again to System Operating place). The firings of these transitions are based on exponential distribution and are determined by the Mean Time Between Failures (MTBF) and the Mean Time to Repair (MTTR).

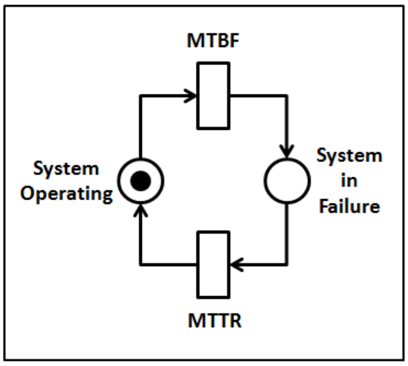

Figure 8. Simple Petri Net

MTBF is a basic measure of reliability for repairable items. MTBF can be described as the time passed before a component, assembly, or system fails, it is the time from one failure to another, it describes the expected time between two failures for a repairable system. MTTR is defined as the total amount of time spent performing all corrective or preventive maintenance repairs divided by the total number of those repairs. MTBF and MTTR are the key metrics used widely across industries to measure equipment or system performance. Organizations seek to achieve higher MTBF and lower MTTR and these two metrics are important key performance indicators to measure a system performance.

Both metrics can be expressed by equations (3) and (4).

$$\text{MTBF} = \text{Total Up Time} / \text{Number of Breakdowns} \tag{3}$$

$$\text{MTTR} = \text{Total of Down Time} / \text{Number of Breakdowns} \tag{4}$$

The failure data for the twelve cells in the cooling tower was obtained from the coal-fired power plant, this way MTBF and MTTR could be calculated. In complex and repairable systems, failures are considered to be those when the system does not meet the design intent. It puts the system out of service and places it into a state for repair. The dynamic behavior of complex and repairable systems are difficult to be described by using the traditional modeling methods (Gu et al., 2016). In order to solve this problem, a SPN model was simulated using TimeNET4.0 software (TimeNET, 2017). A model of the Air Circulating System of the cooling tower was built to analyze its reliability and availability. Figure 9 shows the SPN model developed.

By observing Fig. 9, the twelve cells (fans units) start in the Operating state. At the bottom of Fig. 9, it is shown the places and transitions responsible for computing reliability and availability. Data was collected for one year of operation, where all operating time, breakdowns and down time were captured for all twelve cells in order to calculate MTBF and MTTR. There are some precautions to take when calculating these metrics. For example, when the plant has some unexpected failure due to another system or when it undergoes a planned stop for maintenance, these time intervals should be disregarded from the calculation. Another common mistake is that, some companies do not consider a failure anything that takes less than a work day to fix. It is a misguided way to conduct this indicator and it will never show the truth about the system or equipment. The calculated MTBF for only one cell of the Air Circulating System is 2253 hours and MTTR is 84 hours.

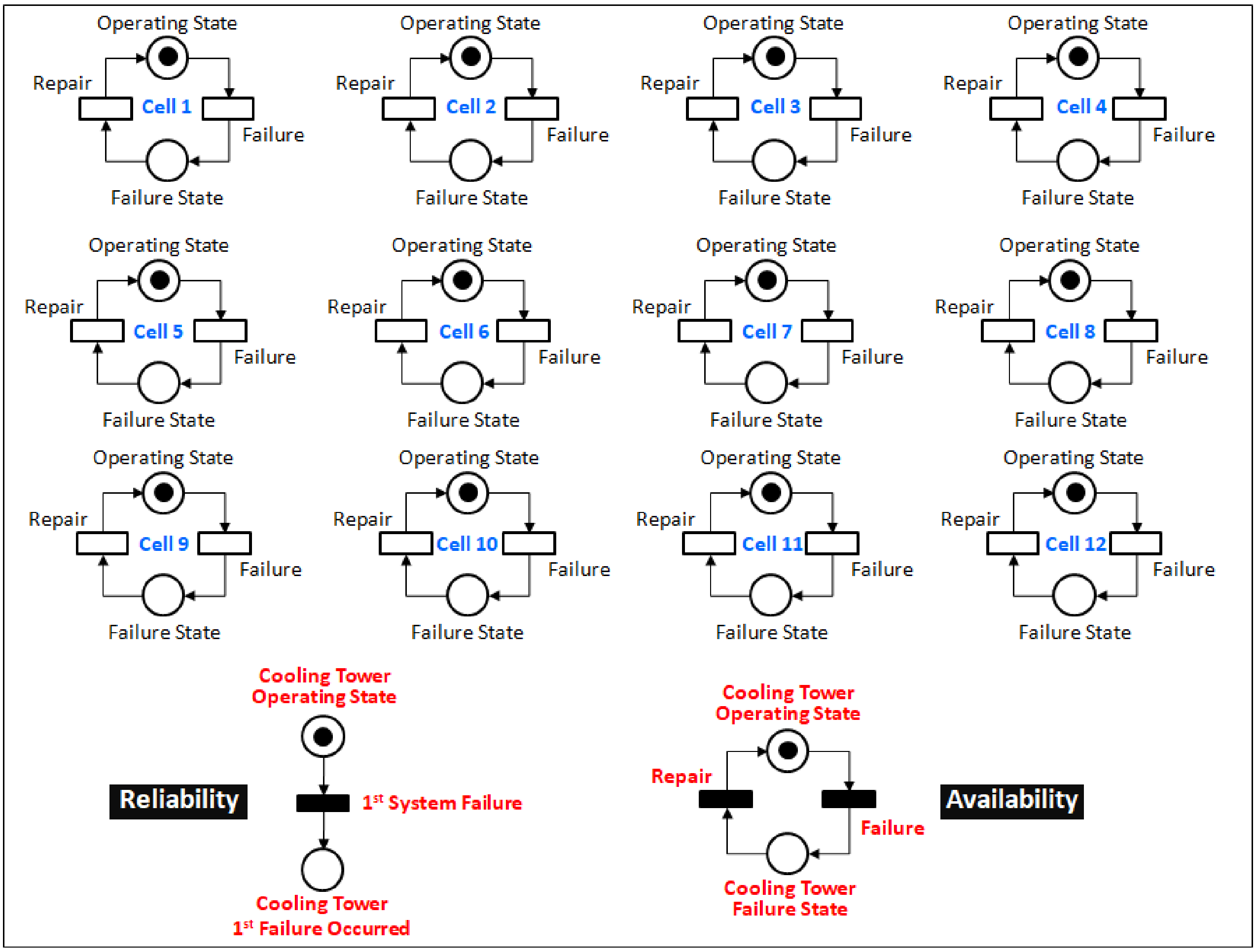

Figure 9. Cooling Tower: Twelve Cells Working (Tokens in Operate State)

The cooling cower operating state will change to failure state when three or more cells tokens also move to failure state. This is the condition for the cooling tower to meet its design intent, in another words, the cooling tower can still supply the heat load up to two cells down. With three or more cells out of work, the water supply for the steam condenser will not reach the ideal temperature as designed and therefore, pressure in the condenser will increase (it will start losing the vacuum). As a result, it can increase fuel consumption during operation, which is not desirable for any coal-fired power plant operation. When cells number three, six and twelve went out of work, for example, the cooling tower could no longer supply cooled water at designed temperature, then the tokens from Operating State move to Failure State, showing it is not working according to design. It means that, the remaining cells are still working, but water is leaving the tower with higher temperature, which is not acceptable in terms of operation. Figure 10 shows the situation described.

Considering one-year operation and using the TimeNET4.0 software for the Petri net simulation, the reliability for the twelve cells was estimated in 0.802 and its availability in 0.987. Figure 11 shows the reliability curve obtained from the one year operation data for the cooling tower. Cooling tower availability and reliability are strongly affected by MTTR, but by improving the quality of the maintenance team (training, standard procedures and practices, proper working tools, and spare parts availability are essential for effective use of maintenance resources), both metrics may increase.

The purchasing team must also use good judgment when selecting replacement components for maintenance. Too many plants select those components considering only costs. Most of the time, little or no consideration is given to a component's life cycle cost or its impact on reliability. Poor maintenance practices are perceived as the dominant factor that limits plant operation capacity. In some cases, this perception is valid; but most of the reliability problems that affect plant performance are not only attributed to poor maintenance. Many of the perceived maintenance problems are really outside of the maintenance function. Improper operating procedures or poor equipment design is the real source of many plant reliability problems. These plant functions must also assume an active role in equipment or system reliability. The practices should ensure proper interval of inspection, adjustment or repair. In addition, these should ensure that each task is completed properly according to standards.

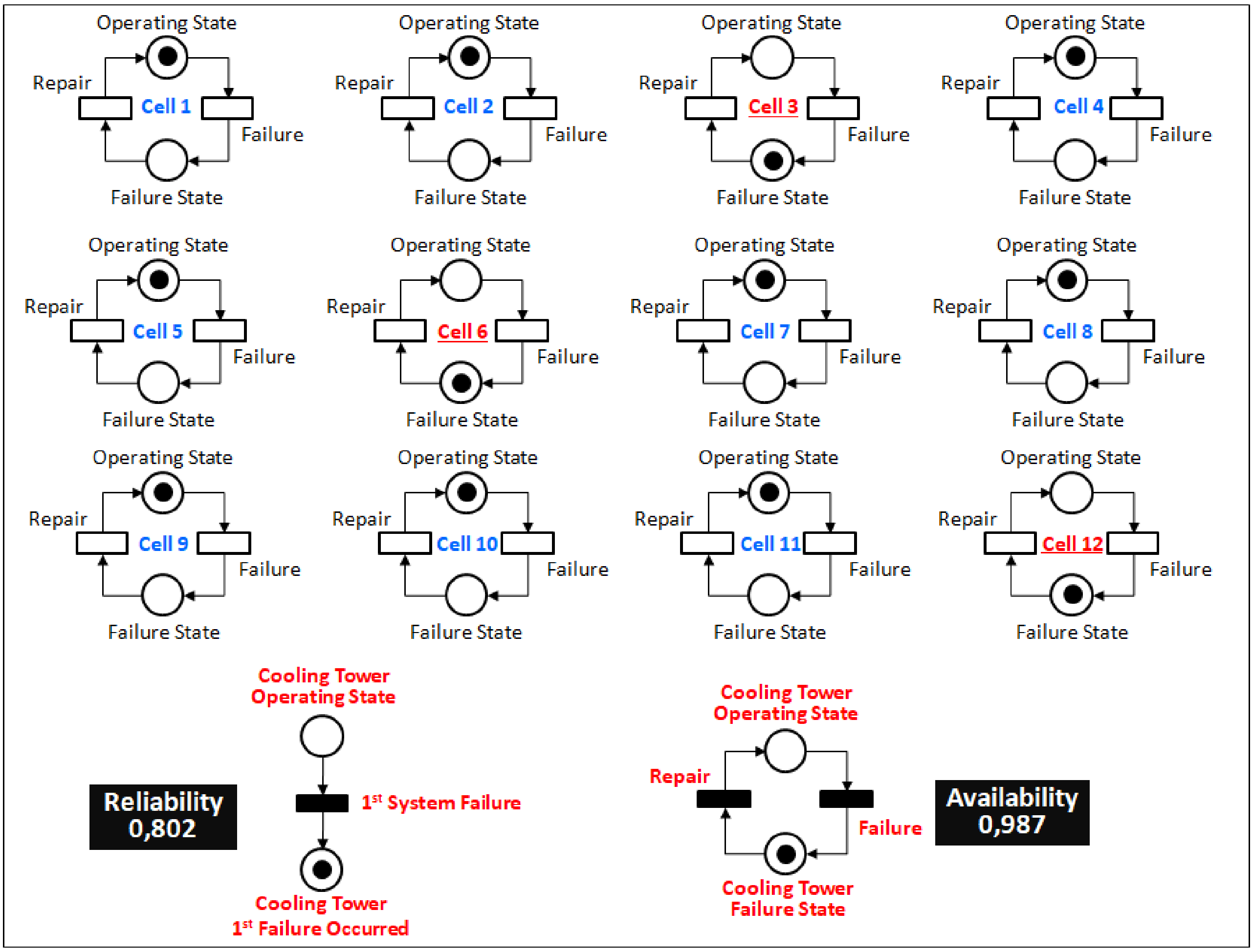

Figure 10. Cooling Tower: Three Cells Out of Work. (Cells 3, 6 and 12 – Tokens in Failure State)

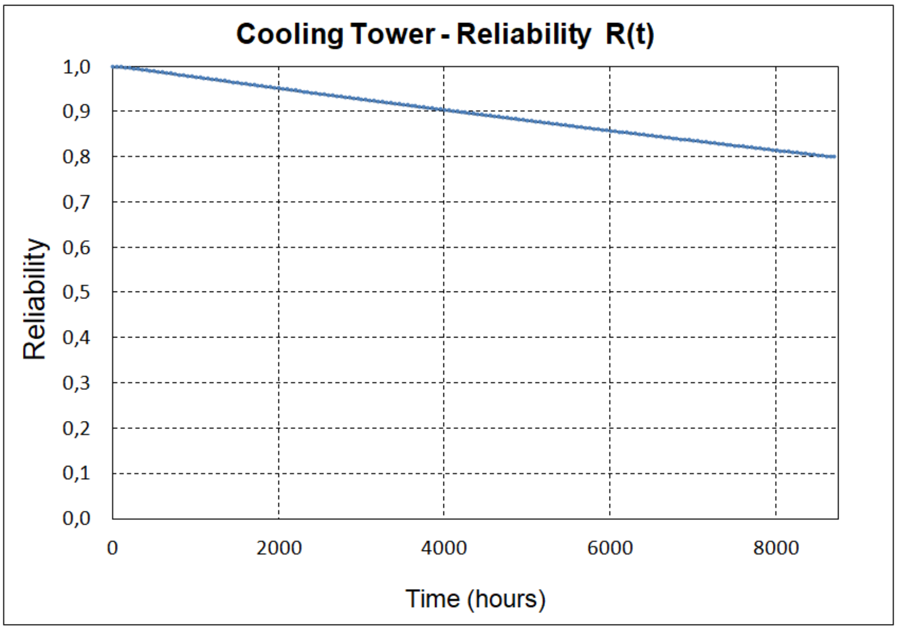

Figure 11. Cooling Tower – Reliability Curve

5. CONCLUSIONS

This paper has adopted Petri net to build a model for a cooling tower with twelve cells. It has given a simple introduction to the Petri net approach and showed how it established the reliability and availability for a system. Reliability and availability were obtained by using the simulation tool TimeNET4.0. The analysis results showed that the model can simulate the system operation. The proposed approach showed that Petri net could be successfully used for both reliability and availability. Petri net is very powerful tool in addressing complex problems, which are difficult to solve by standard approaches.

It is recommended that future research should investigate how it could be connected with the cost of coal consumption when three or more cells are not working. This way, lack of preventive maintenance on cooling tower parts could be easily expressed by the increase of fuel consumption, which means more cost to keep generating the same amount of energy. Other possibility, since the cooling tower can deliver the heat load with only nine cells working, would be to leave the three cells as standby. As soon as any failure occurred in one of the nine cells, one of these three standby cells would start to operate immediately while the faulty cell enters into repair operation. In this way, reliability and availability for the whole system would increase. The company could also use the process of benchmark on its maintenance services against other organizations. Benchmarking is a very useful way to search for optimum methods for Maintenance Management practices in order to improve the overall effectiveness of operations and maintenance of the plant. Finally, at the end of the day, the objective should pursue maintenance prevention, not quick fixes of breakdowns.

6. ACKNOWLEDGEMENTS

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