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Reliability centered maintenance optimization for power distribution systems

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ABSTRACT

Today's electricity distribution systems operate in a liberalized market. These systems should therefore be able to provide electricity to customers with a high degree of reliability and be cost-effective for suppliers. RCM (Reliability Centred Maintenance) was invented by the aircraft industry in the 1960s, to organize the increasing need for maintenance for reducing costs without reducing b safety. Today RCM-methods invented by ALADON [1] are seen as very complex and are not fully accepted by the Algerian power industry. The extensive need of human and capital resources in the introduction phase is also a negative factor that could be one of the reasons of why RCM methods are not used in our branch. This article provides a discussion of the two primary objectives of RCM: to ensure safety through preventive maintenance actions, and, when safety is not a concern, preserve functionality in the most economical manner. For the power distribution systems facilities, the mission should be considered at the same level as safety.

1. Introduction

Reliability centered maintenance (RCM) is a systematic process used to determine what has to be accomplished to ensure that any physical facility is able to meet continuously its designed functions in its current operating context [2]. RCM leads to a maintenance program that focuses preventive maintenance (PM) on specific failure modes likely to occur. Any organization can benefit from RCM if its breakdowns account for more than 20–25% of the total maintenance workload [3].

This paper proposes a practical procedure to develop a cost effective maintenance program for electric power distribution systems. The procedure is mainly based on the reliability centered maintenance (RCM) method that prioritizes maintenance requirement of failure modes, and selects the effective maintenance activity for the critical failure modes. Reliability centered maintenance (RCM) is a decision making process in the selection of a cost-effective maintenance program to improve the reliability, based on determined criticality of failure modes. It prioritizes the maintenance requirement of all failure modes, and selects the effective maintenance activity for the critical failure modes [4,5]. In this paper, the RCM based maintenance program is developed using the proposed procedure for an electric utility in ALGERIA.

2. Reliability centered maintenance (RCM)

RCM is a systematic method to keep a balance between preventive and corrective maintenance. This method chooses the right preventive maintenance activities for the right component at the right time to reach the most cost-efficient solution [6].

The first description came in 1978 by Nowlan. It was introduced in nuclear power in 1980 and in hydro power in 1990 [7]. RCM is characterized by maintaining system function, identifying failure modes, prioritizing functions, and choosing efficient maintenance.

RCM is a technique that is used to develop cost effective maintenance plans and criteria so the operational capability of equipment is achieved, restored, or maintained. The main objective of RCM is to reduce the maintenance cost by focusing on the most important functions of the system. There are several different formulations of RCM processes in the literature. According to [8] an RCM analysis basically provides answers to the following questions

1. What are the functions and associated performance standards of the equipment in its present operating context?
2. In what ways can it fail to full fill its functions?
3. What is the cause of each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?

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7. What should be done if a suitable preventive task cannot be found?

The RCM analysis may be carried out as a sequence of activities or steps. In IEC standards for RCM analysis [9] following basic steps in an RCM analysis are listed, Fig. 1 shows a detailed logic diagram of the RCM method.

- Defining the system and/or subsystems and boundaries.
- Defining the functions of each system or subsystem identifying functionally significant item (FSI).
- Identifying the pertinent FSI functional failure causes.
- Predicting the effects and probability of these failures.
- Using a decision logic tree to categorize the effects of the FSI failures.
- Identifying applicable and effective maintenance tasks which comprise the initial maintenance program.
- Redesign of the equipment or process, if no applicable tasks can be identified.
- Establishing a dynamic maintenance program, which results from a routine and systematic update of the initial maintenance program and its revision assisted by the monitoring, collection and analysis of in-service data?

To avoid waiting again for several years prior to application to obtain this information, it seems necessary to predict the evolution of equipment reliability and so the consequences of implementing the new program. This step involves the modeling and simulation program, before its application [10]. Fig. 1 shows a detailed logic diagram of the RCM method.

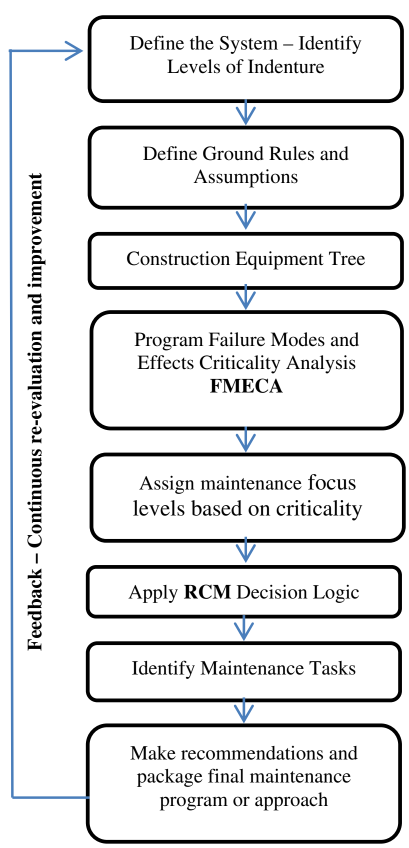

Fig. 1. Performance evaluation of maintenance program: model RCM.

2.1. Practical method of FMECA

FMECA is a useful tool when performing an RCM analysis. FMECA is a way to evaluate potential failure modes and their effects and causes in a systematic and structured manner. Failure modes means the ways in which something could fail. Effects analysis refers to studying the consequences of those failures.

The purpose of the FMECA is to take actions to eliminate or reduce failures, starting with the highest-priority ones. By itself, an FMECA is not a problem solver; it should be used in combination with other problem solving tools. The analysis can be done either in a qualitatively or quantitatively way. Basic steps in performing a FMECA could be [11]:

1. Define the system to be analyzed. Complete system definition includes defining of system boundaries, identification of internal and interface functions, expected performance, and failure definitions.
2. Identify failure modes associated with system failures. For each function, identify all the ways failure could happen. These are potential failure modes.
3. Identify potential effects of failure modes. For each failure mode, identify all the consequences on the system. "What happens when the failure occurs?"
4. Determine and rank how serious each effect is. The most critical pieces of equipment which affected the overall function of the system need to identified and determined.
5. For each failure mode, determine all the potential root causes.
6. For each cause, identify available detection methods.
7. Identify recommended actions for each cause that can reduce the severity of each failure.

Then, a block diagram of the system needs to be created. This diagram gives an overview of the major components or process steps and how they are related. These are called logical relations around which the FMECA can be developed. It is useful to create a coding system to identify the different system elements. The block diagram should always be included with the FMECA. Fig. 2 shows a detailed logic diagram of the FMECA method.

2.2. Analysis FMECA

2.2.1. Evaluation criteria for different parameters of the FMECA

For the evaluation of failure modes, using the usual parameters of the FMEA, the frequency O, which characterizes occurrence failure modes, the severity S characterizes the duration of the outage caused by the failure mode detectability and D, which characterizes the probability of detecting the failure before it starts to take corrective or preventive actions. From the three previous parameters, we define C criticality or risk priority number RPN, which is calculated by the product of three factors O, S and D. It allows analyzing the risk and setting the threshold of acceptability for each failure mode [12].

$$\mathrm{RPN} = S * O * D \quad (1)$$

Quantification and the choice of values for each parameter were obtained from the history of the index of continuity of service (IC) and the number of interruptions over a period of 7 years from the data center operation of distribution (COD) located in the area north west of RELIZANE in ALGERIE de 2007–2010. The rating scale is 1–10 for the three parameters O, S and D.

Tables 1–4 summarizes the evaluation grid for each parameter, O frequency, severity, S, D detectability and criticality C.

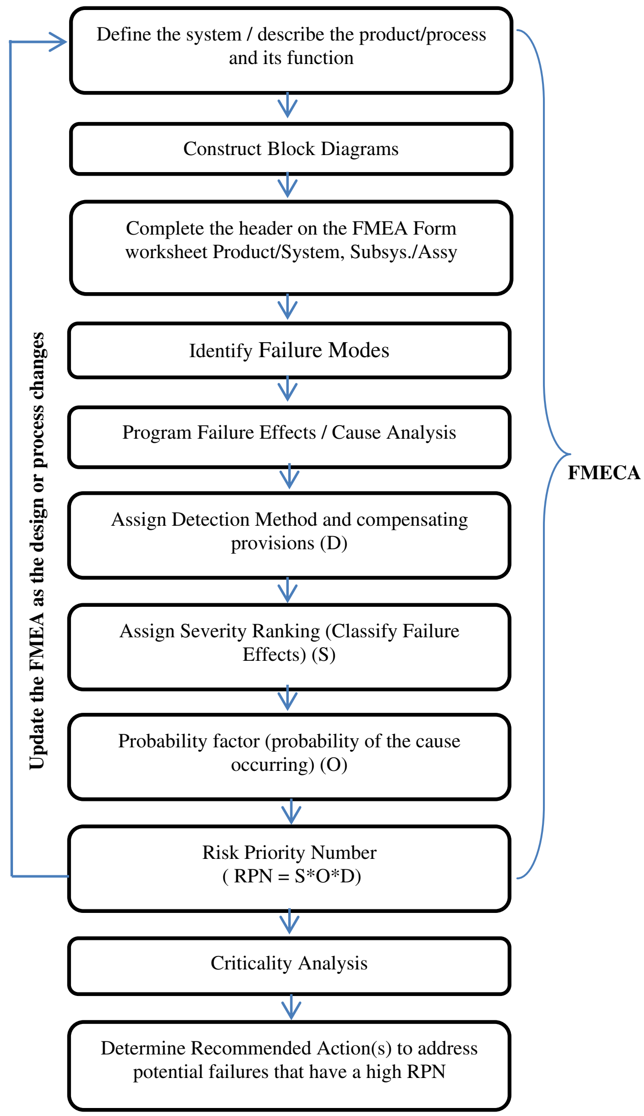

Fig. 2. Logic diagram of the FMECA method.

Table 1
Parameters FMECA (occurrence).

Possible rate of occurrence	Criterion of occurrence	Value
Occurrence (O)		
Once every 12 years	Failure near zero or no	1
Once every 10 years	Very low, failure isolation, rarely	2
Once every 8 years	Low, often fail	3
Once every 6 years		4
Once every 4 years	Average, occasional failure	5
Once every 2 years		6
Once every year		7
Once every 6 months	High, frequent failure	8
Once every month		9
Once every week	Very high, very high failure	10

2.3. General considerations and study assumptions for RCM method

Based on the definition of IEC No: 60300-3-11 for RCM: "method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation", it actually represents a conception of translating feedback information from the past time of the operation installations to the future time of their maintenance, grounding this action on:

Table 2
Parameters FMECA (severity).

Duration of service interruption	Criterion of severity	Value
Severity (S)		
>8 h	Very catastrophic	8
7 h	Catastrophic	7
6 h	Very serious	6
5 h	Serious	5
4 h	Medium	4
3 h	Significant	3
2 h	Minor	2
1 h	Very minor	1
30 min	Small	0.6
<30 min	Very small	0.2

Table 3
Parameters FMEA (detectability).

Level of detectability	Criterion of detectability	Value
Detectability (D)		
Not detectable	Impossible	10
Difficult to detect	Very difficult	9
	Very late	8
Detecting random (Unlikely)	Not sure	7
	Occasional	6
Possible detection	Low	5
	Late	4
Reliable detection	Easy	3
	Immediate	2
Detection at all times	Immediate corrective action	1

Table 4
FMECA (criticality).

Criticality (C)		Risk or Hasard
Degree of criticality	Value	
Minor	0–30	Acceptable
Medium	31–60	Tolerable
High	61–180	
Very high	181–252	Unacceptable
Critical	253–324	
Very critical	>324	

- Statistical calculations and reliability calculations to the system operation.
- The basic components of preventive maintenance (PM), repair/renewal actions.

So, reliability centered maintenance (RCM) implies planning the future maintenance actions based on the technical state of the system over final period (T1), the state being assessed on the basis of the estimated reliability indices of the system at the planning moment (T0). At their turn, these reliability indices are mathematically estimated based on the record of events that is, based on previously available information, related to the behavior over initial period (T0). The equipment of power distribution systems is modeled as one block. For this block the reliability, availability and maintainability distributions are estimated based on failure reports presented by the plant operator. The two-parameter Weibull distribution, typically used to model wear-out or fatigue failures is represented by the following equations:

$$R(t) = e^{-\lambda t} \tag{2}$$

where $R(t)$ is the reliability at time t; t time period [h]; λ is failure rate.

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{\mu}{\lambda + \mu} \quad (3)$$

where A is the availability; μ is repair rate; λ is failure rate, MTBF is mean time between failures, given by the relationship:

$$\text{MTBF} = \frac{1}{\lambda} \quad (4)$$

MTTR: Mean Time To Repair, given by the relationship:

$$\text{MTTR} = \frac{1}{\mu} \quad (5)$$

MTTF: Mean Time To Failure, given by the relationship:

$$\text{MTTF} = \int_0^{\infty} R(t)dt \quad (6)$$

Maintainability function:

$$M(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} = 1 - e^{-\mu t} \quad (7)$$

where $M(t)$ is the Maintainability Function; t the time period [h]; β the Weibull distribution shape parameter and η the Weibull distribution characteristic life [h].

3. Cost of maintenance task

The cost of the maintenance task is the cost associated with each corrective or preventive task, whether time-based or condition-based. The expected corrective maintenance cost is the total cost of maintenance resources needed to repair or replace failed items. Similarly, the expected preventive maintenance cost is the total cost of maintenance resources needed to inspect and/or examine an item before failure takes place and to replace any items rejected. Thus, the total maintenance cost throughout the life of a systems/product is the sum of the corrective and preventive maintenance costs and the overhead costs, which consist of all costs other than direct material, labor and system equipment [13]. The LCC of maintenance task can be divided into two categories.

3.1. Direct cost of maintenance task

The direct cost associated with each maintenance task, DCM, is related to the cost of maintenance resources, CMR of power distribution system. This is the cost of the maintenance resources directly used during the execution of the maintenance task, which is proposed as follows:

$$\text{DCM} = \text{Cm} + \text{Cf} + \text{Cs} + \text{Cu} + \text{Cp} + \text{Cd} \quad (8)$$

where Cm is the cost of material, Cf is cost of facilities, Cs is cost of spare parts, Cu is unavailability cost, Cp is cost of personnel, and Cd is cost of technical data.

3.2. Indirect cost of maintenance task

Indirect costs ICM includes as management and administration staff needed for the successful completion of the task and the cost of the consequences of not having the system available which is related to a complete or partial loss of production. It also includes the overhead costs, i.e. salaries of employers, air conditioning, insurance, taxes, telephone, IT, training and similar which are incurred while the item is in state of failure (and, of course, not included in the direct costs). These costs should not be neglected, because they could be even higher than the other elements cost. Cost of lost production, CLP, is directly proportional to the product of the length of the time which the system spends in the state of failure (down time) and the income hourly rate, IHR (α), which is the money the system would earn whilst in operation. Thus, the cost of lost production could be determined through the following expression:

$$ICM = \alpha \cdot CLP \quad (9)$$

3.3. Total cost of maintenance task

The total cost of maintenance task LCC is the sum cost of direct and indirect costs, thus:

$$\text{LCC} = \text{DCM} + \text{ICM} \quad (10)$$

4. Case studies: application to the power distribution systems

To illustrate our view in this work, we will give a general description of the electrical distribution station located in the region of RELIZANE north west of ALGERIA. The suggested alternative for the power distribution systems can be schematized as follows (Fig. 3):

Where:

1. Electrical line (EL).
2. Circuit breaker (CB).
3. Bus bar (BB).
4. Power transformer (PTR); fuse (F).
5. Sectionalizer (SW). EFS: Electric Feeder System

4.1. Classification of failures and estimated replacement cost for major components

The failures of the various elements are at the base of the failures of the EFS, however the reliability of the complex systems as the EFS depend primarily on their structure of the type of connection of the elements and of the dependability of operation of the elements. It is known that from elements of a no high level of reliability, the design of the reliable system can be obtained on the basis of optimal redundant structure, however to expect a

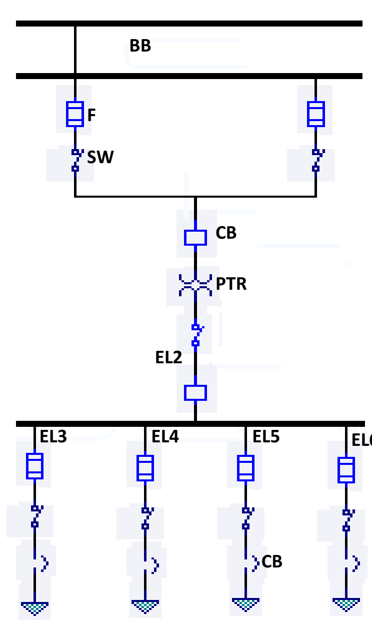

Fig. 3. Standard diagram of the EFS structure.

Table 5
Classification of failures and estimated replacement cost for major components of the EFS in the north west of ALGERIA.

Electric components	Number of analyzed failures	Number of failures of elements		Costs (DA/ 3 years)
Transmission lines (EL)	143	Electric drivers	11/7.7	218500
		Insulators	132/ 92.3	
Transformers (PTR)	96	Insulators	53/ 55.2	745000
		Terminals	31/ 32.3	
		Switch	12/ 12.5	
Circuit breakers of line (CB)	105	Insulators	27/ 25.7	141400
		Control drive	58/ 55.3	
		System of drive	21/ 19.0	
Bus bars (BB)	39	Contact with apparatuses	39/ 100	68500

DA: Algerian dinars.

Table 6
Data of reliability of the elements of the EFS in north west of ALGERIA between 2007 and 2010.

Elements of EFS	High voltage (KV)	Failure rate (1/year)			Average time of repair(h)
		λ_{min}	λ	λ_{max}	
Electric lines on 100 km	30	0.151	0.159	0.175	12
	60	0.148	0.153	0.162	11
Transformers and insulators	30	0.150	0.159	0.173	15.38
	60	0.150	0.156	0.160	14.28
Circuit breaker of line	30	0.139	0.145	0.149	10
	60	0.134	0.139	0.143	10
Bus bars	30	0.078	0.082	0.088	4
	60	0.077	0.080	0.083	4

Table 7
classification table of the elements by their criticality.

Element	Criticality	Maintenance action
ARS	4	Corrective action
SW	8	
BB	24	Improved performance of the elements. Systematic preventive maintenance
FUS	36	
CB	120	Questioning complete design
IS	140	
PTR	200	
EL	265	

great effectiveness of these systems cannot in no case to be assured. In order to locate the weak link of the EFS and its elements, allows to highlight the best means of improvement of their reliability and to determine the source data to ensure the requirements for the reliability of these systems, the first stage to be realized at the time of the study of the reliability of the EFS is the determination and the analysis the reliability of the various elements of these systems. The information collected on a sample of several power distribution system, located in the north west of ALGERIA allowed us to represent the cost curve and distribution of the failures of the various elements of these EFS, Table 5, to the denominator is indicated the distribution of the failures in per cent and estimated replacement cost for major equipment's of the EFS in the north west of ALGERIA.

The failure rate and the average repair time of the elements of the EFS determined with a probability of confidence $\alpha = 0.95$ are represented on the Table 6.

We chose the value of 24 as the threshold of criticality. The critical elements beyond 24 are grouped in ascending order in Table A1. It is these elements that we must act primarily by engaging in actions maintenance, corrective, preventive, improvement or even of replacement. Following the study we did in the resort of power distribution system of RELIZANE north-west in ALGERIA, it will be necessary to make a complete renovation since the majority of equipment is very old and comes from the colonial period from the year 1948, especially electrical lines and power transformers.

Beyond the value of 120 for the criticality, we must think for a complete questioning of design. For this purpose it is recommended to completely change the power lines using the same material, renovate or replace the power transformers by others more powerful and more robust, and ultimately change total the ancient insulators by others in composite material to withstand the high humidity and salinity of this area.

4.2. Appendix: table of FMECA

Table A1 summarizes the work we did on the application of Analysis of failure modes effects and criticality method, (FMECA) to the power distribution system.

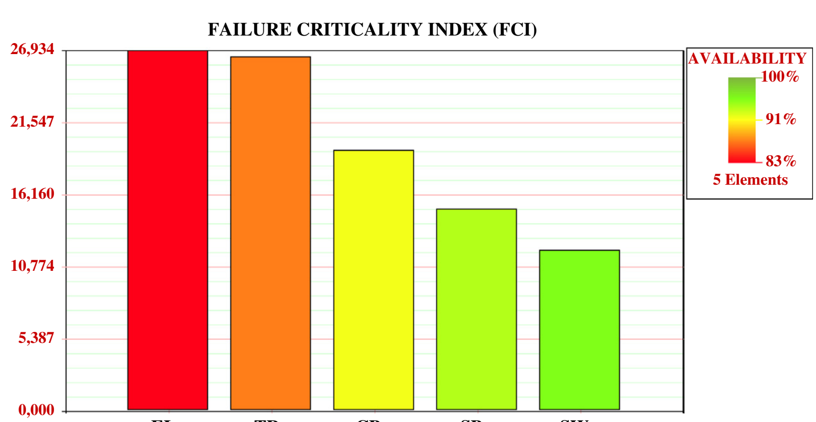

Fig. 4. EFS critical equipment until ten years.

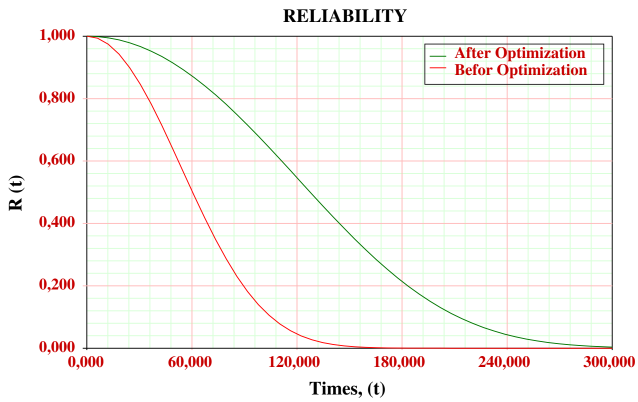

Fig. 5. Reliability $R(t)$ of EFS.

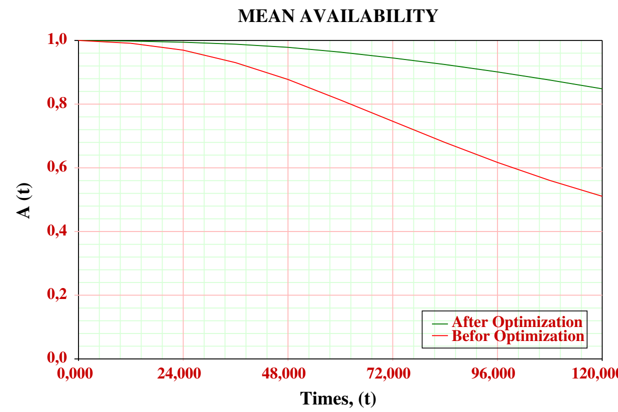

Fig. 8. Mean availability $A(t)$ of EFS.

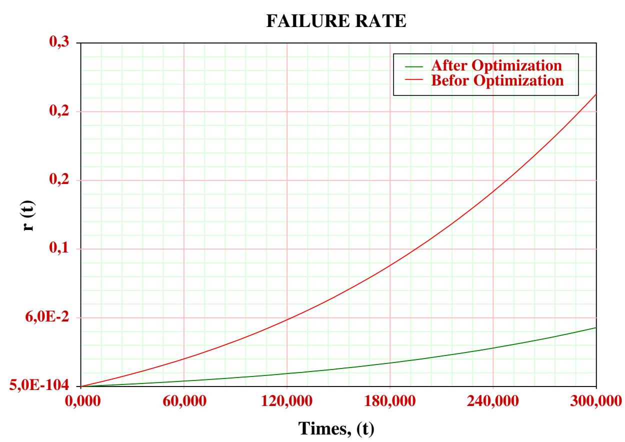

Fig. 6. Failure rate $r(t)$ of EFS.

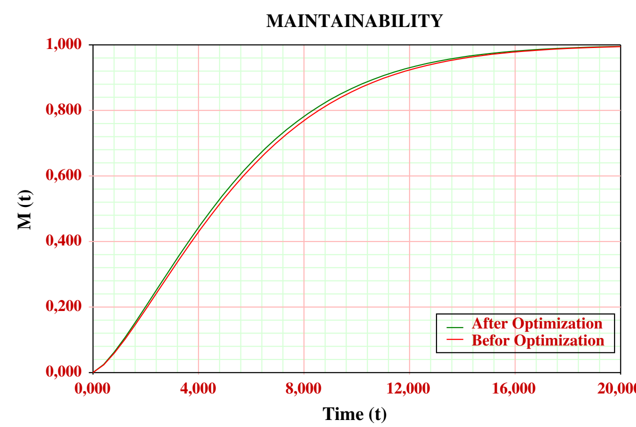

Fig. 9. Maintainability $M(t)$ of EFS.

4.3. Determination of the optimal parameters, λ, μ, A and costs

For determining the optimum parameters (λ, μ, A, R, M and costs) of EFS, we applied a global optimization on a sample of electric distribution systems located in the area of RELIZANE province in the north west of ALGERIA by adopting different models and different simulations that are assigned in this article. After determining of EFS critical equipment until ten years, we have given the priority to the power transformers (TR), electrical line (EL), insulators (IS) and circuit breakers (CB) for starting our approach, then the result of modeling and simulation is summarized in the summary table (Table 7) and the four figures successively named $R(t)$, $F(t)$, $r(t)$ and $A(t)$ (see Figs. 4–9).

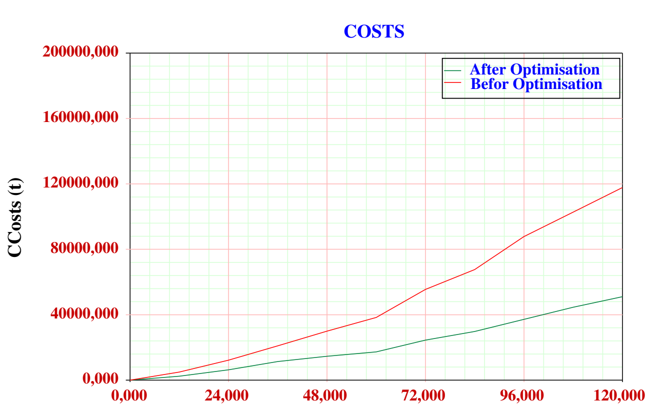

Fig. 7. Costs of EFS.

The optimization model RCM applied to the power distribution system has given many good results. This result we had in the figures and summarized in Table 8 shows the importance of the optimization strategy of maintenance for the purpose of maintaining equipment reliability and availability of EFS electrical system including the reduction of cost of maintenance in order to increase the time between two successive failures and minimize repair time.

Following the study we did in the resort of power distribution system of RELIZANE north-west in ALGERIA, it will be necessary to make a complete renovation since the majority of equipment is very old and comes from the colonial period from the year

Table 8
Optimal parameters, λ, μ, A, R, F and costs. For EFS.

Parameters	Before Optimization	After optimization, (for a mission time = 120 months)
Reliability *R*	0.045	0.5
Unreliability *F*	0.995	0.5
Failure rate λ	0.3	0.051
Costs (DA)	11734	5027: 57.15% of reduction
MTBF (year)	3.33	19.6
MTTR(h/year)	3.33	4.9
Availability A until 10 years	0.5	0.8
Maintainability M until 10 years	0.864	0.874

Table A1
FMECA.

[PDS of *R* in *A*][a]	Analysis of failure modes effects and criticality									
Electrical distribution station located in the region of RELIZANE north west of ALGERIA				Date:						
Element	Function	Failure mode	Cause	Effect	Detection	Criticality				Maintenance plan adopted: action to be taken
						O	*S*	*D*	*C*	
Transmission line EL	Electrical transport	– contact of two lines	Electrodynamics force of the wind	– Line break	Visual	8	8	4	*256*	– Corrective action: If the fault is minor. – Preventive systematic maintenance action. – A new study, using cables of the same material (replacement).
Insulator out of glass, or ceramics IS	Insulation	– Aging – Priming	– Partial or complete discharge of the arc in its volume. – Overvoltage (lightning) streamer surface by an electric arc. – Air pollution (depositing a layer of pollution on the surface of the insulator, progressive wetting layer of pollution, development of dry lands and appearance of partial arcs. – Extension of partial arcs if conditions are favorable to the insulator boot) (dusty environments near-desert or salted ones)	– Perforation – Deformation	Visual	5	7	4	*140*	– Corrective action: They can be covered with grease or washed regularly. – Preventive systematic maintenance action. – A new study, using composite insulator (replacement).
Bus Bar BB	Selection of lines	Short-circuit			Visual	2	4	3	24	– Preventive systematic maintenance action
Power transformer PTR	Used to raise or lower the voltage level of an alternative power source.	- Noise pollutions: phenomena of constriction in the transformers - Low isolation resistance - Triggering of the transformer to the powering at the time of the Unballasting operation	– The vibration of the metal envelope, the sets of bars and the maker badge. – An abnormal dust contamination. – An incrassate by fatty vapor's and dust. – The electronic converters are badly connected or the supply voltage does not conform. The fuses are badly gauged. The transformers of current (TC) are saturated by the currents with interlocking. Starting with the mass or between whorls of rolling up of the transformer.	– Excessive heating – deformation – No voltage	– noise – visual – heat	5	8	5	*200*	Special surveillance, conditional / preventive maintenance – Review the fasteners and clamping panels and supports. – Check the mechanical condition of the transformer. – Measurements of noise. – Check the timing and balance coils' hypertension. – Review the determination of the plate. - Review the determination of the plate. – Inhale the dust and clean all accessible parts then blow the transformer to the 'nitrogen or air dry. – Use a cold degreaser to clean the resin and blocking. – Check connection and power with voltages specified on the case of electronic converters. – Change the fuse rating – Revise the definition of current transformers. – Perform a visual inspection and diagnosis with measurement of insulation resistance of windings. – In the critical case, if the Buchholz relay is open? Then the replacement of the transformer will be required.
Arrester ARS	Protection	Long and short interruptions	– The lightning – Maneuver of equipment – Failure isolation	– Breakdown of materials	– Visual	4	1	1	4	Corrective maintenance – To maintain the Lightning protectors

										– Control of the default isolation of the earth electrodes – Choice of the level of insulation
Circuit breaker CB	Protection and control	Overvoltage	– Food network – Reset – Internal Failures – Permutations sources	– Stop of equipment – Stop of installation – Production loss – Power Electronic Dysfunction	– noise – visual – heat	4	6	5	*120*	– Preventive systematic maintenance action. – New study (Improvement). – Editing architecture system.
Fuses FUS	Protection	Overcurrent		Fusion	Visual	3	4	3	36	Replacement
Sectionalizers SW	– Galvanic isolator – Electrical separation	– Closing difficult or – Opening difficult	– Food network – Reset – Internal Failures – Permutations sources	Blocking	– Visual – Noise	4	1	3	12	– Aspire the dust and clean all accessible parts then blow the transformer to the 'nitrogen or air dry. – Replacement.

[a] PDS of R in A: Power Distribution System of RELIZANE in ALGERIA

1948, especially electrical lines and power transformers. For this purpose it is recommended to completely change the power lines by using a homogeneous material, renovate or replace the power transformers by others more powerful and more robust, and ultimately change total the ancient insulators by others in composite material to withstand the high humidity and salinity of this area.

5. Conclusion

This paper presents the application of RCM model to optimize the maintenance management of equipment EFS. The main results that we had are recommendations for the re-integration of this maintenance strategy, including an optimal implementation of this approach. This work showed the feasibility of conducting an optimization method of maintenance RCM. This approach is based on the analysis FMECA. The implementation of this approach shows its contribution in reducing maintenance costs. Indeed it can:

– Define the requirements of dependability in a precise.
– Identify critical functions for the system.
– Define the maintenance policy for the system and its components.

At the level of system reliability, we have identified the components on which special attention should be paid. The example discussed in the context of this work was developed following a logical and structured analysis. It allowed better control the system under study while identifying weak links and knows the types of maintenance applied to each subsystem and component. In the end, it is a real process of optimizing maintenance costs.

Acknowledgments

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Appendix A

See Table A1

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