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International
Journal
Of Modern Engineering Research (IJMER)

Determiningthelifecycle and futurereplacementcostofdistribution network equipment

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ABSTRACT: *This article presents the methodology developed by Hydro-Québec Distribution (HQD) in partnership with the Institut de rechercheélectrique du Québec (IREQ) to estimat ethe replacement volume and costs of the major assets for the coming years. This methodology, based on the statistical analysis of operational data, will applyto all theassets in a distribution network. Its application will be illustrated with pole-mounted transformers. The results obtained will Be significant for developing replacement strategies for ageing equipment.*

KEY WORDS: *Statistical analysis, Weibull distribution, Life expectancy, Life cycles, Risk management*

Date of Submission: 21-05-2020 Date of acceptance: 07-06-2020

I. INTRODUCTION

Electrical distributor risk management seeks to balance performance, costs and risk [2]. This balance takes into consideration the desired reliability and the optimal life cycle of assets based on the risk of outages, safety required for the public and workers as well as customer satisfaction (see Fig. 1). Costs will depend on whether business strategies focus on optimizing performance, minimizing risks or optimizing resources.

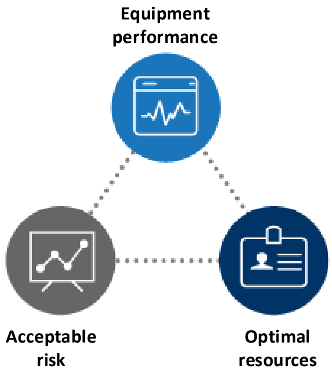

Figure 1. Interrelations between performance, risks and costs

Fig.2 maps the replacement strategy development process at HQD. This article presents the methodology for estimating the volume, costs and causes of future major-asset replacement.

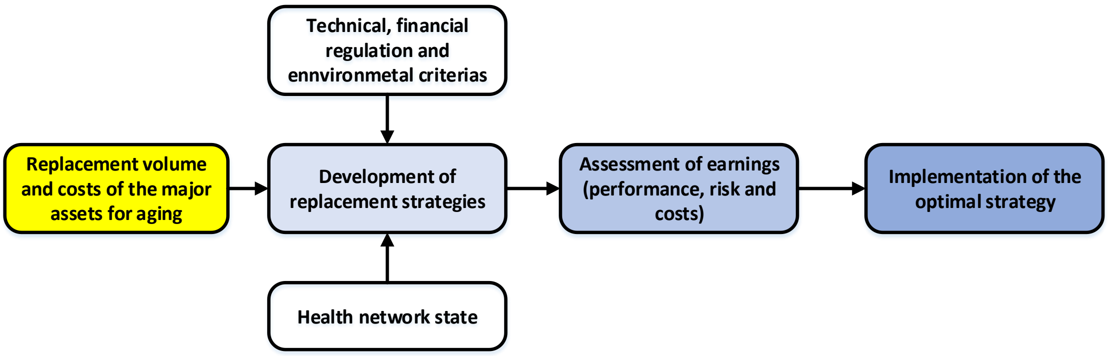

Figure 2. Process for developing asset replacement strategies

The methodology is based on a rigorous operational data analysis process in which information availability and quality is essential[11]. This information comes from the database developed by IREQ in partnership with HQD [14]. This database integrates all the information from the distribution network, including observed outages, weather events, maintenance results and other relevant information. This database is continually being improved through development and by integrating the expertise of data-analysis specialists.

Economic estimates are obtained with a Monte-Carlo simulator, which is also developed in partnership with IREQ. The results obtained with pole-mounted transformers will illustrate this methodology.

II. LITTERATURE REVIEW

Several experts agree on the effectiveness of statistical analysis to estimate the useful life of assets. This type of study has been the subject of several publications. Chmura [5] proposes a method applicable in the presence of highly censored data. Jongen[12] details a methodology for estimating future failures, from the estimation of the useful life of the equipment. Mehairjan[16] is developing a similar model applicable for large populations of equipment with limited data.

Other authors specify the evaluation of the parameters of the life distribution from the combination of several Weibull distributions. The use of separate subpopulations allows this distinction. [13][15]. These analyzes are essential for families of equipment subject to different degradation mechanisms or operated in different environments.

The contribution of this article is the definition of a methodology highlighting the processing and integration of operational data, despite the limitations in terms of their quantity or quality. The means used to validate the data, as well as the results are also specific to the method proposed by this article.

III. DISTRIBUTION NETWORK ASSETS

Hydro-Québec is made up of three separate business units: Hydro-Québec Production, responsible for generating electricity; Hydro-Québec Trans-énergie, responsible for high-voltage transmission from power transformers to the substation; and Hydro-Québec Distribution (HQD), responsible for distributing medium- and low-voltage electricity to customers.

This work addresses the equipment in the HQD administrative division. This network is made up of more than 3,500 lines totalling 118,000 km of medium-voltage (MT) lines, spread over a 250,000-km2 territory [6]. The distribution network is largely overhead (88%). The total consumption of 4.3 million customers in 2018 was 172.8 TWh[7].

Table I lists HQD’s major assets, which have a book value of several billion dollars. For the methodology, these assets are grouped into the following large categories:

1) Equipment covered by an inspection program such as:
a) Maintenance and repairsareperformed on sitetomaintaintheasset’slifecycle. Wood poles and vaultsarepartofthiscategory.
b) Maintenance and repairsareperformed in a workshop and makeit possible toextendtheequipment’slifecycle. These are pole-mountedreclosers, pole-mounteddisconnectswitches-switchgear and voltageregulators
c) Equipment isreplacedwhendegradationisobserved. This is Pad-mounted and submersibletransformer.
2) Equipment that is the subject of a use-to-failure policy, including:
a) The age of active equipment may be inferred from information systems. This category includes equipment with an electrical address such as transformers.
b) The age of the equipment in service or withdrawn is unknown. These are essentially overhead conductors and cables.

Many assets must be replaced every year for external causes [3]. Quebec weather is harsh, with winter temperatures below -20°C and the possibility of several freeze and thaw cycles. In the summer, the temperature may be above 30°C with high humidity for several days. The network is subjected to numerous weather events and a variety of precipitation depending on the season (thunderstorms, low-pressure systems, winter storms, ice, wet snow). Vegetation is prevalent on more than 50% of the overhead network. Several pieces of equipment are located in aggressive environments, as they are near saline environments (sea water) or major roads where a significant amount of de-icing product is used.

Table I. Hydro-Québec Distribution Major Assets

Major Assets		Quantity	% $
Civil structures	Wood poles	1,930,000	18%
	Vaults and piping	16,000vaults 2,000 km piping	8%
Cables and conductors	Overhead	105,000 km MV 98,500 km LV	28%
	Underground	14,000 km MV 8,200 km LV	15%
Transformers	Pole-mounted	680,000	18%
	Pad-mounted or submersible	25,000	5%
Other (Note 1)	Pole-mounted	Note 2	5%
	Pad-mounted or submersible		2%

1. Pole-mountedcapacitorbankbatteries, disconnectswitches, pole-mountedreclosers, switchgear, voltageregulators, other.

2. A fewthousandstoseveraltensofthousandsdepending on the type ofequipment.

IV. METHODOLOGY

Fig. 3 maps the analysis process for estimating replacement volume, costs and causes. This process is based on operational data from the HQD distribution network. The methodology requires homogenous equipment and sufficient data [5][16]. It is adapted based on the quality of data available and their consistency.

The analysis requires distinguishing replacements for external causes from those due to ageing. It requires an in-depth knowledge of the mechanics of deterioration and their rate of development based on the operating environment. The law of reliability that characterizes replacements involves two Weibull distributions—one for external causes and one for ageing [10][13][15].

Performing this analysis is challenging when the technical life cycle of the equipment is several decades [4]. During this period, the following changes may occur:

1) Operating practices, the maintenance program and regulatory requirements may evolve.
2) The availability and quality of equipment history data (commissioning date, failures, withdrawal, maintenance) in the information and management systems.

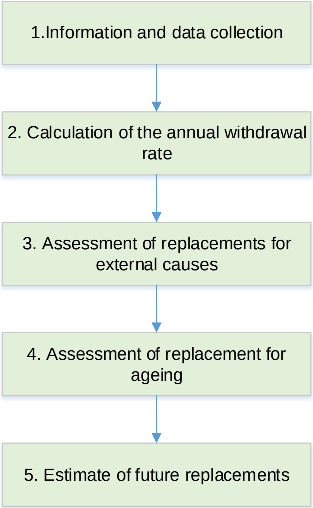

Figure 3. ***Process for estimating replacement volume, costs and causes***

4.1 Information and data collection

Information and management systems give the volume of equipment on the network and, since the 2000s, replacements for outages and breakage as well as withdrawal for architecture changes. The age of equipment, on the network or at withdrawal, is established based on the data available.

For equipment with an inspection program, information is compiled during inspections (condition, age and, if required, the withdrawal cause), which makes it possible to establish the demography of the equipment on the network (volume and age).

Several assets have a unique electrical address providing the date of the first installation since 1986. Equipment age is inferred by identifying replacements based on outages and breakage analysis, equipment withdrawals for architecture changes as well as inventory movements since the early 2000s.

Several assets have a nameplate that provides information including the manufacturing date. Since 2008, the information on these plates is compiled for all scrapped equipment. Other sources of information are consulted, including the data from recyclers that collect equipment withdrawn from the network and archival inventory documents.

Uncertainties are identified and measures are taken to validate results. Several methods can be used to correct the data, such as ground surveys of equipment in service (generally between several hundred and several thousand surveyed), archival inventory documents and the intersection of several independent sources of data.

4.2 Calculation of the annual withdrawal rate

The data collected in the previous step make it possible to determine the volume of equipment withdrawn and, for some, their age. It is therefore possible to calculate an annual withdrawal rate and, potentially, the failure rate based on age. The correlation between maintenance programs and the failure rate based on age is verified.

These results help, with the previously established demography, to validate the study's conclusions. They make it possible to establish a correlation between the rate of withdrawal for external causes and the parameters that characterize ageing.

4.3 Assessment of replacements for external causes

The rate of withdrawal for external causes is calculated based on all causes not related to equipment deterioration or age. It includes, among other things, weather events, accidents and configuration changes. The future volume of equipment withdrawn from the network is determined by multiplying this rate by the volume of equipment on the network.

A representative sample of assets withdrawn following outages or breakage is analyzed to identify the main causes of replacement. This analysis makes it possible to characterize withdrawals and replacements for external causes (unrelated to equipment age) versus those due to ageing. The exact cause is established by using all the information noted on maintenance work including, as needed, the analysis of free text.

4.4 Assessment of replacements for ageing

The duration of equipment technical life is fundamental in developing and optimizing asset management strategies. This information is obtained from operational failures related to ageing. In the process, three analyses are performed:

1) First with only the equipment withdrawn, whether for external causes or ageing. The volume and age of equipment in service are therefore excluded. This analysis is a conservative estimate of the life cycle. It is considered a minimal value depending on operating conditions and maintenance strategies.
2) Second with equipment withdrawn whether for external causes or ageing and with equipment in service. This analysis corresponds to the life cycle expected in actual operating conditions that considers withdrawals for external causes. The result is a double mixed Weibull.
3) Finally, with equipment withdrawn for ageing and equipment in service. Withdrawals for external causes are excluded from this analysis. This sometimes results in a three-parameter Weibull. These parameters characterize ageing and are used to estimate the future number of replacements for ageing based on demography.

The analyses are performed using Weibull ++ software [18]. The distribution of the appropriate life cycle is selected based on analysis experience and goodness-of-fit tests.

4.5 Estimate of future replacements

Future investments to renew assets are based on a Monte-Carlo simulation conducted using a simulator developed at IREQ as part of the ODEMA (decision-making tool for maintenance and analysis) project. The simulator input is the demography of the equipment in service, the withdrawal rate for external causes, ageing distribution and parameters and emergency and planned replacement costs.

Equipment replacement costs are established following the analysis of maintenance work. Work where the cost of materials is significantly less than the purchase cost of the equipment, i.e., unusual costs, is excluded. Exceptional costs, such as soil decontamination following oil loss, are also excluded.

The Monte-Carlo simulation consists in determining the age of each piece of equipment at withdrawal in assets grouped by homogenous family, considering its current age and the probability of withdrawal for external causes and for ageing. The simulation is conducted on all equipment starting with the oldest. The simulation assumes that each piece of equipment withdrawn is replaced by a new one. This process is repeated until convergence.

When there is a lot of equipment to simulate, few Monte-Carlo simulations are required before the results converge. Conversely, fewer pieces of equipment require more simulations. Costs are determined by considering a cost variation between the lesser value and the higher value; the highest probability is attributed to the average.

Results are validated throughout the process. This involves several sources, including the technical information available for depreciation mechanisms, the life cycle and the experience from a review of the literature of recognized organizations (IEEE, EPRI, CEATI) and from international conferences (IEEE PES, Jicable, other).

Results are also corroborated with IREQ's technical analyses and the judgment of experts and specialists from HQD and IREQ. The validation also integrates the experience of operating and maintenance staff.

V. CASE STUDY: POLE-MOUNTED TRANSFORMERS

5.1 Equipment in service

Transformer demographyisestablishedbased on thecomminglingofseveralsourcesofinformation:

1) Installation date ofthefirsttransformer at a givenlocation (availablesince 1986).
2) Numberofpiecesofequipmentboughtnew (since 1987).
3) Date newequipmentisreleasedfrominventory (since 2000).
4) Date a pieceofequipmentisreplaced, byinstallation date ofthefirsttransformer at thelocation (since 2000).
5) Manufacturing datesofequipmentscrapped and refurbished (since 2008).

Depending on the source, the level of confidence in the data quality may vary. It is therefore necessary to validate the demography. This validation is performed from a sampling of 4,153 transformers mounted to 2,885 poles. Fig. 4 presents the corroborated demographic data for pole-mounted transformers in 2017. The average age is 25 years. Approximately 10% are aged 40 years and over.

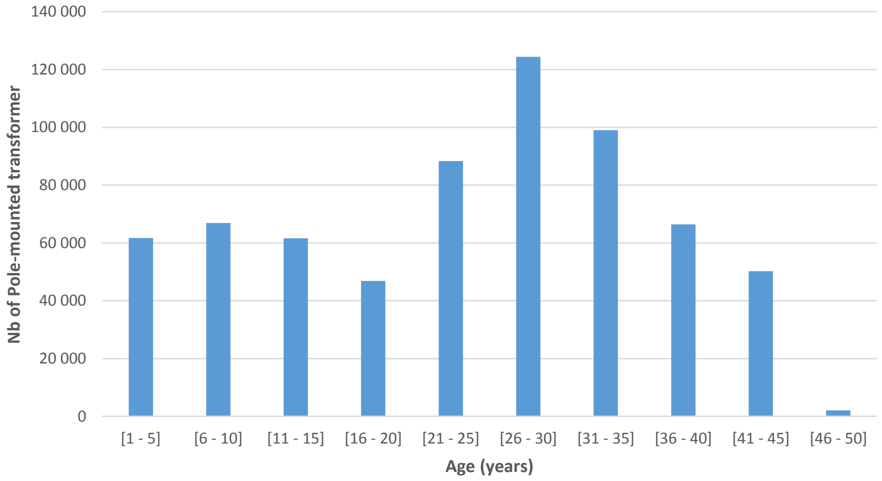

Figure 4. Demography of active pole-mounted transformers on the network

5.2 Annual replace rate

Data on scrapped equipment are obtained from companies responsible for equipment scrapping and refurbishing. These data are available for equipment scrapped or refurbished since 2008. The analysis integrates data for 60,000 transformers.

For pole-mounted transformers, the annual replacement rate is 1% of the population. Approximately 20% of the equipment withdrawn is repaired and returned to service. This may consist in a minor repair (painting the case, for example), or a major repair that is, itself, considered a refurbishment. For this study, a transformer that has undergone a major repair is considered refurbished. The refurbishment date corresponds to the new manufacturing date of the equipment.

Figure 5 presents the failure rate based on age. This rate is constant up to 30 years, at 0.85%. It corresponds to the random failure rate.

During the first 18 months, certain transformers are returned to the manufacturer under warranty. For the first 10 years, transformers in good condition are refurbished. Based on their condition, transformers under 30 years old are repaired or scrapped based on their condition. Transformers over 30 years old withdrawn from the network are scrapped.

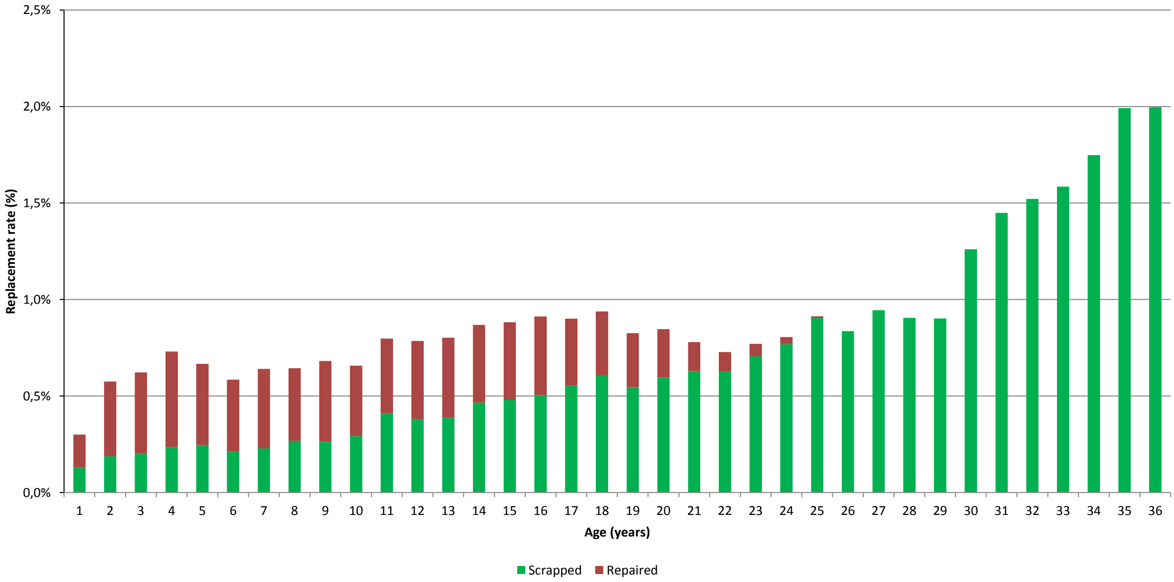

Figure 5. Replacement rate according to transformer age

5.3 *Replace causes*

The analysis of a sampling of 2,600 jobs, performed between 2000 and 2017 shows that replacement causes are largely external. The random withdrawal rate calculated with this method is 0.87%, similar to that obtained with the failure rate based on age. Fig. 6 provides the breakdown based on the principal causes.

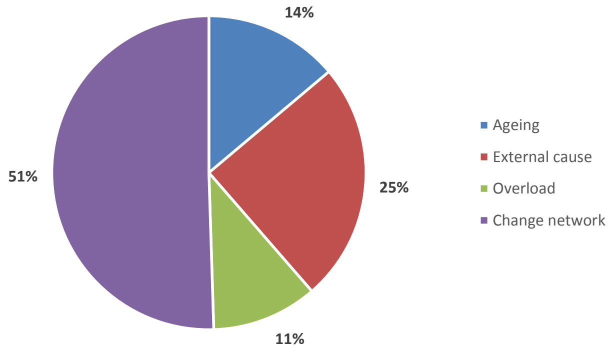

Figure 6. Distribution of transformer withdrawal causes

5.4 Estimated life cycle

The analysis integrates all the data from transformers withdrawn from the network (60,000 pieces of equipment) and from active transformers (665,000 pieces of equipment). It considers the replacement of transformers withdrawn and replaced with a new one or repaired. It also includes the addition of several thousand new transformers per year for network expansion. According to the process defined earlier, three analyses were performed:

1) Conservativelifecycle: 27 years (Table II, case1,Fig. 5).
2) Realisticlifecycle: 50 years (Table II, case 2, Fig. 6).
3) Optimisticlifecycle: 59 years (Table II, case 3, Fig. 7).

Table II: Parameters of the Weibull law, according to the case under analysis

Parameter		Case 1	Case 2	Case 3
Pop. 1	β	1.6	1.5	1.9
	θ	16.9	40.5	37.4
	γ	---	---	28.2
	%	32.4	8.6	100
Pop. 2	β	4.6	5.2	---
	θ	33.5	55.1	---
	γ	---	---	---
	%	67.6	91.3	---

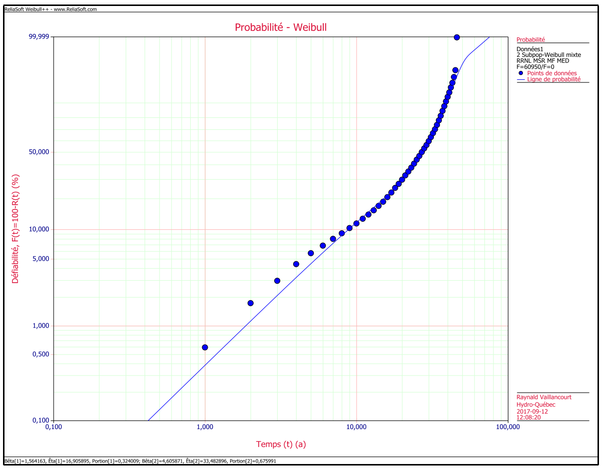

Figure 7. Weibull analysis with transformers withdrawn for external causes and ageing (Case 1)

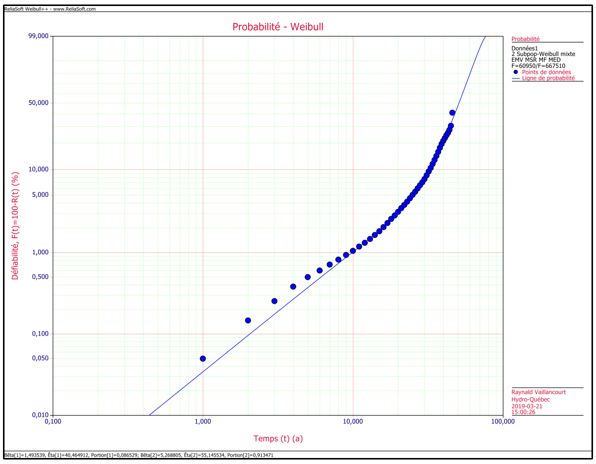

Figure 8. - Weibull analysis with transformers withdrawn for external causes and ageing and equipment active on the network (Case 2)

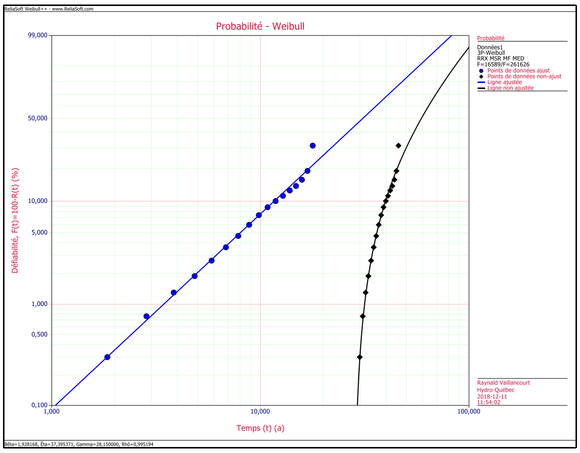

Figure 9. - Weibull analysis with transformers withdrawn for ageing and equipment active on the network (Case 3)

5.5 Validation

Published studies on transformers primarily concern power transformers. Few recent articles address the reliability or life cycle of pole-mounted distribution transformers.

IREQ conducted a study on the condition of 121 devices based on their age and demonstrated that insulation is the factor that dictates the life cycle of this equipment. The study concluded that transformers do not experience any major ageing with respect to their insulation, even after 40 years (Noirhomme et al., 2013).

A study conducted on 20 North American electrical distribution networks [4] indicates that the life cycle of transformers is assessed between 30 and 69 years, with most giving 40 years and more for this equipment.

5.6 Asset replacement costs

The average cost for replacing transformers varies between $6,100 and $18,400 depending on the number of transformers to replace simultaneously (1 to 3 transformers on the same pole). Table III presents the replacement costs for pole-mounted transformers. Costs are established based on 5,773 maintenance jobs performed between 2015 and 2017. The ratio of material costs compared to the total is provided for information purposes. The lower and higher cost is calculated with 80% confidence.

Table III: Replacement costs for pole-mounted transformers (2015-2017)

		Number of pieces of equipment			
Transformers		1	2	3	1
Poles		0	0	0	1
Costs ($ thousands)	Average	6.1	10.7	18.4	10.9
	Lower	2.8	5.1	9.8	6.4
	Higher	9.4	17.2	27.0	15.4
Material/total ratio		51%	56%	57%	33%

5.7 Future investments required

For pole-mounted transformers, equipment ageing has resulted in an increase in the number of transformer replacements from 450 to 500 units annually (Fig. 10). The cost increase is estimated at $3 million per year. This estimate is based on the ageing parameters (Table II, case 3) and on a cost of $6,100 per transformer (Table III, case with one transformer and no pole). Simulations can be performed with various combinations (Table III).

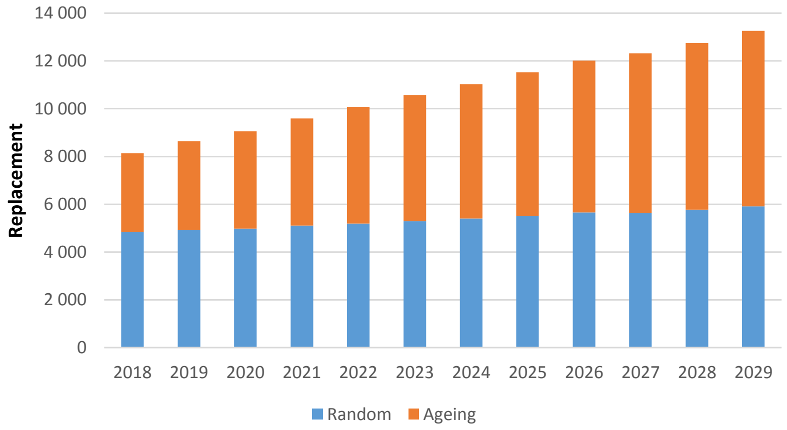

***Figure10* – Forecast of the volume of pole-mounted transformer replacement**

VI. CONCLUSIONS

The results obtained will make it possible to select replacement strategies according to the company's objective, either to optimize performance, minimize risk or optimize costs. The next step will therefore be to assess the following replacement strategies:

1) Use to failure: this strategy maximizes the asset's life cycle. It is useful when repair costs are equal to or less than the costs of other strategies or when failures are primarily due to external causes (weather events, the public, wildlife, etc.).
2) Replacement based on the observed degree of deterioration: this strategy optimizes the life cycle and the value of the asset while minimizing the possibility of an outage. It is efficient in a systematic inspection program for a network in good condition (few defects).
3) Replacement based on age: this strategy is useful when refurbishing lines without completely rebuilding. It consists in repairing defects and replacing ageing equipment on several sections. It is aimed at minimizing workforce travel and improving reliability.
4) Replacement based on targeted inspection: this approach makes it possible to optimize inspection while changing the frequency of inspections. For example, young equipment may be inspected infrequently while equipment in an aggressive saline environment requires more inspections.

The decision must consider the adequacy of limited resources with the various priorities and the following concerns:

1) The safety of the public and workers.
2) Environmental and regulatory requirements.
3) The various needs for failures, maintenance and investment projects.
4) Customer satisfaction regarding service reliability and service demands.

The main difficulty is defining customer satisfaction criteria and quantifying the associated costs.

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G. Biard, et. al."Determiningthelifecycle and futurereplacementcostofdistribution network equipment." *International Journal of Modern Engineering Research (IJMER),* vol. 10(03), 2020, pp 51-60.