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System dynamics modelling method optimizing CAPEX/OPEX Performance in electrical distribution networks

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Today in developing countries, Electrical distribution companies are facing ageing network, which represents significant value in terms of operating expenses (OPEX) and capital expenditures (CAPEX); that are respectively used to maintain and to replace ageing underground cable and to invest in RTUs which will highly serve the automation of the grid strategic substations. This work aims to develop a System dynamics based on integrated modelling to find the optimal balance between CAPEX and OPEX in order to reach a reliability that can meet the needs of interested parties. This optimum is determined following three main steps: first, the prioritization of underground cables to be replaced using a genetic algorithm and Weibull generalized process, second, the RTUs investment (location, number) using a multi-criteria optimization, and third, cost benefit analysis to determine options that provide the best solution by studying and modelling interdependency and dynamic behavior of the two preceding steps. The proposed approach is illustrated with simulated data of a reel distribution Feeder, and the results responds well to the needs and constraints of electrical distribution operator.

Keywords: Multi-criteria optimization, System dynamics, Reliability, Electrical distribution network, CAPEX/OPEX optimization.

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1. Introduction

Planning the growth of electrical distribution networks, its maintenance and operations and operation/maintenance are subject to constant changes to meet demand, to satisfy the operating constraints, and to minimize the investment costs, operating and unserved energy cost in accordance with the reliability objective.

At the same time, SCADA and RTU technology are increasingly present in the planning and operating process in order to control, supervise, and minimize the downtimes when electrical faults occur.

Reliability depends not only on the power restoration, but also on the frequency of failure which depends on how and where the underground cables have been operated, repaired, or even replaced.

The first challenge for electric utilities is often to understand the level of service to be provided within the context of a contract. Service level depends on both, time to restore service and failure frequency which is related to Feeders' aging rate (serviceability), whereas time to restore service is related to the investment on remote terminal units (RTUs) and on the reactivity of local operators.

Although, some studies have been carried out to optimize reliability/planning cost of electrical distribution and transmission systems, [1] establishes a multi-objective

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optimization using a nonlinear mixed integer optimization to find out the optimal distribution network expansions cost. [2] Develops two methods to estimate the mean life and its standard deviation of a power system equipment group with limited end-of-life or aging failure data using normal and Weibull distribution model. [3] Gives a cable segment replacement optimization based on diagnostic measurements to identify relevant segments to be replaced without taking into account the failure rate evolution and corrective maintenance cost. Reliability-centered asset maintenance (RCAM) method is proposed in [4] to relate the impact of maintenance on the cost and reliability of power distribution systems. [5] Develop a quantitative maintenance optimization for electrical system with renewable energy sources taking into account both, cost and system reliability. A statistical analysis is presented in [6] to determine the critical assets for distribution components in power system. [7-8, 9] attempt to model maintenance using Generalized Renewal Process maximum likelihood estimators to find the expected number of failures. [10] Demonstrate that the failure rate estimation for maintenance must take into consideration the repairable characteristic of electrical cable. [11] Is interested in improving the performance of MV underground distribution networks using only the distribution automation system. Other works have tried to solve the problem of reliability by reducing restoration time using metaheuristic algorithm to solve the multi-objective problem to choose the substation to be remotely controlled [12-16] without taking also into account the corrective maintenance and the cable replacement optimization. [17] evaluate the financial risk incurred by installing the remote-controlled switch in electrical distribution network. System dynamics methods also used to enhance strategy design and planning in public utilities in a strategic learning perspective [18], these methods are constructed to deal with several issues related to energy sector, civil, electrical, and industrial engineering to tackle investment efficiency and to study the relationships between cause and effect under technic, economic, social and environmental constraints [19-26].

This study is the extension of our work [27] in which we have attempted to develop a multi-criteria optimization to determine the optimal choice of substations to be remotely controlled in order to reduce time to restore service. It became clear that investment on RTUs cannot solve the reliability problem of the network [17] and that is also necessary to invest in reducing the failure rate which strongly impacts the system average interruption duration index.

All papers mentioned above do not address the Power grid reliability especially power restoration in its broad sense, taking into account cable replacement optimization problem, corrective maintenance and RTUs locations optimization,

In the light of what has been done in recent studies and in an attempt to overcome their shortcomings, i.e. neglecting the pragmatic points associated with RTU placement such as substation accessibility, different load types, system topology, and expert's knowledge incorporation, this paper is to introduce an approach to sensibly and meanwhile methodically solve the problem.

Contribution:

In the light of what has been addressed in recent works and trying to overcome their shortcomings, neglecting important point: the feedback loops governing the RTUs locations/investment optimization, the cable replacement optimization and corrective maintenance cost. This paper is to introduce an approach that takes the three points in one model.

The main contribution of these work is to establish a system dynamics method to minimize the SAIDI by exploring the impact of all decision's combinations, decision to continue to maintain underground cables, decision to replace underground cables and decision to invest in RTUs. This undertaking is very complex because the change in one decision means the change in the others, as shown in Figure 1 these decisions are all interconnected in many ways.

the merit of our approach is the combination of the cable replacement prioritization optimization and the RTUs location optimization in a dynamic way taken into account the distribution operator preferences and knowledge.

To do that we have developed a mathematical model to determine where investments are needed, which investment and which combination is the best for every specific Feeder to get the highest service level that meets the quality requirements of the interested parties and the budgetary requirements of the stakeholders. To summarize, our contribution is synthetized in 3 points:

- Modeling the problem of prioritization of underground cable replacement.
- Modeling the process of finding the optimal choice of substations to be remotely controlled.
- Modelling the global problem as multi-objective optimization problem to handle with all conflicting objectives: CAPEX, OPEX, hidden cost (cost of energy not supplied).

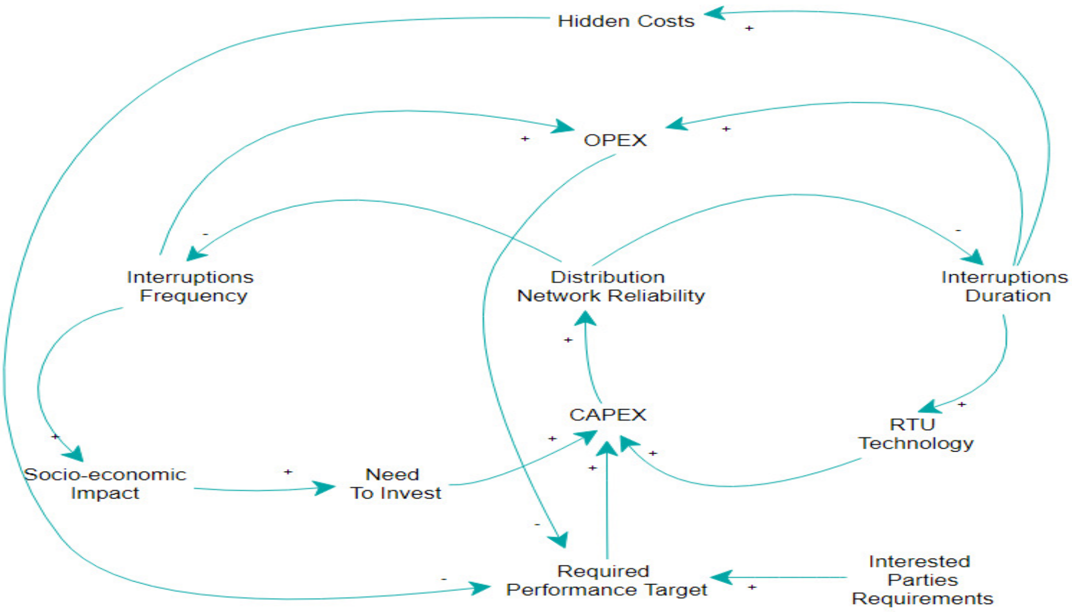

Figure 1: feedback loops diagram governing CAPEX, OPEX and hidden costs.

Our approach follows the flowchart in Figure 2:

Step1: Failures repair modelling as imperfect corrective maintenance using WGRP

Step2: Constraint optimization MLE system formulation

Step3: WGRP parameters are determined using GA to solve constraint optimization MLE system,

Step4: Monte Carlo simulation is used to estimate failures' expected number. Go to step 5 and step 8

Step5: Underground cables replacement prioritization optimization process modelling as constraint optimization problem, Go to step 6 and step 8

Step 6-7: Multi-criteria optimization to determine the optimal substations to be remotely controlled

Step8: Modelling the global cost objective function in a way to master all conflicting objectives: CAPEX, OPEX, hidden cost (cost of energy not supplied).

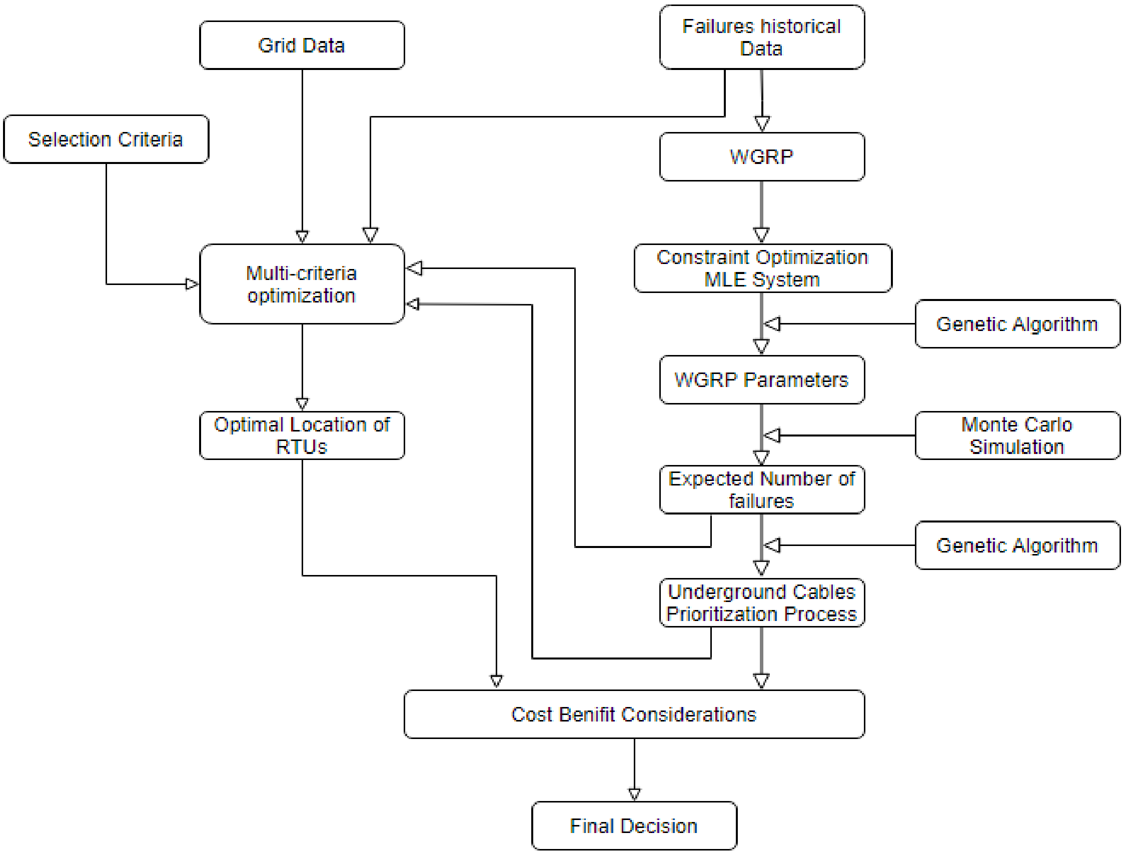

Figure 2: Flowchart showing the proposed methodology.

2. System modelling

2.1. Weibull Generalized Renewal Process (WGRP)

An essential criterion for the system safety is the maintenance effectiveness. Indeed, effective maintenance will have the effect of delaying the failure events. The two most common assumptions are to assume that the maintenance is either perfect and puts the system back to its new condition, or minimal, and only restores the system to the state “as bad as old”. It is obvious that reality of electrical distribution networks maintenance lies between these two extremes. This is called imperfect maintenance.

Imperfect maintenance is an action that improves the state of the system without putting it back into a new state better than old and worse than new.

Mathematically speaking, it is a question of constructing punctual processes which are intermediary between non-homogeneous Poisson processes (NHPP) and renewal processes (RP) [28].

The most widespread imperfect maintenance models are virtual age models [29], which assume that a maintained system behaves like a new system whose age is lower than its actual age.

Since failures inevitably occur at random times, consequently, the resulting corrective maintenance is also random in nature. To model the underground cable failure process, we will combine Weibull distribution with generalized renewal process to apply them to reliability data,

The cumulative distribution function of a Weibull random value is defined by:

$$F_W(t,\beta,\alpha) = 1 - exp\left[-(t/\alpha)^{\beta}\right] \tag{1}$$

Generalized Renewal Process (GRP) is a probabilistic model for repairable Assets that can represent any of the three possible post-repair states of equipment. In this section, we present briefly GRP in general and WGRP in particular KIJIMA type 1.In the GRP type 1 model, corrective maintenance has a rejuvenating effect on the underground cable proportional to the time elapsed since the previous maintenance. The virtual age A_n of the equipment at the time T_n just after the n^{th} repair is equal to:

$$A_n = A_{n-1} + q(T_n - T_{n-1}) = qT_n \tag{2}$$

With q the rejuvenation parameter (the repair effectiveness parameter): $q = 0, q = 1$ correspond to RP and NHPP, respectively.

Let T_k be the actual cumulative time until the k^{th} repair, also as shown in Fig. 1 we note X_k he time interval between the $(k-1)^{th}$ and the k^{th} repairs.

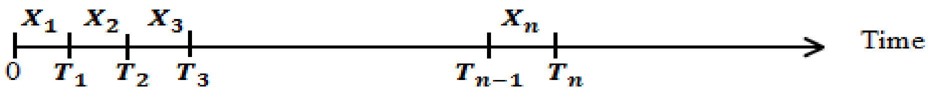

Figure 3: Relationship diagram between T and X

Based on the knowledge of Weibull distribution and according to the definition of reliability function including the conditional probability concept, the probability that the underground cable will fail in a subsequent period X_i after having repaired at the time T_{n-1} is equal to:

$$F_{T_i}(x+V_{i-1}/V_{i-1}) = \frac{F(x+A_{i-1})-F(A_{i-1})}{R(A_{i-1})} = \frac{1-\exp\left[-(\frac{x+A_{i-1}}{\alpha})^{\beta}\right]-1+\exp\left[-(\frac{A_{i-1}}{\alpha})^{\beta}\right]}{1-1+\exp\left[-(\frac{A_{i-1}}{\alpha})^{\beta}\right]} \tag{3}$$

α and β represent respectively the scale and shape parameters of WGRP,
Then, the Conditional cumulative distribution function in WGRP can be expressed as follows:

$$F_{T_i}(x+A_{i-1}/A_{i-1}) = 1-\exp\left[(\frac{A_{i-1}}{\alpha})^{\beta} - (\frac{x+A_{i-1}}{\alpha})^{\beta}\right] \tag{4}$$

Then, the probability density function can be expressed as:

$$f_{T_i}(x+A_{i-1}/A_{i-1}) = \frac{\beta}{\alpha}(\frac{x+A_{i-1}}{\alpha})^{\beta-1}\exp\left[(\frac{A_{i-1}}{\alpha})^{\beta} - (\frac{x+A_{i-1}}{\alpha})^{\beta}\right] \tag{5}$$

Therefore, under Kijima I and from (3) and (5), we conclude the hazard rate function in WGRP:

$$\lambda_i = \frac{f_{T_i}}{1-F_{T_i}} = \frac{\beta}{\alpha}(\frac{x+A_{i-1}}{\alpha})^{\beta-1} \tag{6}$$

In the next section we will bring out the methodology for computing Maximum likelihood estimation to calculate, from an observed sample, the best values of parameter of WGRP.

2.2. Maximum likelihood estimation of WGRP

In this section an estimation approach of WGRP parameters using maximum likelihood [30] approach will be shown.

$$L(\alpha,\beta,q)=\prod_{i=1}^{n} f_{T_i}(\alpha,\beta,q) \tag{7}$$

And so:

$$L(\alpha,\beta,q)=\prod_{i=1}^{n}\frac{\beta}{\alpha}\left(\frac{x_i+q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta-1}\exp\left[\left(\frac{q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta}-\left(\frac{x_i+q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta}\right] \tag{8}$$

Maximizing L (α, β, q) is equivalent to maximizing Ln (L), so:

$$Ln(L(\alpha,\beta,q))=\sum_{i=1}^{n}Ln\left[\frac{\beta}{\alpha}\left(\frac{x_i+q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta-1}\exp\left[\left(\frac{q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta}-\left(\frac{x_i+q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta}\right]\right] \tag{9}$$

Then:

$$Ln(L(\alpha,\beta,q))=n(Ln(\beta)-\beta\ln(\alpha))+(\beta-1)\sum_{i=1}^{n}Ln\left(x_i+q\sum_{k=1}^{i-1}x_k\right)+\sum_{i=1}^{n}\left[\left(\frac{q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta}-\left(\frac{x_i+q\sum_{k=1}^{i-1}x_k}{\alpha}\right)^{\beta}\right] \tag{10}$$

To obtain the maximum of the modified MLE for the parameter estimation we will proceed by modelling the logarithm likelihood function as a constraint optimization problem:

$$MinF_{obj} : MinLL(\alpha,\beta,q) \tag{11}$$

Subject to:

$$\alpha \geq 0 \tag{12}$$

$$\beta \geq 0 \tag{13}$$

$$0 \leq q \leq 1 \tag{14}$$

This objective function seeks the parameters of WGRP that best fit failures data. For that a genetic algorithm is used.
Genetic algorithm is an optimization method based on techniques derived from genetics and evolution to solve constrained and unconstrained multi-objective optimization problems. For more details see [31-32].

Genetic algorithm runs according to the following steps:

- Step1: Generate randomly initial population
- Step 2: Evaluate population generated and check stopping criteria: if no one of the stopping criteria is met go to Step 3 else, go to Step 5.

- Step 3: Generate new population using the operations of selection, crossover and mutation
- Step 4: Replace the current population with the new generated population and go to Step 2.
- Step 5: Loop the process and return the best solution.

2.3. Expected number of failures

As we have mentioned above, our goal is to determine the optimal investment in terms of renewal of the critical sections and in terms of remote controlled of our electrical distribution network, therefore it is necessary to determine the expected number of failures, which can be determined using Monte Carlo simulation.
The Monte Carlo method is broadly defined as a technique for solving a model using random or pseudo-random numbers that are uniformly distributed over the interval [0, 1].
Whenever simulation is realized, there are a number of possible outcomes. After performing the simulation several times, we can see that some results occur more often than others and that it is possible to assign probabilities of occurrence. The sampling space of a stochastic process contains all the possible results. The results are consequences of the events to which the studied system is subjected.
Each operation period can be simulated by drawing a random value between 0 and 1 and applying to it the inverse of Eq. (1) for the first failure and Eq. (4) for the subsequent failures:

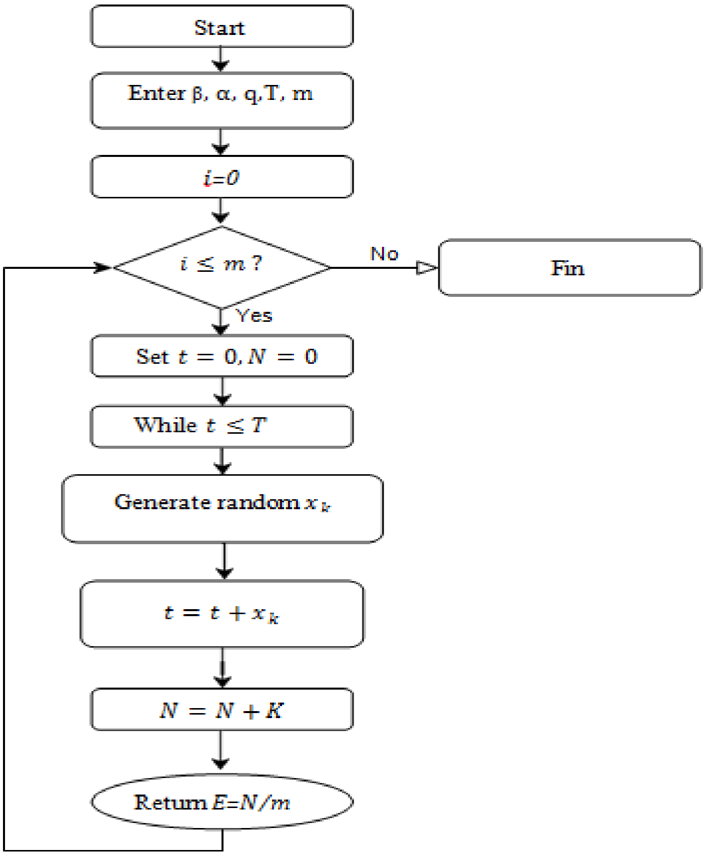

Figure 4: Flowchart of the failures' expected number finding process using Monte Carlo simulation

$$\begin{cases} x_i = \alpha(-\ln(1-F_w(x_i))^{1/\beta} & i=1 \\ x_i = \alpha\left[\left(\dfrac{q\sum_{k=1}^{i-1} x_k}{\alpha}\right)^{\beta} - \ln(1-F_w(x_i)\right]^{1/\beta} - q\sum_{k=1}^{i-1} x_k & i=2,3,,,,n \end{cases} \tag{15}$$

2.4. Prioritization of underground cables renewal

The aim of this subsection is to find where replacements are needed to optimize the global reliability function of electrical distribution network. For that we have proceeded by an optimization of the global expected gain function resulting from replacement operation of a length's combination of underground cables using Genetic Algorithm.
Before modelling the problem, we will put forward some assumptions:

- The underground cables are divided into a set of 50 m segments.
- Every segment has its own expected number of failures.
- The expected number of failures for a replaced segment is assumed to become zero.

The proposed formulation problem is given by:

$$\underset{i,j}{Max}\sum_{i=1}^{n}\sum_{j=1}^{m} a_{ij} g_{ij} \tag{16}$$

Subject to:

$$\sum_{j=1}^{m}\sum_{i=1}^{n} a_{ij} l_j = l_k \tag{17}$$

$$\sum_{j=1}^{m} a_{ij} = 1 \qquad \forall i \in 1 \ldots n \tag{18}$$

$$a_{ij} \in \{0,1\} \quad \forall i, j \in 1 \ldots m \tag{19}$$

$$l_j = j * S \quad j \in 1 \ldots m \tag{20}$$

With:

g_{ij} ; Expected gain resulting from replacement of l_j of i^{th} underground cable section.

l_j : Segment length j.

S: Segment unit length.

3. Optimal substations to be remotely controlled

The main aim of this section is to find the optimal locations of RTUs in electrical distribution network in order to isolate faults and restore healthy parts in real time to minimize interruption and subsequently minimize the cost of unserved energy.
The choice of substations to be automated strongly depends on several criteria such us accessibility, load, type of load, distance, topology of grid, and failure rate which related to the expected number of failures that have been calculated in the previous section.

To prioritize all the judgment criteria, we use the analytical hierarchy process [33] which captures subjective and objective aspects and which are particularly suited for decision-making in multi-objectives problems, for more details consult [27,33].

The optimal substations to be remotely controlled are obtained by maximizing the expected utility operator.

Formulation problem:

$$\begin{aligned} MaxU_{Exp}(X) = {} & F_{1-x_1} l_{x_1,n-1} + F_{x_1+1,x_2}\left(l_{1,x_1} + l_{x_2,n-1}\right) + \cdots + F_{x_{N-1}+1,x_N} l_{x_N,n-1} \\ & + F_{x_N+1,n} l_{1,n-1} + \sum_{m=0}^{n-1}\sum_{i=1} F_{x_i m} l_{1,n-1} \end{aligned} \tag{21}$$

With:

$$F_{x-y} = \sum_{i=x}^{y} F_i \tag{22}$$

$$l_{x-y} = \sum_{x}^{y} l_j = \sum_{j=x}^{y} \left(\frac{\sum_{i} Ws_{j/CRi} * W_{CRi}}{\sum_{j=1}^{n}\sum_{i} Ws_{j/CRi} * W_{CRi}} \right) \tag{23}$$

F_{x-y} : The Normalized failure probability between the substation number x and number y.

l_{x-y} : The normalized multi-criteria flow between x-y.

l_i : The weight related to criterion i.

n: The number of substations in the feeder.

$U_{Exp}(X)$: The expected utility value associated with insertion of N-RTUs in the substations number $X = (x_1, x_2, ..., x_n)$.

The normalized multi-criteria flow is constituted only with the criteria of accessibility, distance, load and type of load while the criteria of grid topology and failure rate are taken into account in the function objective to accurately capture the impact of these criteria.

4. Cost benefit considerations

In the previous section we have tried to find the optimal technical solutions, furthermore in this section we develop a model to achieve defined reliability level which responds to the needs by modelling cause and effect relationship between CAPEX, OPEX and hidden costs. Figure 5 and Eq 24-30.

To achieve that we have been involved model which accordingly take into consideration and meet the benefits of all interested parties (customer, delegating authority, municipality…), and benefits shareholders.

The point of view focusing on both reliability and the economic aspect can be assessed in a consistent manner by comparing the CAPEX needed to fulfil the defined reliability level with the reliability worth. Subsequently the total cost objective function is the sum of all costs:

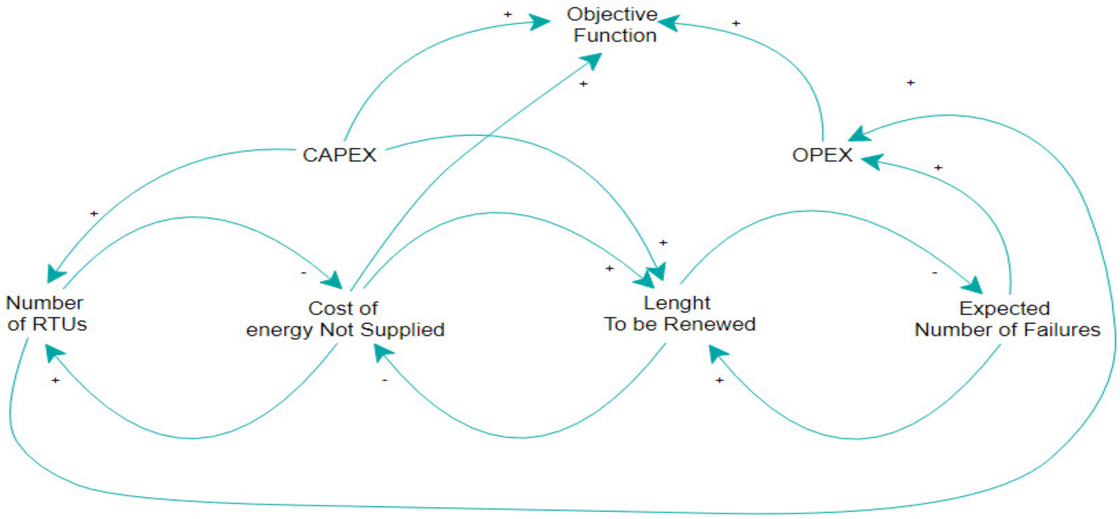

Figure 5: Causal loop diagram showing how different parameters are interrelated

$$F_{TC.obj} = CAPEX + OPEX + TC_{ENS} \tag{24}$$

With:

$$CAPEX = C_{RTU} + C_{RP} \tag{25}$$

$$OPEX = TC_{CM} + N_{RTU} * C_{UM-RTU} \tag{26}$$

$$C_{RTU} = N_{RTU} * C_{U-RTU} \tag{27}$$

$$C_{RP} = l * C_{U-RP} \tag{28}$$

$$TC_{ENS} = \sum_{k=1}^{m} E_{NF_k} C_{ENS_k} = \sum_{k=1}^{m} g_k(l) f_k(N_{RTU}) = f_1(N_{RTU}) \sum_{k=1}^{m} g_k(l) \left(\frac{1}{1+t}\right)^{k-1} \tag{29}$$

$$TC_{CM} = \sum_{k=1}^{m} E_{NF_k} C_{CM_k} = C_{U-CM_1} \sum_{k=1}^{m} g_k(l) \left(\frac{1}{1+t}\right)^{k-1} \tag{30}$$

Where:

C_{RTU} : RTU investment cost.

C_{RP} : Replacement of underground cables investment cost.

TC_{CM} : Total cost of corrective maintenance

C_{CM_k} : Corrective maintenance cost of the k^{th} year.

TC_{ENS} : Total cost of energy not supplied.

C_{ENS_k} : Cost of energy not supplied of k^{th} year.

C_{U-RTU} : Unit cost of RTU

N_{RTU} : Number of RTUs.

C_{UM-RTU} : Unit maintenance cost of RTU.

C_{U-RP} : Unit replacement cost.

l : The length of cable to be renewed.

N_{EF_k} : expected number of failures of k^{th} year.

W_j : Weight of substation number j.

r_j : Average outage duration of substation number j.

n : Number of substations.
m : The life time of RTU.
t : Discount rate.

5. Case study

The proposed method has been applied on a real 55-bus power distribution feeder of the North Moroccan's electrical distribution network.

In order to give useful results and to raise the possibility of reproduction, the real data used is available in table 1 and table 2.

The choice of sections to be renewed is related to the concentration of failures on the section which impact the cable insulation, because of failure expresses degradation and imperfection of the cable insulation in a local area and propagates progressively within the insulation when the cable is in use and increases according to several parameters that are related to the operating environment of cable especially Transient overvoltage and thermal effects when a short-circuit occurs.

Table 1: Historical Data

Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
L(m)	1000	700	2000	717	440	4000	950	1150	500	2200	250	51	1350	595	67	901	1000	890	1600
Date	2008	2008	1998	1998	2008	2013	1998	2008	2010	1998	2011	2012	1998	2008	2007	1998	2008	2008	2008
Failure rate%	0,68	0,75	8,01	6,09	1,03	0,68	4,38	0,62	0,62	8,42	0,55	0,41	6,3	0,41	0,55	4,38	0,34	0,41	0,68
Number of failures	10	11	117	89	15	10	64	9	9	123	8	6	92	6	8	64	5	6	10

Section	20	21	22	23	1,1	3,1	3,2	3,3	4,1	6,1	6,2	6,3	6,4	6,5	6,6	7,1	9,1	9,2	9,3
L(m)	2220	1750	300	500	510	615	345	480	202	280	350	100	120	145	190	600	200	225	165
Date	2009	2009	1998	2009	2008	2008	2008	1998	1998	2012	2008	2008	2008	2008	2010	2016	2008	2008	2008
Failure rate%	0,82	0,82	4,93	0,62	0,82	0,55	0,48	6,5	3,9	0,68	0,75	0,68	0,62	0,62	0,68	0,41	0,68	0,68	0,82
Number of failures	12	12	72	9	12	8	7	95	48	10	11	10	9	9	10	6	10	10	12

Section	9,4	10,1	11,1	11,2	11,3	11,4	11,5	12,1	12,2	14,1	14,2	14,3	17,1	17,2	17,3	17,4	19,1
L(m)	315	250	170	250	280	350	220	550	420	140	80	213	355	415	767	300	900
Date	2008	1998	2009	2009	2013	2008	1998	2009	2009	2010	2015	2010	2009	2009	2010	1998	2010
Failure rate%	0,62	8,56	0,82	0,75	0,62	0,89	4,79	0,75	0,68	1,03	0,41	0,82	1,03	1,03	0,82	4,72	0,89
Number of failures	9	125	12	11	9	13	70	11	10	15	6	12	15	15	12	69	13

As a result, we have to deal with the confusing decisions whether to repair or replace the defective sections of underground cable system. To make these decisions we have used the approach described in section 2 and the results are shown in table 4 and table 5.

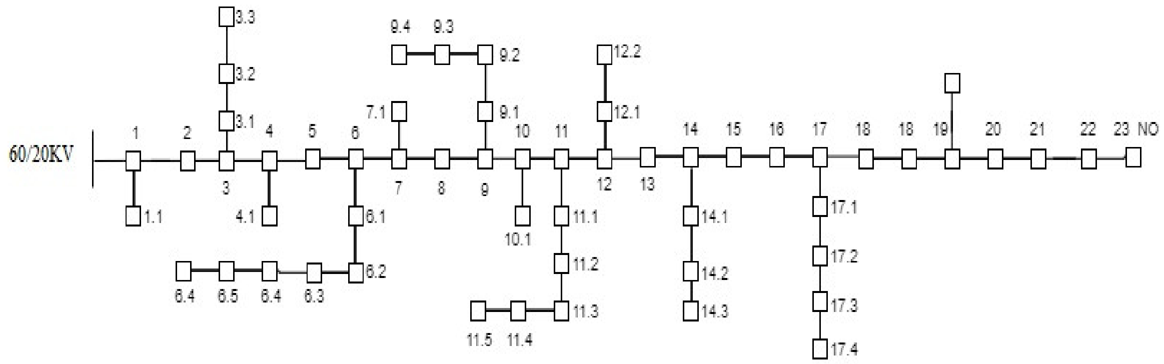

Figure 6: A 55 bus Real Feeder in North of Morocco power distribution network

Table 2: Real Feeder characteristics and final normalized substation weight

Number	Distance	Capacity	Accessibility	weight accessibilty	Residential load	Comercial load	Special load	distance weight	normalized substation weight
1	1000	250	N	0,07	90%	10%	0%	0,0281	0,00739
2	700	400	N	0,07	85%	15%	0%	0,0196	0,00739
3	2000	250	D	0,32	0	100%	0%	0,0561	0,03377
4	717	250	N	0,07	90%	10%	0%	0,0201	0,00739
5	440	250	N	0,07	90%	10%	0%	0,0123	0,00738
6	4000	100	D	0,32	100%	0%	0%	0,1123	0,03375
7	950	400	N	0,07	0%	100%	0%	0,0267	0,00740
8	1150	160	N	0,07	98%	2%	0%	0,0323	0,00739
9	500	400	VD	0,62	90%	10%	0%	0,0140	0,06538
10	2200	250	N	0,07	98%	2%	0%	0,0617	0,00739
11	250	160	N	0,07	0%	100%	0%	0,0070	0,00738
12	51	630	N	0,07	70%	30%	0%	0,0014	0,00738
13	1350	400	N	0,07	90%	10%	0%	0,0379	0,00739
14	595	160	N	0,07	0%	100%	0%	0,0167	0,00739
15	67	250	N	0,07	0%	100%	0%	0,0019	0,00738
16	901	250	N	0,07	0%	100%	0%	0,0253	0,00739
17	1000	250	D	0,32	70%	30%	0%	0,0281	0,03375
18	890	160	D	0,32	0%	50%	50%	0,0250	0,03376
19	1600	400	N	0,07	98%	2%	0%	0,0449	0,00739
20	2220	250	N	0,07	98%	2%	0%	0,0623	0,00739
21	1750	630	N	0,07	0%	100%	0%	0,0491	0,00743
22	300	250	N	0,07	0%	100%	0%	0,0084	0,00738
23	500	-	NO	-	-	-	-	0,0140	-
1,1	510	50	D	0,32	95%	5%	0%	0,0143	0,03374
3,1	615	250	N	0,07	80%	20%	0%	0,0173	0,00739
3,2	345	400	N	0,07	80%	20%	0%	0,0097	0,00738
3,3	480	160	D	0,32	95%	5%	0%	0,0135	0,03374
4,1	202	50	D	0,32	80%	20%	0%	0,0057	0,03374
6,1	280	630	D	0,32	0%	0%	100%	0,0079	0,03378
6,2	350	250	D	0,32	95%	5%	0%	0,0098	0,03374
6,3	100	100	N	0,07	95%	5%	0%	0,0028	0,00738
6,4	120	160	N	0,07	20%	80%	0%	0,0034	0,00738
6,5	145	160	N	0,07	95%	5%	0%	0,0041	0,00738
6,6	190	160	N	0,07	95%	5%	0%	0,0053	0,00738
7,1	600	50	VD	0,62	0%	0%	100%	0,0168	0,06538
9,1	200	630	D	0,32	0%	0%	100%	0,0056	0,03377
9,2	225	630	N	0,07	95%	5%	0%	0,0063	0,00738
9,3	165	400	N	0,07	95%	5%	0%	0,0046	0,00738
9,4	315	100	N	0,07	99%	1%	0%	0,0088	0,00738
10,1	250	50	D	0,32	0%	100%	0%	0,0070	0,03374
11,1	170	100	VD	0,62	0%	0%	100%	0,0048	0,06538
11,2	250	160	N	0,07	0%	0%	100%	0,0070	0,00739
11,3	280	400	N	0,07	95%	5%	0%	0,0079	0,00738
11,4	350	250	N	0,07	95%	5%	0%	0,0098	0,00738
11,5	220	250	N	0,07	95%	5%	0%	0,0062	0,00738
12,1	550	100	D	0,32	80%	20%	0%	0,0154	0,03374
12,2	420	50	N	0,07	95%	5%	0%	0,0118	0,00738
14,1	140	100	D	0,32	80%	20%	0%	0,0039	0,03374
14,2	80	160	N	0,07	95%	5%	0%	0,0022	0,00738
14,3	213	50	N	0,07	80%	20%	0%	0,0060	0,00738
17,1	355	400	VD	0,62	20%	80%	0%	0,0100	0,06538
17,2	415	250	N	0,07	95%	5%	0%	0,0116	0,00738
17,3	767	250	N	0,07	20%	80%	0%	0,0215	0,00739
17,4	300	50	N	0,07	0%	0%	100%	0,0084	0,00738
19,1	900	50	D	0,32	0%	0%	100%	0,0253	0,03375

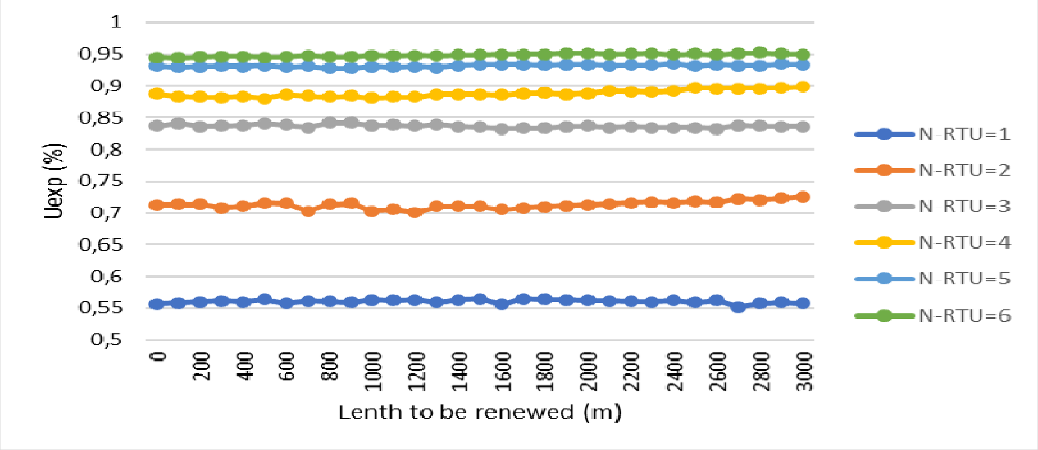

Figure 7: Utility expected operator variation in the case of average expected number of failures

Table 3: Simulated parameters of GRP and Monte Carlo simulation

Section	Lenght	Renewed section	Historical failures	Alpha	Beta	Expected number of failures		
						N min	N aver	N max
12_13	1350	0	32	3056,98	3,59	73	92	103
		100	22	3398,66	3,66	57	68	85
		150	22	2678,32	2,82	28	42	57
		250	12	3366,92	2,77	13	20	27
		600	4	3807,37	1,84	0	3	3
17_17,4	300	0	24	3050,00	3,41	51	69	83
		100	14	2861,17	2,80	24	33	49
		200	6	2884,72	2,02	5	9	17
		300	0	-	-	0	1	3
02_03	2000	0	37	3061,63	3,77	95	117	142
		300	27	2887,92	3,35	59	76	93
		600	17	2031,83	2,16	18	23	30
		900	7	3223,65	2,34	9	12	19
06_07	950	0	29	2700,91	3,09	51	64	77
		150	20	2722,62	2,86	35	44	53
		200	20	2336,41	2,46	20	32	41
		350	11	2953,71	2,43	10	17	19
		600	3	5000,00	2,98	2	8	15
03_04	717	0	27	3409,67	3,86	67	89	99
		150	17	3137,71	3,25	36	54	75
		200	14	2990,81	2,65	14	23	26
		350	4	2970,85	1,62	1	3	7
09_10	2200	0	41	2674,94	3,49	100	123	145
		400	29	2555,71	3,18	72	86	102
		700	19	2592,28	2,98	47	59	71
		1000	9	2891,00	1,99	2	8	11
10_10,1	250	0	19	4154,14	4,86	97	125	159
		100	9	4596,59	4,63	48	61	80
		100	10	4715,11	4,53	35	49	65
		250	0	-	-	0	1	3
3,2_3,3	480	0	25	3703,66	4,18	76	95	123
		200	13	3680,04	3,36	27	35	45
		300	4	4693,85	3,00	3	10	15
		480	0	-	-	0	1	3
11_11,5	220	0	15	4341,60	4,50	53	70	90
		100	8	4915,26	4,35	24	35	46
		100	8	4524,02	3,83	18	29	39
		200	0	-	-	0	1	3
15_16	901	0	28	3439,00	3,65	50	64	75
		200	16	3210,99	3,09	28	40	49
		200	20	2401,06	2,52	19	33	47
		400	8	3329,65	2,50	10	13	19
		900	0	-	-	0	1	3
4_4,1	202	0	24	2848,84	3,10	44	48	63
		100	12	2861,33	2,41	12	17	27
		150	5	3007,28	1,82	2	5	7
		200	0	-	-	0	1	3
21_22	300	0	22	3411,00	3,71	56	72	95
		200	5	4573,82	2,99	3	11	16
		300	0	-	-	0	1	3

Table 4: Simulated results of prioritization of underground cable to be renewed in the case of average expected number of failures.

Lr	LSn	Sn	G
100	100	7	5,20%
200	100	7	5,20%
200	100	9	2,81%
300	100	2	2,46%
300	100	7	5,20%
300	100	9	2,81%
400	100	2	2,46%
400	100	7	5,20%
400	100	9	2,81%
400	100	11	2,12%
500	150	1	3,42%
500	250	7	8,49%
500	100	9	2,81%
600	100	2	2,46%
600	200	5	4,52%
600	100	7	5,20%
600	100	9	2,81%
600	100	11	2,12%
700	100	2	2,46%
700	200	5	4,52%
700	100	7	5,20%
700	100	9	2,81%
700	200	12	4,18%
800	150	1	3,42%
800	100	2	2,46%
800	200	5	4,52%
800	250	7	8,49%
800	100	9	2,81%
900	150	1	3,42%
900	100	2	2,46%
900	200	5	4,52%
900	250	7	8,49%
900	100	9	2,81%
900	100	11	2,12%
1000	150	1	3,42%
1000	100	2	2,46%
1000	200	5	4,52%
1000	250	7	8,49%
1000	100	9	2,81%
1000	200	12	4,18%
1100	150	1	3,42%
1100	100	2	2,46%
1100	200	5	4,52%
1100	250	7	8,49%
1100	100	9	2,81%
1100	100	11	2,12%
1100	200	12	4,18%
1200	150	1	3,42%
1200	200	2	4,11%
1200	200	5	4,52%
1200	250	7	8,49%
1200	100	9	2,81%
1200	100	11	2,12%
1200	200	12	4,18%
1300	150	1	3,42%
1300	100	2	2,46%
1300	200	5	4,52%
1300	250	7	8,49%
1300	200	8	4,11%
1300	100	9	2,81%
1300	100	11	2,12%
1300	200	12	4,18%
1400	150	1	3,42%
1400	100	2	2,46%
1400	200	5	4,52%
1400	250	7	8,49%
1400	200	8	4,11%
1400	100	9	4,72%
1400	100	11	2,12%
1400	200	12	4,18%
1500	250	1	4,93%
1500	100	2	2,46%
1500	200	5	4,52%
1500	250	7	8,49%
1500	200	8	4,11%
1500	200	9	4,72%
1500	100	11	2,12%
1500	200	12	4,18%
1600	250	1	4,93%
1600	200	2	4,11%
1600	200	5	4,52%
1600	250	7	8,49%
1600	200	8	4,11%
1600	200	9	4,72%
1600	100	11	2,12%
1600	200	12	4,18%
1700	250	1	4,93%
1700	200	2	4,11%
1700	200	5	4,52%
1700	250	7	8,49%
1700	300	8	5,82%
1700	200	9	4,72%
1700	100	11	2,12%
1700	200	12	4,18%
1800	250	1	4,93%
1800	200	2	4,11%
1800	200	5	4,52%
1800	250	7	8,49%
1800	300	8	5,82%
1800	200	9	4,72%
1800	200	11	3,22%
1800	200	12	4,18%
1900	250	1	4,93%
1900	200	2	4,11%
1900	200	4	2,19%
1900	200	5	4,52%
1900	250	7	8,49%
1900	300	8	5,82%
1900	200	9	4,72%
1900	100	11	2,12%
1900	200	12	4,18%
2000	250	1	4,93%
2000	200	2	4,11%
2000	200	4	2,19%
2000	200	5	4,52%
2000	250	7	8,49%
2000	300	8	5,82%
2000	200	9	4,72%
2000	200	11	3,22%
2000	200	12	4,18%
2100	250	1	4,93%
2100	200	2	4,11%
2100	300	3	2,74%
2100	200	5	4,52%
2100	250	7	8,49%
2100	300	8	5,82%
2100	200	9	4,72%
2100	200	11	3,22%
2100	200	12	4,18%
2200	250	1	4,93%
2200	200	2	4,11%
2200	300	3	2,74%
2200	150	4	1,37%
2200	200	5	4,52%
2200	250	7	8,49%
2200	300	8	5,82%
2200	200	9	4,72%
2200	150	11	2,94%
2200	200	12	4,18%
2250	250	1	4,93%
2250	200	2	4,11%
2250	300	3	2,74%
2250	200	4	2,19%
2250	200	5	4,52%
2250	250	7	8,49%
2250	300	8	5,82%
2250	200	9	4,72%
2250	150	11	2,94%
2250	200	12	4,18%
2400	250	1	4,93%
2400	200	2	4,11%
2400	300	3	2,74%
2400	150	4	1,37%
2400	200	5	4,52%
2400	250	7	8,49%
2400	300	8	5,82%
2400	200	9	4,72%
2400	200	10	2,12%
2400	150	11	2,94%
2400	200	12	4,18%
2500	250	1	4,93%
2500	200	2	4,11%
2500	600	3	6,43%
2500	200	5	4,52%
2500	250	7	8,49%
2500	300	8	5,82%
2500	200	9	4,72%
2500	200	11	3,22%
2500	300	12	4,86%
2600	250	1	4,93%
2600	200	2	4,11%
2600	600	3	6,43%
2600	200	5	4,52%
2600	250	7	8,49%
2600	300	8	5,82%
2600	200	9	4,72%
2600	200	10	2,12%
2600	100	11	2,12%
2600	300	12	4,86%
2700	250	1	4,93%
2700	200	2	4,11%
2700	600	3	6,43%
2700	200	4	2,19%
2700	200	5	4,52%
2700	250	7	8,49%
2700	300	8	5,82%
2700	200	9	4,72%
2700	200	11	3,22%
2700	300	12	4,86%
2800	250	1	4,93%
2800	300	2	4,65%
2800	600	3	6,43%
2800	200	4	2,19%
2800	200	5	4,52%
2800	250	7	8,49%
2800	300	8	5,82%
2800	200	9	4,72%
2800	200	11	3,22%
2800	300	12	4,86%
2900	250	1	4,93%
2900	200	2	4,11%
2900	600	3	6,43%
2900	200	4	2,19%
2900	200	5	4,52%
2900	250	7	8,49%
2900	300	8	5,82%
2900	200	9	4,72%
2900	200	10	2,12%
2900	200	11	3,22%
2900	300	12	4,86%
3000	250	1	4,93%
3000	200	2	4,11%
3000	600	3	6,43%
3000	200	4	2,19%
3000	350	5	5,89%
3000	250	7	8,49%
3000	300	8	5,82%
3000	200	9	4,72%
3000	200	10	2,12%
3000	150	11	2,94%
3000	300	12	4,86%

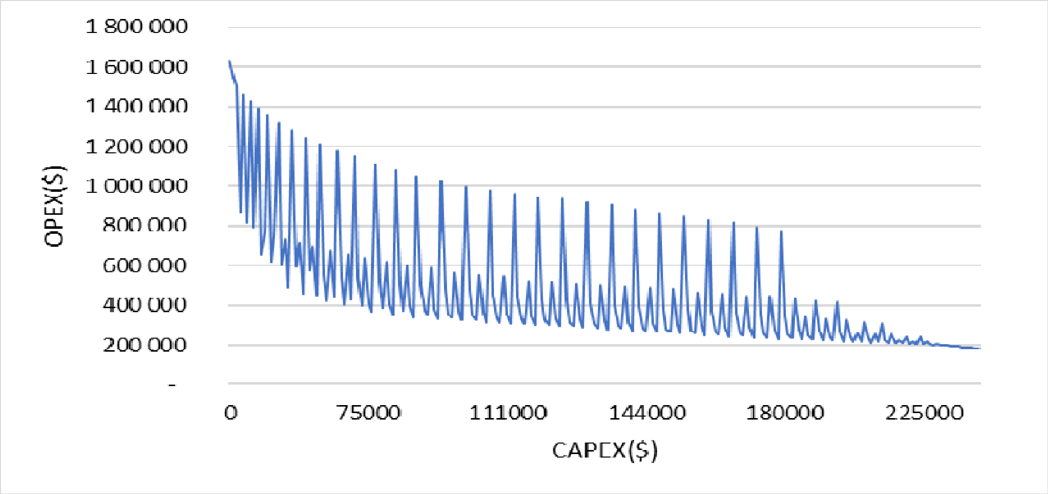

Figure 8: Variation of OPEX in function of CAPEX in the case of unit replacement cost equal to 60$

With:
Lr: The length to be renewed.
LSn: The length to be renewed of the section n.
G: The gain in term of failure rate
Sn: Section n.

Table 5: The optimal couple (Number of RTU, Length to be renewed), the average scenario

RTU cost (pu)	15000$																	
Corrective maintenance cost	150$																	
Unit replacement cost	60$																	
Cost of Energy not supplied	0,1			0,25			0,5			1			1,5			2		
Average current	100	125	150	100	125	150	100	125	150	100	125	150	100	125	150	100	125	150
Number of RTUs	3	3	3	3	5	5	5	5	5	6	6	6	6	6	6	6	6	6
Length to be replaced(Km)	0,3	0,8	0,9	1,3	1	1,4	1,4	1,6	1,6	1,7	1,7	1,7	1,7	1,9	2	1,9	2,7	2,7

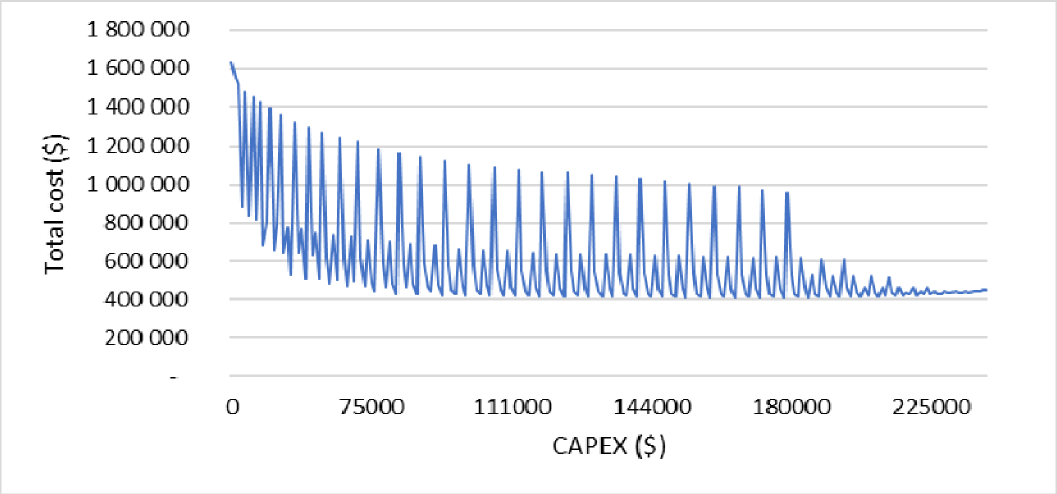

Figure 9: The variation of the total cost in the case of unit replacement cost=60$, Corrective maintenance cost=150$, cost of energy not supplied=0.5$ and average current=125A

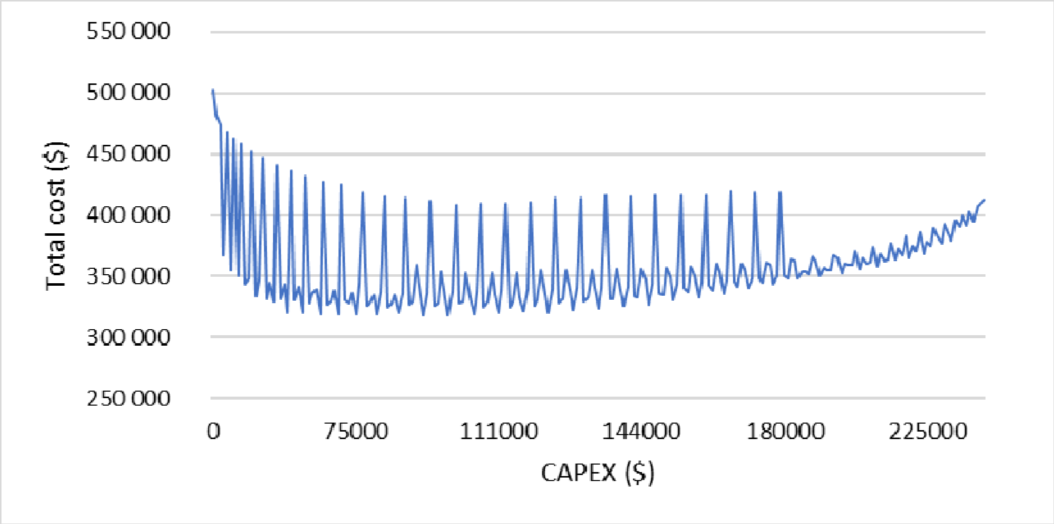

Figure 10: The variation of the total cost in the case of unit replacement cost=60$, Corrective maintenance cost=150$, cost of energy not supplied=0.1$ and average current=100A

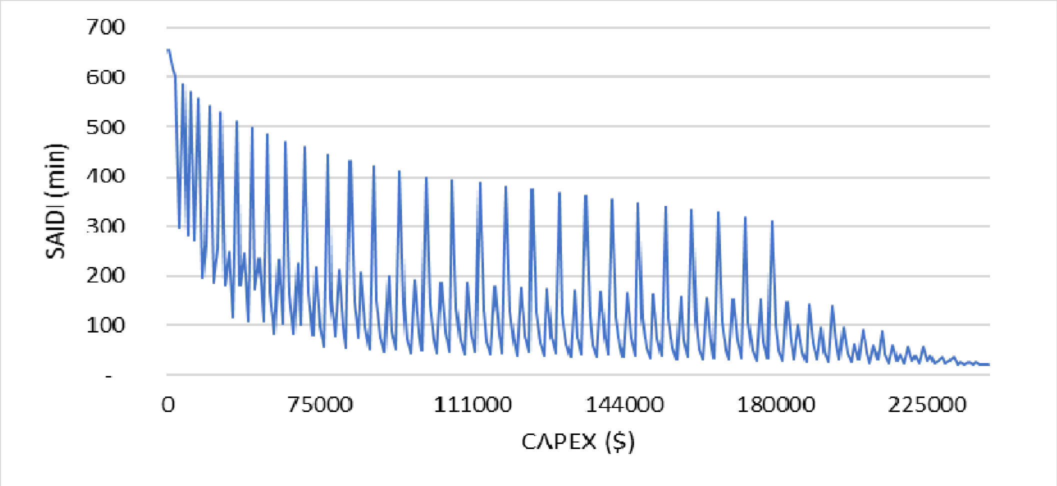

Figure 11: Variation of the total cost and level of service in function of the energy not supplied cost

5.1 Discussions and comparisons

In our case, the studied system is the underground cable making an important part of the distribution network.

Failure in the underground cable can occur as a result of the insulation system deterioration. The underground cables' design life is in the range of 30-35 years, and a large portion of segments making our Feeder will reach 30 years of use in the next 10 years.

After analyzing table 1; the Reliability data of 55 real bus power distribution feeder subject of our study; we noticed that there are some segments that have been renewed in the 10 last years and other segments that have been operating for 22 years.

By analyzing the Feeder historical failures, we can conclude that some segments present signs of premature aging as the feeder is operated in a difficult environment. The feedback we have received from the network managers confirmed that we are on the right track.

When a cable is on service, its insulation is at the heart of thermal, electrical, mechanical constraints related to the operating environment; Over time, these various constraints lead to irreversible changes in the insulation. It is generally referred to an intrinsic aging of the cable, during which the insulation degrades in a homogeneous way.

The act of repairing faults in an underground electricity network cannot, in any case, rejuvenate the underground cable. The reparation acts locally on the cable's state which depends on the degradation of the insulation. Subsequently the rejuvenation parameter q of the WGRP will be equal to 1 which corresponds to an NHPP.

As shown in table 2 the normalized substation weight is deeply impacted by the criterion of accessibility because, the importance of this criterion is due to the fact that a substation whit difficult accessibility impacts the time to restore power when a failure occurs. We can also see that the special load criterion has an impact on the normalized weight because of the sensitive character of these costumers related to the security, the health or the socio-economic development.

In our approach, instead of the importance of cable taken as unique criteria in [3] or Failure Rate and Repair Time in [17,] we have taken multi criteria related to substation such as load capacity, load type, substation accessibility and grid topology, because of even if we use the importance of cable in the cable replacement optimization process , a failure in one of the other segments affects all the Feeder ‘s substations, and it is for this reason that we have took it in the RTUs optimization process that impact highly restoration operation. The results shown in table 4 and figure 6 confirmed we are right, we show that without any RTU and with a replacement of 3 Km of cable we can only reduce the failure rate by 52.5% which will reduce SAIDI with 52.5 approximately, while with only 1 RTU we can reduce the SAIDI by 54.6%. In other hand as mentioned above we cannot take RTUs as unique solution because of they will not be useful in the case of double or multiple failure, hence the interest of our work.

Regarding the results in table 3, we noticed that those segments (underground cable) have a hight WGRP parameters which confirmed the suppositions mentioned previously. On the other hand, we have also shown that the expected failures decrease according to the cable length to be renewed.

After calculating the expected number of failures in table 3, the suitable substations to be automated is determined by injecting the expected number of failures in the process with the other criteria of load, type of load, accessibility, distance using the methodology described in section 3 and figure 2.

The results shown in figure 7 are interpreted by the causal relationship between the RTUs investment and replacement investment, Length to be renewed impact Uexp which determines the optimal RTUs locations, and we remark also that in our case the Utility expected operator varies very little depending on the underground cable length to be renewed, the same remark also for the number of RTUs which varies very little with the variation of the length to be renewed because of the result of the prioritization of underground cable renewal process described in the sub-section 2.4 shown in table 4.

The variation shown in Figure 7 is also due to the fact that we did not take a constant failure rate as [3-27], on the contrary Our method takes into account the expected failure rate in the decision-making process of cable replacement by modelling the cable degradation model as a WGRP with coefficient of rejuvenation equal to 1.

In figure 8, the variation in OPEX as a function of CAPEX is due to the fact that capex is made up of investment in replacement and in RTUs, investment in renewal decreases OPEX while investment in RTUs increases both CAPEX and OPEX.

Figure 8 and figure 9 show the relevance of taking into consideration the hidden costs in the total cost and consequently in the decision-making process, hidden costs depend strongly to the cost of interruption which is related to the importance of consumers supplied by the Feeder.

In table 5 we show the optimal couple (Number of RTU, Length to be renewed), in the case of average expected number of failures simulated for different cost of energy not supplied which related directly to the cost of interruption, taken into account 3 scenarios of the evolution of electricity demand. Analyzing the results, we notice that the optimal couple is very sensitive to the evolution of the demand which confirmed our assumption that the installation of RTUs does not solve the unreliability problem and that we have to invest by combining installation of RTUs and replacement of defective segments prioritized in table 4.

As we see in figure 11, the rapid decrease in SAIDI confirms the fact that the Feeder has reached an aging situation and that an investment is largely justified.

The high variations shown in figure 8,9,10 and 11 are due to the fact that each variation of the underground cable length to be renewed generates a variation of the expected number of failures which consequently generates a variation of the locations of the RTUs and may be a variation of the number of RTUs, all these variations are mastered in the equation 24, Figure 5.

The strength of our approach is an optimization that incorporates in one model the Manager’s preferences and knowledge in a dynamic way to explore all possible investment/solution and search the best one enhancing reliability, economy indicators, and network operations.

6. Conclusion

In this study, a new approach was developed to find fair "investment (CAPEX) and operating (OPEX) expenses/ performance / criticality" optimizing reliability in electrical distribution networks. Unserved energy reduction, maintenance cost and investment cost, were taken as objectives, and failure rate, accessibility, grid topology, distance, load and type of load were taken as criteria.

Firstly, expected failures’ number was determined using Genetic Algorithm to solve MLE system used to determine WGRP parameters that fit historical outage data. Secondly, expected failure number was injected in the both, process prioritizing segments of underground cable to be renewed and process of determining the optimal number and location of RTUs. Finally, an objective function was modeled to find the optimal solution that satisfies all interested parties. The approach developed was applied to a 55-bus real feeder. The results elaborated prove that our approach is an effective tool to improve the electrical distribution network reliability taking in one model corrective maintenance cost and expected failure rate in the cable replacement optimization and in the optimization of strategic substations to be remotely controlled to reduce power outage and to minimize power restoration time under constraints of accessibility, grid topology, failure rate, distance, load, type of load. More effort will be taken to manage the couple reliability-investment taking into consideration the presence of decentralized generation in the medium voltage network.

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