CHAPTER 2

Principle and Theory

This research has been studied in various fields including the related theory to bring a reference or as a basis information for this work, which is giving the work can achieve the objective. Base on the principle of RCM (Reliability Centered Maintenance) for the maintenance of the distribution system to improve the distribution system reliability and maintenance activities using the RCM method. The details of the theory and relevant knowledge will be presented in this chapter.

2.1. Distribution System Maintenance

The maintenance refers to an activity or a process that may be an activity planned before and an activity carried out instantly, which was not planned for maintaining the system or restoring the system to keep the system in good condition. The maintenance is included the system inspection and system repairing. The system maintenance purposes to extend the lifetime of equipment and system, reduce the damage or impact due to the critical failure in the system and consider the human safety.

The best performance of distribution system maintenance should have the applicable planning to help the performance and reliability of the system are higher and also reduce the maintenance cost. The most maintenance for distribution system can be classified by maintenance activities as follow [7-8]:

- Improvement maintenance (IM)
- Preventive maintenance (PM)
- Corrective maintenance (CM)

2.1.1. Improvement maintenance

The improvement maintenance (IM) means to implement the maintenance activities by improving or modifying the electrical system to keep the system or equipment in the better condition. The IM can keep the system more effective and it often carry out one time including design out (DO) and life time extension (LTE) as shown in the Figure 2.1

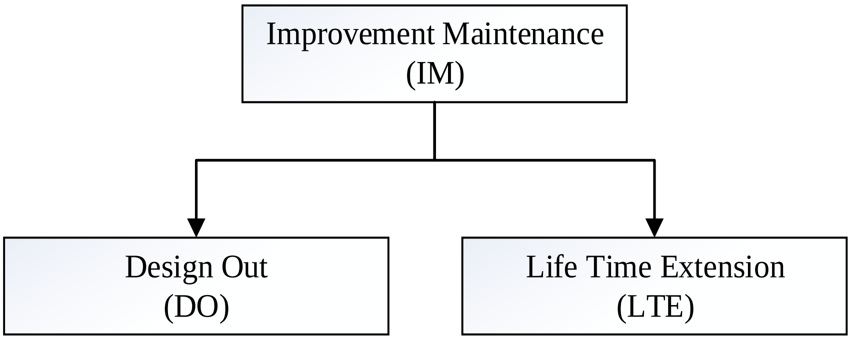

Figure 2.1 The concept of improvement maintenance

2.1.1.1. Design out (DO):

The way to improve the system by designing or verifying for the existing system. This way can decrease the damage and eliminate the problem which occurs in the system. As well as, the worth of investment must be considered. For example: in the area that has the power interruption due to the tree or any objects, which is touched the power line. The conductor replacement from bared conductor to insulated conductor can help to arrest the power interruption or reduce the power outage.

2.1.1.2. Life time extension (LTE):

The way of maintenance to extend the lifetime of equipment for reducing the number of failures, which occurs with equipment. For example: the limit of transformer loading without exceed 80% of transformer rated for extending the useful life of the transformer.

2.1.2. Preventive maintenance

The preventive maintenance (PM) is the performance of inspection and servicing task that have been pre-planned for accomplishment at the specific point in time to retain the functional capabilities of operating equipment or system. The PM has been included direct maintenance or Condition Base Maintenance (CBM) and indirect Maintenance or Fixed Time Maintenance (FTM) as shown in Figure 2.1

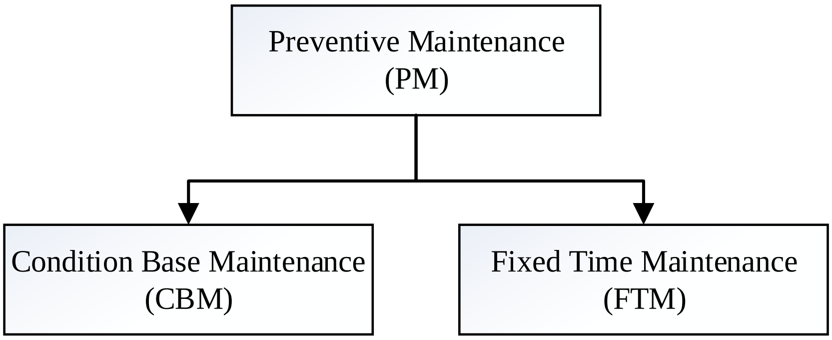

Figure 2.2 The concept of preventive maintenance

2.1.2.1. Condition Base Maintenance (CBM):

The task of indirect preventive maintenance for finding the failures that have occurred with the equipment in the system before damaging to the power supply. The CBM will be used to check the condition of the device or equipment for knowing the operative conditions of the equipment in the system. The CBM does not affect directly to the condition of equipment. However, it will be used for the maintenance planning in the future. It try to implement the maintenance using objective and subjective as shown in Figure 2.3

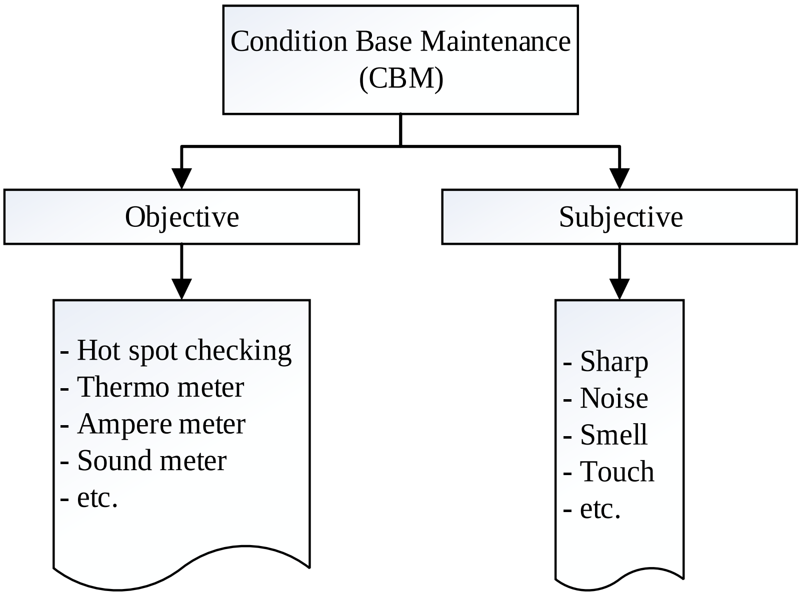

Figure 2.3 The concept of condition base maintenance

Objective: is used the tool to detect the irregularity that occurring in the system, such as ampere meter, hotspot checking using the infrared camera, etc.

Subjective: this method has required a person who has the skill and experience to check for the abnormality of equipment that occurred in the system, such as smell, touch, noise, etc.

2.1.2.2. Fixed Time Maintenance (FTM):

The task of direct preventive maintenance to prevent the damage of equipment in the system ant it will be directly affected the equipment that has been maintained, such as cleaning of an insulator, tree trimming around the power line or equipment, replacement of equipment in the system on schedule, etc.

The FTM can help to provide equipment or system be better because the spare parts or equipment are periodically changed. The FTM is suitable for equipment that cannot be inspected by inspection or inspection equipment, which may be prohibitively expensive. The FTM has used the calendar period for controlling the maintenance activity. It can be the number of hours or the number of times for each work.

2.1.3. Corrective maintenance

The Corrective Maintenance (CM) is applied to implement the maintenance activity for correction of failure, which occurred with the equipment in the distribution system. The CM may be called Emergency Maintenance (EM) or Breakdown Maintenance (BM). However, the CM is not necessary to maintain when the system is damaged by equipment failure. It also can be corrected the defect that occurs on the equipment before it is too aggressive to the emergency damage of equipment. The CM in included the planned and unplanned maintenance as shown in Figure 2.4

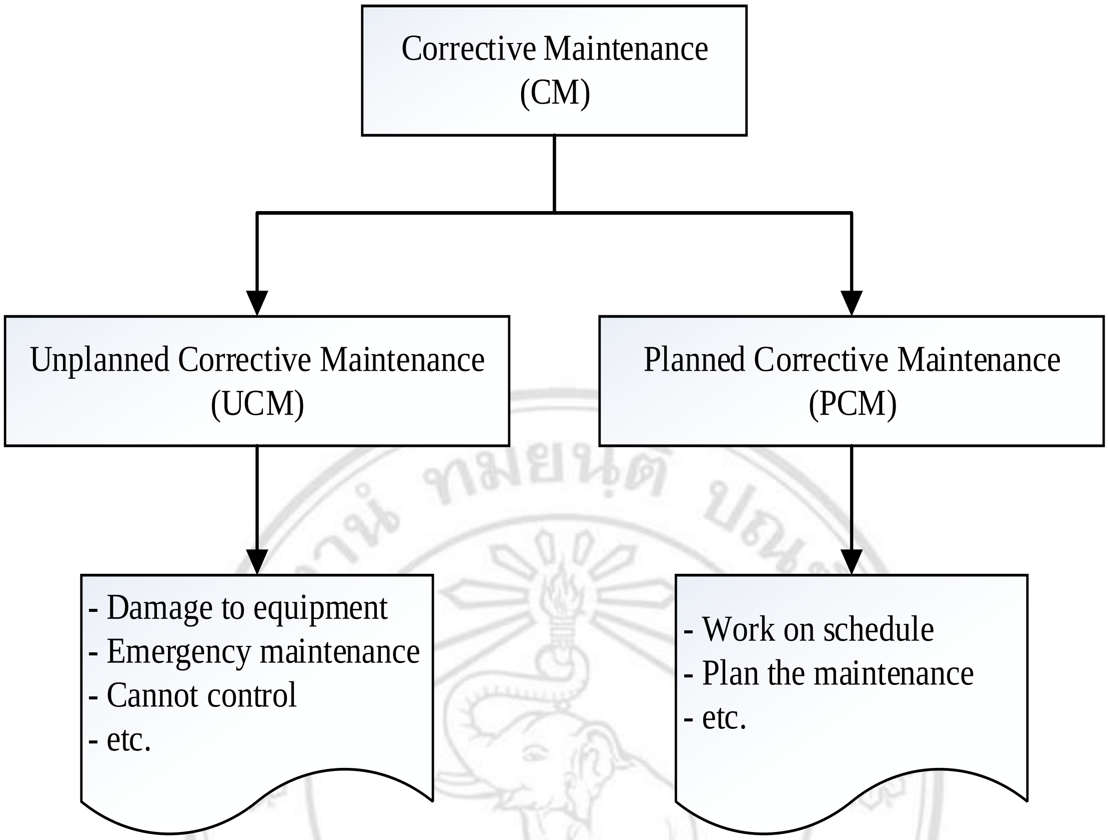

Figure 2.4 The concept of corrective maintenance

2.1.3.1. Unplanned Corrective Maintenance (UCM)

A maintenance activity that does not has a plan or time for preparing the maintenance before occurring the failure with the equipment in the system, such as cannot prepare a number of workers, document, equipment or spare parts before starting the activity of maintenance. The implementation of unplanned corrective maintenance can cause the high expenses and also emergency power supply could be stopped. The cause will be affected many customers that mean this interruption can be an expense in indirect maintenance.

2.1.3.2. Planned Corrective Maintenance (PCM)

A maintenance activity that has a maintenance plan or an implementation of maintenance on schedule. This maintenance activity will be used when known issues, which will occur with the equipment causing the damage to the system if it is not resolved. The issues can be detected from the indirect preventive maintenance, such as a part of equipment or system will be problematical. Therefore, the PCM has a time to prepare the tools, spare parts, equipment, etc. before the maintenance activity. It also help to reduce the period of maintenance and minimize the outage cost due to the no power supply.

2.2. Reliability Centered Maintenance (RCM)

RCM can be used as a guideline for distribution maintenance improvement and management of maintenance activities that can lead to the effective results of the power supply. It is widely used and has been successful in the industry. Therefore, if the distribution system is still faced with the problems of maintenance management searching for a solution, RCM method is the appropriate choice to improve and manage the maintenance programs.

The reliability concepts are the probability which an equipment or device will be satisfied and it can perform specified function for a specified period of time under given operating conditions. The satisfied performance of the device can be under commonly specified constraints as following [9-12]:

1) Function
2) Time
3) Operating conditions (environment, cyclic, steady state, etc…)

RCM provides a framework for maintenance issues which have the principles and the procedures in different ways. But the concept and fundamental principles of RCM to maximize the reliable system or minimize the system operating costs and also ultimately fit into system maintenance. The process can be classified in several steps, which will be implemented from the experiences as a most convenient way to systematically delineate the required information as below:

1) System selection and data collection
2) Failure mode and effects analysis (FMEA)
3) Logic tree analysis (LTA)
4) Specification of preventive maintenance (PM) for each events
5) Selection of final maintenance task

2.2.1. System selection and data collection

2.2.1.1. System selection

To improve the electrical distribution system reliability, the power interruption statistical data is used including date of interruption, operating equipment, outage duration and interruption cause. All data will be used for analyzing and finding the impact and the failure rate in each area. The system selection also considers the higher number of the interruption for reducing the expenses of spare parts, maintenance cost and outage costs.

The system selection was determined to understand the precise scope of the system, which will be applied the principle of RCM and held to manage systematically. This may be specified as an individual device or specified a type of device or system identification with or without subsystem that can be grouped by device function. For example, the grouping devices that perform the same function such as pole, conductor, etc. The grouping devices that were related such as protecting equipment. Other devices that are not related to the main function will be separated or be not considered.

The system selection should have the determination of system scope because it is important if the scope is not necessary and it will make the scope of the maintenance too wide. It also will give the difficulty of the system consideration.

2.2.1.2. Data collection

The consideration data from the reparative history data and maintenance activities data. The data source can be compiled from maintenance work order, problem report, and interview of employees. The maintenance data can be divided into two types as following:

1) **Quantitative data:** is an information, which can be expressed or a number that can know the level of severity, such as Mean Time before Failure (MTBF), Mean Time to Failure (MTTF), damage rate, etc.
2) **Qualitative data:** is an information, which can be expressed in number such as a problem occurred with the equipment, work order, equipment design, maintenance techniques, etc.

2.2.2. Failure mode and effects analysis (FMEA)

Failure mode and effects analysis or FMEA is a generally recognized as the most fundamental tool employed in engineering of reliability, because it is a practical, qualitative approach. It is also the most widely understood and applied form of reliability analysis that is encountered throughout the industry. Additionally, the FMEA forms the headwaters for virtually all subsequent reliability analysis and assessments because it forces an organization to systematically evaluate the equipment and system weaknesses and their interrelationships that can lead to product unreliability.

The characteristic of damage will be the beginning of the analysis for determining what equipment is very important. It is also a possibility for determining the optimal maintenance plan. An important analysis to determine the damage pattern for the maintenance process that will consider the functional classification and failure of equipment or system called System Function and Functional Failures (SFFF), which will be occurred whit the equipment or system. The SFFF can be explained as following:

1) **System Function:** is a classification of what each equipment or system is responsible for. For example, Circuit Breaker (CB) is responsible for protecting the overcurrent, CT is responsible for measuring the current, etc. The function is included as following:
    - Overall system function
    - Important system function
    - Identifying function
    - Equipment within multi-function
2) **Functional Failure:** is an irregularity in function of equipment operation displaying the function failures such as Failure Identification and Sequencing the Identification of Functions and Functional Failures that can be explained as below:
    - Fail to function: is a complete failure of equipment in operating. For example, the break of three phase power lines caused the interruption of the power supply.

- Fail to properly or accurately function: is some part failure of equipment in operating. For example, the break of single phase power line caused the power supply cannot energize properly.
- Inadvertently functions or functions without demand: is sometimes occurred in the system. For example, the trip of circuit breaker in normal condition.

2.2.2.1. Equipment failure mode

The start by selecting an equipment that is very important to the system and classify the failure mode of the equipment. It also tells how the damage to the equipment is.

2.2.2.2. Classification of impact level

To consider the severity level of the equipment damage type, it is important to know what the impact to the system is. The FMEA is divided into 3 levels, Local Effect, System Effect and Remote Effect to determine the severity of the damage, which will be occurred in the system as explained below:

1) **Local effect:** is only the effect of the observed damage to the equipment or environment is nearby the equipment or equipment that is near a defective device.
2) **System effect:** is the effect of damage caused by the failure of equipment to the system. The system effect expects for the local effect and also consider the effect on maintenance, such as the high cost of repairing work.
3) **Remote effect:** is any effect that is directly related to the equipment, which is not in the system or is not in the scope.

To determine the impact level for each event can be used a percentile principle that is a measure used in statistic indicating the value, which is given a percentage of observation. There is no standard definition for percentile. The most common definition of a percentile is a number where a certain percentage of scores fall below that percentile. For example, you have an examination score is 67 out of 90. But that number has no real meaning unless you know what percentile you fall into. If you can get the score is in the

90th percentile that means you scored better than 90% of people who took this examination.

Table 2.1 The example for distribution data of student's score

Score	Frequency	Cumulative Frequency
92.5 - 95.5	1	120
89.5 - 92.5	0	119
86.5 - 89.5	0	119
83.5 - 86.5	0	119
80.5 - 83.5	2	119
77.5 - 80.5	10	117
74.5 - 77.5	3	107
71.5 - 74.5	13	104
68.5 - 71.5	15	91
65.5 - 68.5	20	76
62.5 - 65.5	28	56
59.5 - 62.5	19	28
56.5 - 59.5	6	9
53.5 - 56.5	0	3
50.5 - 53.5	3	3
	N = 120	

➢ **Percentile calculation from the graph**

From the distribution data to calculate the cumulative frequency and the percentage of the cumulative frequency. The cumulative frequency is the summation of the frequency from the value that is lower to highest or descending.

The Figure 2.5 is shown the graph, which has been plotted from the percentage of the cumulative frequency of the distribution data in Table 2.1. Consequently, the percentile value can be found directly from this graph by positioning the value at the percentile of the cumulative frequency. Then, drag the convergence line and drag it down perpendicular to the data line for reading directly the value of the data.

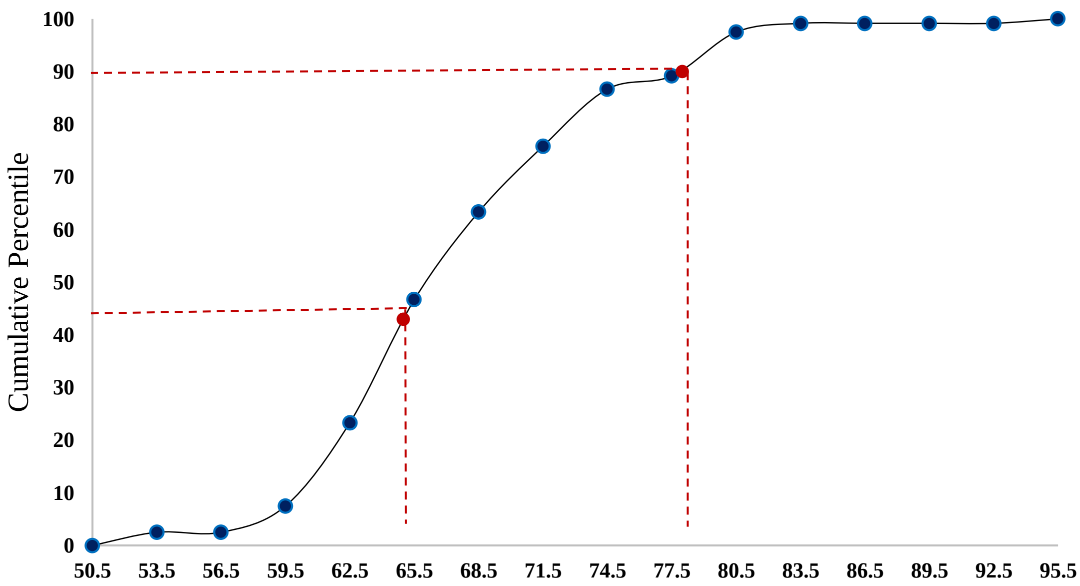

Figure 2. 5 The graph of cumulative frequency percentage

From The graph of cumulative frequency percentage. In this case, finding the 65th data percentile. First, positioning the 65th data at the horizontal axis. Then, draw the straight line perpendicular to the horizontal axis until touching graph. From this touching point, draw the straight line perpendicular to the vertical axis. Finally, the 43rd percentile was found.

In another case, if the position of 90th percentile has to find. First, positioning the 90th percentile on the vertical axis and draw the straight line perpendicular to this axis until touching the graph. From this touching point, draw the straight line perpendicular to the horizontal axis and read the data, which is 78th.

- **Percentile calculation from the table of frequency distribution data**

Besides of the percentile calculation from the cumulative frequency percentage graph. The percentile position calculation from the table of the frequency distribution can be found by using the formula as below:

$$\text{Percentile} = \frac{CF_u + \left(\frac{X - X_u}{I}\right) \times f_i}{N} \times 100 \qquad (1)$$

Where:

CF_u Cumulative frequency of layer that is lower than the layer where the percentile is

X Data that has to find the position of percentile.

Xu Limitation of the lower layer where the percentile is.

I Width of the layer.

fi Number of frequency where the percentile is.

N Total of the data number.

In the first case, for calculating the percentile position of the 65th data. First, find the layer of 65th data that is in the layer range of 62.5 to 65.5. The cumulative frequency of the lower layer is 28. The limitation of the lower layer is 62.5 and the difference between the score and the limitation of the lower layer is 65 - 62.5 = 2.5. The width of the layer is 3. Consequently, the percentile position of the 65th data can be calculated as following the formula 1 showing below:

$$\text{Percentile} = \frac{28 + \left(\frac{65 - 62.5}{3}\right) \times 28}{120} \times 100$$

$$\text{Percentile} = 42.78$$

The percentile position calculating by the formula 1 has the value is 42.78. It has the value that is very close to the percentile position value, which is found from the graph.

- **Number of data calculation at percentile position**

The cumulative frequency must be known at the percentile position before finding the number of data at that position of percentile. The cumulative frequency can be calculated by multiplying the percentile by N and divide by 100 as following the formula below:

$$CF = \frac{\text{Percentile} \times N}{100} \qquad (2)$$

And the cumulative frequency can be calculated by the formula below:

$$X = X_u + \frac{I \times (CF - CF_u)}{f_i} \qquad (3)$$

Where:

X Data that has to find the position of percentile.

X_u Limitation of the lower layer where the percentile is.

I Width of the layer.

CF_u Cumulative frequency of layer that is lower than the layer where the percentile is.

CF Cumulative frequency of layer where the percentile is.

fi Number of frequency where the percentile is.

N Total of the data number.

Based on the data in Table 2.1, to find out what the 90th percentile position matching any data, which has the total of 120. The cumulative frequency at this percentile position can be calculated by using the formula (2) and the result shows as below:

$$CF = \frac{90 \times 120}{120}$$

$$CF = 108$$

Considering the table 2.1, the cumulative frequency 108 is in the layer range of 77.5 to 80.5. In this layer has 10 frequencies and the width of layer range is 3. Therefore, the number of data at the 90th percentile position can be calculated by following the formula (3) and the result shows below:

$$X = 77.5 + \frac{3 \times (108 - 107)}{10}$$

$$X = 77.8$$

Based on the Table 2.1, in case the finding the score at the 42.78th percentile position. First, the cumulative frequency must be calculated as below:

$$X = \frac{42.78 \times 120}{100}$$

$$X = 51.34$$

The score 51.34 has the limitation of lower layer is 62.5 and the width of the layer range is 3. The 28 of cumulative frequency at the lower layer where the score is. Consequently, the percentile position of data can be found as following:

$$X = 62.5 + \frac{3 \times (51.34 - 28)}{28}$$

$$X = 65$$

Finding the data at the percentile position of 42.78 has the result value is 65. It is the same value that is found the 42.78 percentile position, which has the number of data is 65.

2.2.2.3. Finding the failure causes

The process of damage cause finding should be applied for selecting the appropriate preventive maintenance to line between the severe failure mode and the suitable preventive maintenance work. The finding the failure causes can be implemented by determining the cause of the failure and the analysis of equipment failure cause root as explained below:

- Determining the cause of the failure: is very important because the determination of the appropriate protection should know the failure cause. The cause of any failures are needed to know why they are failed.
- Analysis of equipment failure cause root: is an analysis of the cause root, but sometimes it may be required more details that more than is necessary. Therefore, the Analysis of equipment failure cause root may be applied only the severe failure group.

2.2.2.4. Determination of severity level

From the impact of failure, which was occurred will be focused on the system effect and remote effect. Because they are related to the safety, the ability of power supply and also the repairing cost. The determining the severity level of any failure mode should consider the impact of failure mode and possible opportunity in failing of equipment. If the impact of failure is severe, but the opportunity of failure is minimal over the lifetime of the operation. In this case, the severity level will consider that severity is less than the damage occurred frequently.

For considering a system within backup devices will be defined as a non-critical device. For considering a system within backup devices will be defined as non-critical devices because it can reduce the impact of damage by themselves. But these device may be neglected for scheduling the maintenance. Therefore, the consideration should be carefully given how to properly maintain for backup devices without no damage to the system reliability.

2.2.3. Logic tree analysis

The purpose of this step is to further prioritize the emphasis and resources that should be devoted to each failure mode. The RCM process uses a simple three questions decision structure that permits the analyst to quickly and accurately place each failure mode into one of four bins. For each question can be answered Yes or No.

The decision process will identify each failure mode in one of three bins such as (1) safety-related, (2) outage-related and (3) economic-related. It also distinguishes between evident to the operator.

Each failure mode is entered into the top box of the tree, where the first question is posed: Does the operator, in the normal course of his or her duties, know that something of an abnormal or detrimental nature has occurred in the plant? It is not necessary that the operator know exactly what is awry for the answer to be Yes as shown in the Figure 2.6.

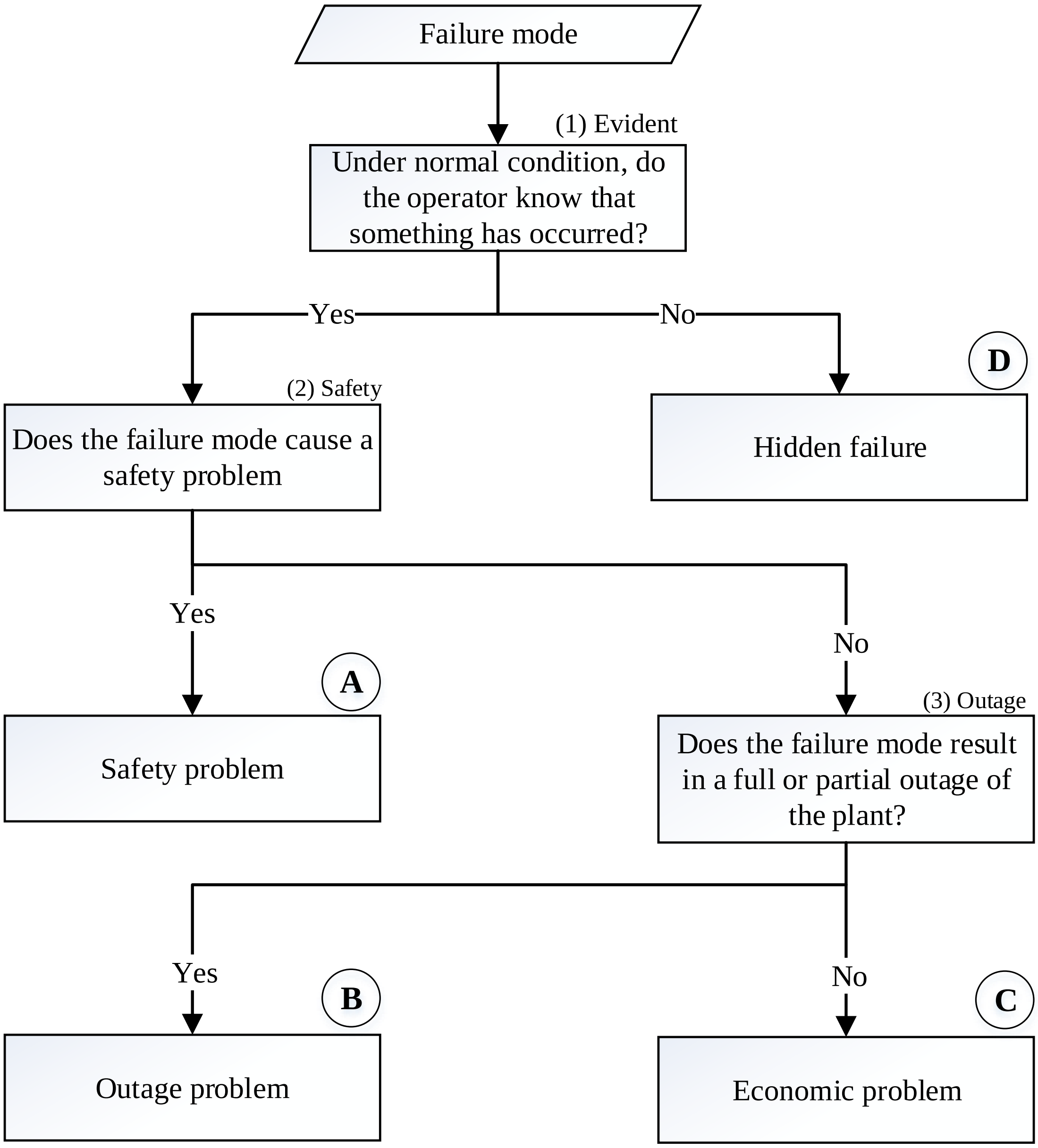

Figure 2. 6 Logic Tree Analysis structure

2.2.4. Guideline to determine the maintenance type

To prevent each severe failure causes should be selected the appropriate maintenance, which can be done and effective by considering the selection of maintenance activities as follows:

- Applicable and cost effective task
- Condition-monitoring task
- Time-directed task

- Run to failure
- Design change
- Failure-finding task
- Basic maintenance for non-critical equipment
- Maintenance templates

2.2.4.1. Applicable and cost effective task

There are several maintenance activities that can be used for solving the failure mode. But the effective value of investment must be considered including the invested resource to improve the reliability.

2.2.4.2. Condition-monitoring task

The monitoring task can be provided an overview where the system needs the maintenance. The system monitoring must be consistently performed and measures for avoiding the system failure.

2.2.4.3. Time-directed task

In term of technique and investment value, the time-directed task should be selected after the consideration of condition-based maintenance (CBM). Therefore, the decision of fixed time maintenance (FTM) must be sure to invest in value and analyze the frequency of maintenance by considering the equipment design characteristic, the environment around the equipment is operated, the statistical failure of equipment.

2.2.4.4. Run to failure

Run to failure or operate to breakdown (OTBD) will be done in the event of breakdown, which can be acceptable with incurred damage and worth investing. The key point to consider in choosing this maintenance are:

- The subsequent impact and the frequency of equipment failure. In some cases, the CBM and FTM can be more satisfied than the OTBD.
- The preparation of tools and spare part to be used for repairing before the breakdown of the system to reduce the repairing time.

2.2.4.5. Design change

In the case of the pre-planned maintenance and preventive maintenance are possible difficulties or cannot be done in practice or be not clearly worth investment. The consideration of new design change will be applied and it is also considered the short-term and long-term effects.

2.2.4.6. Failure-finding task

This method will be used in cases that the preventive maintenance, new design change cannot be performed or cannot find the evidence when the event occurred. The failure-finding task will be implemented similarly the condition monitoring. But this method will be done when the failure occurred.

2.2.4.7. Basic maintenance for non-critical equipment

The consideration of redundant devices, which are classified as a device that does not affect the system. The basic maintenance is required to prevent the failure with them and keep them properly working. Therefore, they do not affect the reliability.

2.2.4.8. Maintenance template

The maintenance report sheet should be made. It should have the list of all maintenance methods to get the appropriate maintenance activities for each equipment. For the same equipment can be used the same maintenance method.

2.2.5. Task selection

Our system analysis efforts to this point, the activities maintenance will give us the biggest return for the investment and can select the most effective task and also explain the relationship between reliability indices and maintenance activities cost. Therefore, the consideration of maintenance activities can be done as follow the flow chart in Fig.2.7

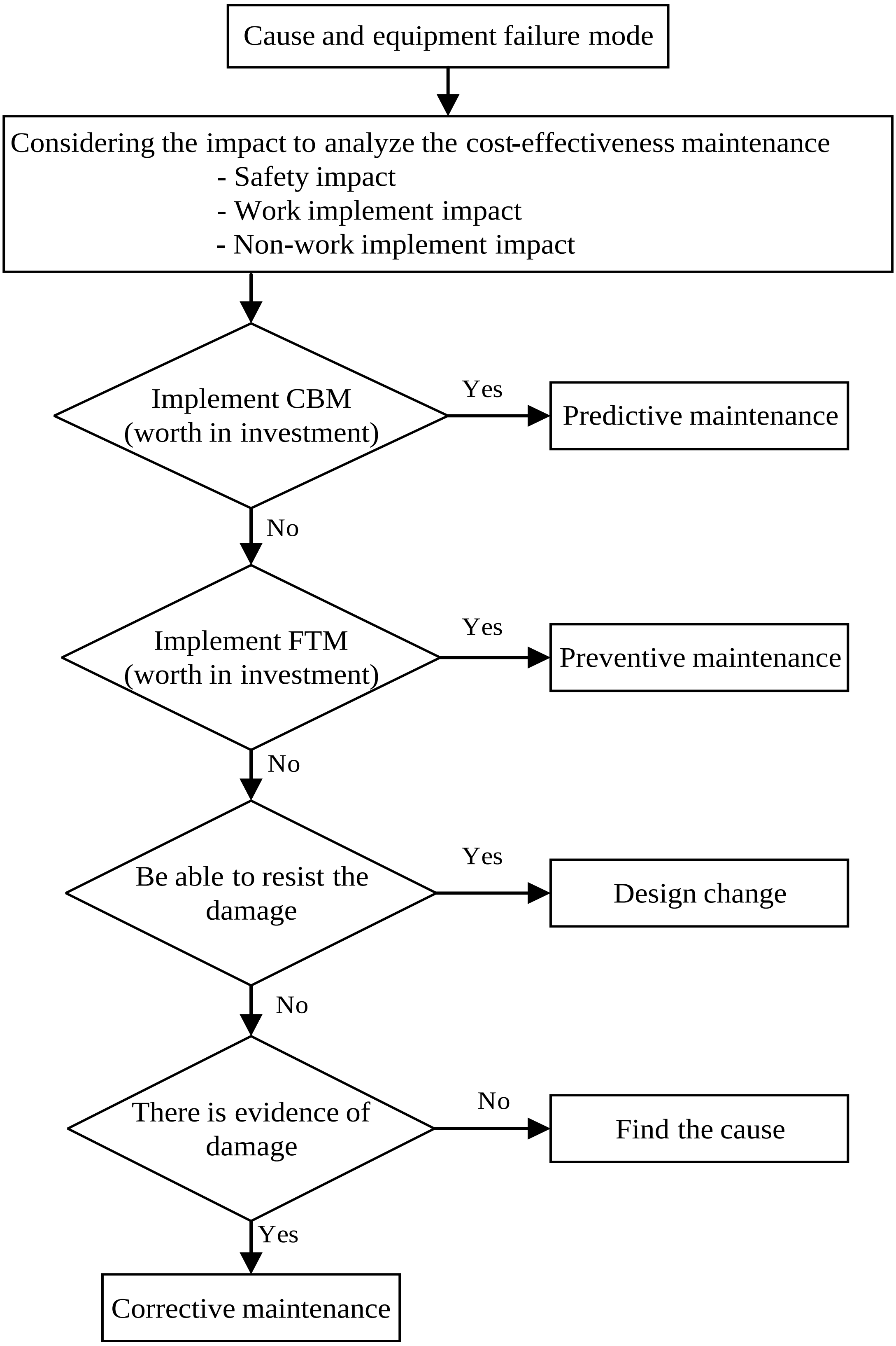

Figure 2. 7 Task selection road map

2.3. Reliability Indices

The reliability indices can be evaluated from the customer based indices and load based indices. In this case, the reliability indices will applied the customer based indices, which are the main factors that are affected the utilities most commonly using two indices such as System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI). The reliability indices will be used to benchmark the reliability of the distribution system and these also characterize the frequency and interruption duration during the period of report.

According to the outage duration, EDL can classify the momentary and sustained interruption. The momentary interruption is defined as the any event which has the outage duration is less than one minute and the sustained interruption is the event which has the outage duration is greater than one minute.

2.3.1. System Average Interruption Frequency Index

SAIFI is used to indicate how often the average customer experiences a sustained interruption over a predefined period of time and SAIFI can be calculated in interruption per year as formula below:

$$\text{SAIFI} = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} \tag{4}$$

2.3.2. System Average Interruption Duration Frequency Index

SAIDI is used to indicate the total duration of interruption for the average customer during a predefined period of the time and SAIDI can be calculated in minutes per year as formula below:

$$\text{SAIDI} = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customers served}} \tag{5}$$

The example of the reliability index calculation in the distribution system, which has the feeder information in the Figure 2.8 and the interruption information in Table 2.2 below:

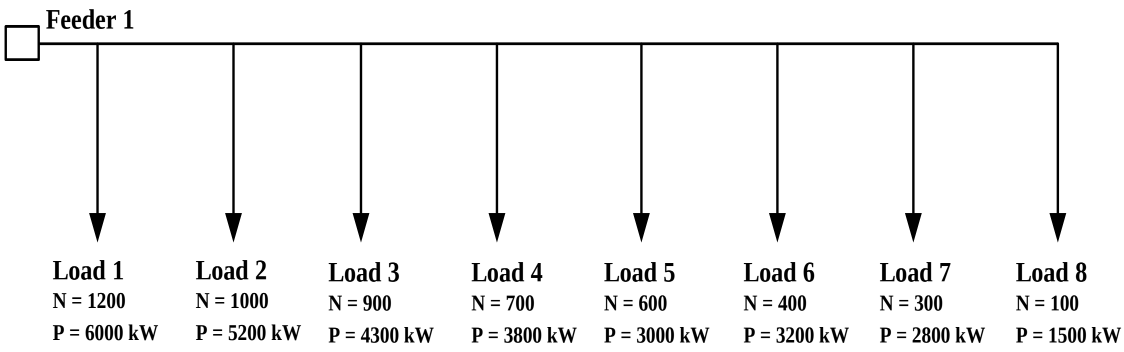

Figure 2. 8 The single line diagram of the feeder

Table 2.2 The interruption information of customers in each load point

Number of Interruption	**Interrupted Load**	**Duration of Interruption (h)**
1	1	2
	6	1
2	3	2
	8	3
3	2	1.5
	7	3
4	5	2
	6	2.5
5	2	1
	4	2.5
6	1	2
	3	2

Based on the interruption information of customer in Table 2.2, the failure rate or SAIFI of feeder 1 can be calculated as following the formula (4).

$$\mathrm{SAIFI} = \frac{(1200+400)+(900+100)+(1000+300)+(600+400)+(1000+700)+}{5200}$$

$$\frac{(1200+900)}{5200}$$

$$\mathrm{SAIFI} = 1.673 \text{ times per year}$$

Based on the interruption information of customer in Table 2.2, the SAIDI of feeder 1 can be calculated as following the formula (5).

$$\mathrm{SAIDI} = \frac{(1200 \times 2 + 400 \times 1) + (900 \times 2 + 100 \times 3) + (1000 \times 1.5 + 300 \times 3) +}{5200}$$

$$\frac{(600 \times 2 + 400 \times 2.5) + (1000 \times 1 + 700 \times 2.5) + (1200 \times 2 + 900 \times 2)}{5200}$$

$$\mathrm{SAIFI} = 3.163 \text{ hours per year}$$