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Risk based replacement policy for RTE’s Instrument Transformer (IT)

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SUMMARY

Rte has initiated a new approach to manage its asset in 2020: the risk-based analysis. The goal is to use a similar approach and methodology for all of RTE’s maintenance policies. In this article we present the risk-based asset management and its application to the Instrument Transformers (IT). The methodology relies on a 5 steps risk analysis:

1. Identification of the decision problem
2. Identification of the related hazardous event (What can go wrong?)
3. Characterization of the likelihood of the event (event frequency analysis)
4. Consequence analysis (What are the consequences if the hazardous event occurs?)
5. Search for the optimal decision (acceptable risk)

The Instrument Transformers are one of the major components (~53000 units) of RTE’s substations, they present a large amount of operational expenditure (OPEX – 14M€ per year). It is essential to update the technical policy based on this new risk-based analysis. Thus, the result of a risk analysis is not only an answer to the question « What is a risk? » but, more important, a framework for intelligent and visible risk management. However, these steps of quantitative risk analysis, which allows for the clearest and most accurate decision-making process, require informed and ordered databases.
The path taken in order to review the current IT renewal policy will be presented in the paper:

- Several questions have been addressed before starting this study (ex: is the problem related to one specific type of IT or is the entire population concerned, what is the best solution: repair or replacement of IT?
- In this paper the definition of the failure has been done for combined transformers (voltage and current transformers). Fitting a parametric distribution to the survival data requires knowledge of the time to failure or, in case of censored data, on the age of an equipment that has not yet experienced any failure within the window of observation (2010-2020 in our case).
- One of the biggest part of the study concerns the construction of a reliable database of past events on the equipment, after identifying the decision problem and the hazardous event, most of the study revolves around constructing the database of past events on the equipment. Several cross-checking from different sources were necessary.
- The identification and evaluation of the consequences of a failure are essential elements for carrying out a cost-benefit analysis and justifying the expenditure of a technical policy. The spectrum of consequences allows us to identify all the consequences following the occurrence of failure: an additional emergency replacement cost, non-evacuated energy, undistributed energy, etc.

Concatenation of above analysis allows us to optimize the age of replacement for each asset, depending on the data collected and the valuation of the consequences.

KEYWORDS

Instrument Transformer - Risk based policy - Oil - Paper - IT Failure - Reliability – Risk analysis

1. CONTEXT

The substation department of the National Center for Grid Expertise (CNER) of RTE ensures the specification, qualification and monitoring of the Instrument Transformers (IT) and establishes policies for the renewal and maintenance of this high voltage equipment. Currently, the IT's replacement policy is established based on the PCB[1] pollution, on the risk of failure during high temperature seasons and mainly on the age of the Instrument Transformers. The robustness of the existing replacement policy is well proven. However, RTE wishes to anticipate the response to new challenges: on the one hand, the CRE's[2] request for the establishment of auditable policies, and on the other hand, the desire to have a common "**Risk-based**" method to build the various asset management strategies. For this purpose, CNER worked with the R&D teams on this project. The objective is to support asset managers in setting up technical policies, using the principles of quantitative risk analysis. It allows a framework for making and implementing decisions that seek an optimal balance between the performance, costs and risks associated with the use of assets to achieve an organisation's strategic objectives.

To reach this purpose a large amount of work on data quality has been carried out over the period 2010-2020. Thus, in this paper we present the quantitative risk analysis framework and its application to the IT maintenance policy. Special attention is paid to data quality. The paper is organized according to the five steps of quantitative risk analysis

2. IDENTIFICATION OF THE DECISION PROBLEM

The purpose is to identify a risk mitigating solution. Different solutions can be brought (preventive replacement by age, conditional replacement, failures inspection) and they lead to different quantities to be optimized (age of replacement, warning threshold of an indicator, inspections dates).
The decision problem in our study is to find the optimal age of preventive replacement of each category of IT in order to control the risk associated with equipment subject to failure with damaging consequences. Hence it is possible to determine in financial and human resources.

3. DEFINITION OF HAZARDOUS EVENT FOR EACH CATEGORY OF IT

One of the primary tasks in this study is the qualification of hazardous events which is characterized by the dismantling of the equipment. The likelihood of failure is the probability distribution of time between the installation of the equipment on the network and its hazardous event failure. It is therefore necessary to determine the date of commissioning of each asset and its current state. **This information is at the heart of the survival analysis and must be as precise as possible.**

Collecting the relevant data has required a real archaeology of the data, as described in the next paragraph. The occurrence of the failure is deduced from the nature of damage (or the absence of damage) and the evolution of the status of the asset which are collected each year within our database. For each piece of equipment in operation over 2010-2020, the target database must present exactly **one observation**:

- If it has not been scrapped, the lifetime of the asset is its current age
- If it has been scrapped, for whatever reason, the asset is no longer observed and the date of the IT decommissioning is used to compute its lifetime.

The work to be done mainly lies in the creation of the Entry, Time and Event variables. Before qualifying the hazardous event, it is necessary to clarify the **notion of damage.** Several damage categories were defined based on IT knowledge, then each damage was classified using a keyword search:

  - Destruction (destruction, explosion, internal failure, etc.)

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[1] Polychlorinated biphenyl

[2] French Energy Regulatory Commission

- Oil damage (leakage, over or under pressure of oil according to oil indicator, etc.)
- Structural damage (over increase of oil compensation device, insulator or flange broken, etc.)
- Electrical damage (ANO TCT / U, voltage drift, etc.)
- Accessory damage (noise, hot spot, short circuit, etc.)
- Storage / handling damage (assembly problem, storage problem, etc.)

Unclassified reported anomalies are, after verification, not considered as damage. The date of the scrapped IT and the nature of the anomaly are sufficient information to determine whether a piece of equipment has experienced a failure or not.

4. DATA COLLECTION

4.1. STRUCTURING DATA FOR RISK ANALYSIS

Data collection needs to be carried out rigorously, in particular to take into account possible censoring and truncation biases.

Censoring bias: the random variable whose distribution we wish to know is the time between the installation of the equipment on the network and the hazardous event. When an asset has failed, the information about this time for this asset is complete. However, when the equipment is still on the network at the time of the study or when it has been preventively replaced, we do not know when it will experience or would have experienced the hazardous event. But we still have an information about the time to event: the time is greater than the age of the equipment when the study is done or the equipment age was when it was preventively replaced. This is what we call a censored data and not taking it into account can lead to bias on the estimation of the ageing form.

Truncation bias: The digitisation of information on equipment failures can only be traced back to 2010. Thus, all equipment that failed before this date cannot be taken into account. The recorded data therefore tends to extend the life of the equipment since we do not have information on those that would have failed earlier. This is known as truncation bias and must be properly accounted for in the likelihood of the hazardous event. If it is not included, it could shift the survival law to overestimate the life expectancy.

To distinguish between failed assets, a simple numeral code is used: an ‘event’ is either 1 (failed asset) or 0 (replaced or currently-in-use asset). Since the window of observation for the study is from 2010 to 2020, whereas substations have been in operation for decades, failures and replacement before that time have not been recorded. To account for this truncated data, the age of the surviving assets at their entry in the study is included in the data field ‘entry’. Most of the available data is left-truncated (LT) meaning their age at entry is not 0. The database contains three variables for the survival analysis:

- Entry: The age of the equipment at the start of the observation period (2010)
- Time: The age of the equipment at the end of the observation period or when it is scrapped
- Event: Did the equipment experience the dreaded event during the observation period? Yes (1), No (0).

4.2.CONSTRUCTION OF A RELIABLE DATABASE FOR INSTRUMENT TRANSFORMERS

At this stage, the aim is to prepare the data for a survival analysis. As part of its missions, CNER collects and archives the information (anomaly, high voltage damage) occurring on the ITs. Currently, this data is fed back by the teams during periodic substation visits (control, maintenance, and repairs), the Daily Event Reports (RJE) and seven maintenance centers feedback. This database is not exhaustive, because it contains only the damages for which CNER has been called upon, but this corresponds to at least half of the damage that led to the scrapping of equipment (destruction, repairs, and preventive replacements).

The target database lists all the equipment that has experienced an anomaly reported and also includes equipment that has not suffered any damage or the damage of which has not been reported. The first step is to establish the structure of the target database. The most important information which will allow us to perform survival analysis has been collected: category and model of the IT (CT, VT, combined, CVT, …), suppliers, date of fabrication and commissioning, serial number, phase number, date and time of the failure, substation, localisation of the IT (line, busbar..), Equipment number[3], nature of the anomaly, oil reference, estimated replacement date by IT policy. To obtain the information needed for the study, several difficulties had to be overcome: **multiple sources**, **multiplicity of formats**, **heterogeneity of data, access to data**, etc.

Multiple databases:

- Asset manager's database: which collect the information related to the failure/anomaly of the equipment reported. These files contain technical information on the damaged equipment, the follow-up to discussions by emails, the results of all analyses and examination of failure. This information must make it possible to find at least: nature of the damage, damaged equipment, number, phase, substation and the location of the equipment, but these are not the only data that interest RTE.
- Daily event reported by dispatching teams: allows you to retrieve the dates and times of events, as well as contextual information (undistributed energy for example).
- Damage / event notice emitted by maintenance teams: when an anomaly is detected, a ticket is supposed to be opened and then validated for processing (description, start date, end date, cause of the failure or anomaly …).

Multiplicity of formats: the multiplicity of formats, sometimes for the same information, complicates data retrieval. Equipment files are generally saved in .pdf format, but sometimes they are an image, or a PDF containing an image of the information. However, a PDF in vector format (structured information, automated retrieval) and a PDF containing an image (unstructured information) cannot be processed in the same way.

Heterogeneity of data: The information reported varies widely from one case to another. Some files contain geographic information, email tracking, technical documents and references for equipment, analysis results and event conclusions, others do not contain any information.

The balance between the automation of information retrieval and manual retrieval was one of the challenges of this work. The whole could not be automated[4], and when possible, significant time savings were expected. However, this was not obvious because of the strong heterogeneity of the data, which causes the codes to become more complex. Figure 1 shows the evolution of the equipment number after assessment of missing data and implementation of data recovery methodologies.

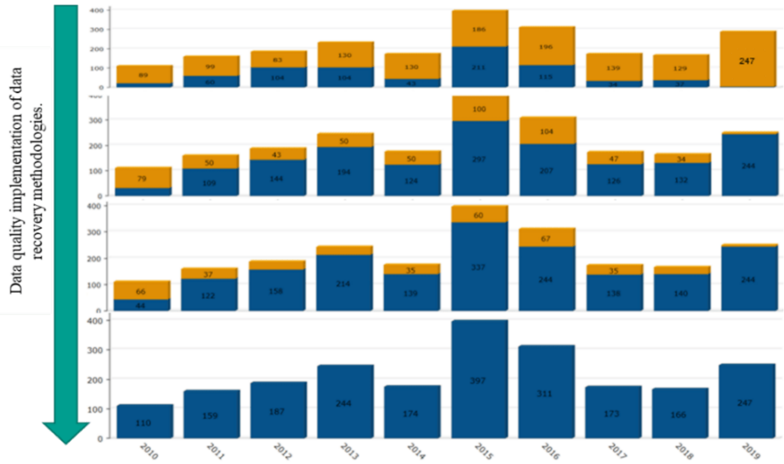

Figure 1.Assessment of missing data and implementation of data recovery methodologies (blue: known data, orange: unknown data).

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[3] : unique number of the equipment, associated with the place of operation

[4] R: programming language for statistical computing and graphics.

5. IDEFINITION OF THE THREE VARIABLES FOR THE SURVIVAL ANALYSIS

The risk analysis study requires knowing the previous life of each IT in order to evaluate its probability of failure and its consequences on the network. This work has enabled RTE to set up a reliable database on all the event that have occurred on the Instrument Transformer since 2010. The flowchart Figure 2 (hazardous events) describes the method for detecting hazardous events, according to the definitions adopted. The key points here are the evolution of the status of the asset (reception on site, commissioning, uncommissioning…) and the association of this change with an event on the network. This procedure is specific to the ITs, but can be generalized to the other types of equipment.

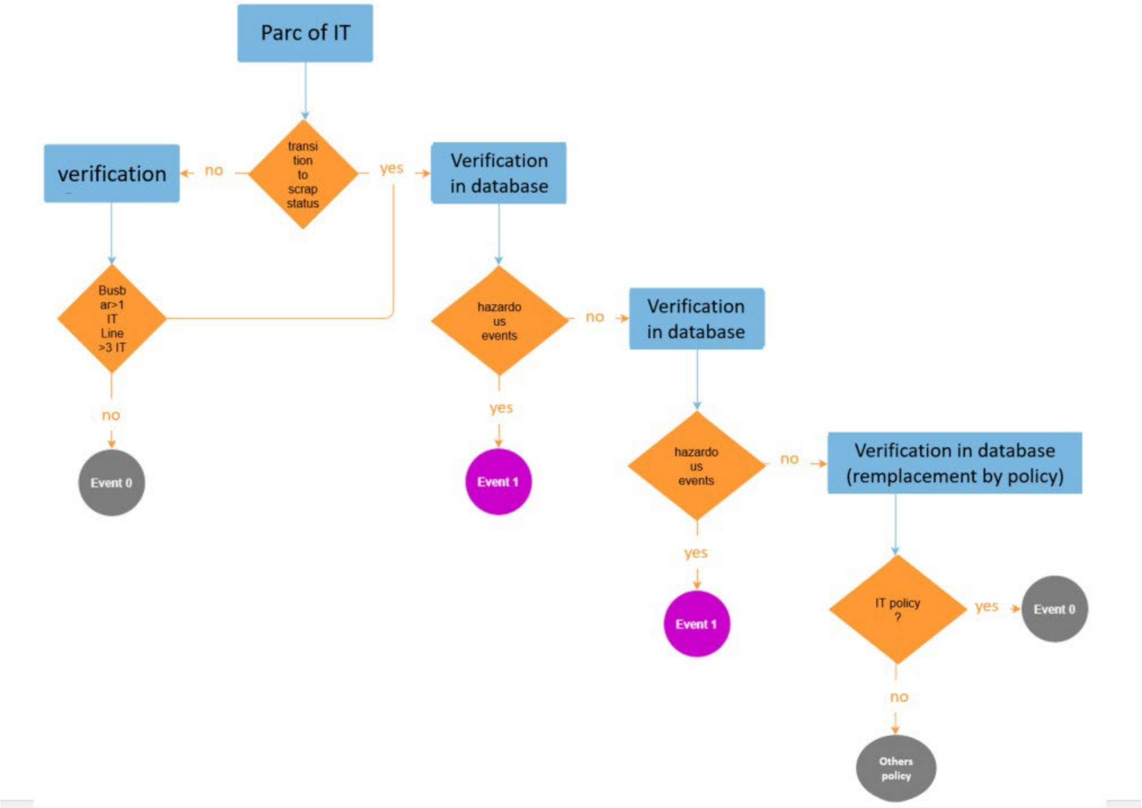

Figure 2: Complement to identification of hazardous event flowchart.

This database contains all the damage reported to the CNER as well as the background elements necessary for their understanding and resolution. This database has been improved and it now includes all IT information since 2010.

6. SURVIVAL ANALYSIS ON THE COMBINED TRANSFORMERS

6.1. Survival function

Characterizing the likelihood of the event consists in defining the probability distribution of the time between the installation of the equipment on the network and the hazardous event, and its parameters. Different probability distributions can be used such as Weibull, Gompertz or exponential, which model different kinds of ageing [4]. Their parameters are estimated by maximizing the statistical likelihood of the collected data. Once the parameters of the distribution are determined, it becomes easy to derive the survival function S that gives us the hazardous event likelihood.

$$S(t; l)=e^{-lt} \qquad \text{(1) Exponential law}$$

$$S(t;\alpha,l)= e^{-(lt)^{\alpha}} \qquad \text{(2) Weibull law}$$

$$S(t;\alpha, l) = e\,(-\alpha(e^{lt}-1)) \qquad \text{(3) Gompertz law}$$

With α and l the function parameters to be estimated. We also use the non-parametric estimation of the survival function [1]. In this model, there is no assumption about the form of the distribution, which results in a flexible survival function that can fit the data specificity. However, it does not allow us to project beyond the ages contained in the dataset, which is essential for our final application. We use it to validate the hypothesis about the shape of the parametric function. We complete this validation by using the AIC criteria used for model selection [2].

The results for the Combined Transformers (Current and Voltage Transformers) are given in Figure 3 and Figure 4. In the Figure 4 only the EJ33 model are represented and in the Figure 3 all the other CT. Particular attention has been paid to the EJ33s because they have repeatedly failed in the summers of 2005 to 2015. One can see both the non-parametric (Kaplan-Meier) and parametric (Gompertz) models. The x-axis represents the age of the combined transformer and the y-axis represent the probability of surviving beyond this age. For example, if we put 100 new CTs at the same time on the grid, 83 years after, 50 will have encountered their hazardous event. One can see a very good agreement between the non-parametric estimation of the survival function (Kaplan-Meier) and the assumption of the parametrical Gompertz shape.

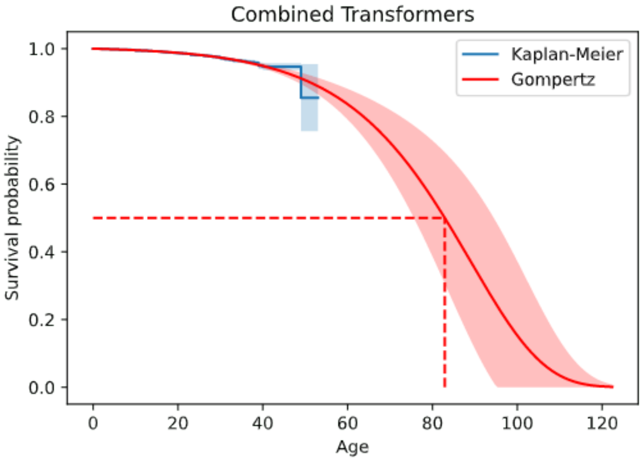

Figure 3: survival function for combined transformers (without the EJ33 model). The red dashed lines indicate the age at which half of the assets experienced their hazardous event

In the Figure 4 one can see the non-parametric estimation of the survival function for the EJ33 model of combined transformers. The curve seems to represent different types of ageing. A first rapid ageing from 0 to 10 years and a second slower one after 10 years. It is then necessary to deepen the analysis in order to verify that there are no hidden variables that would explain this superposition of ageing.

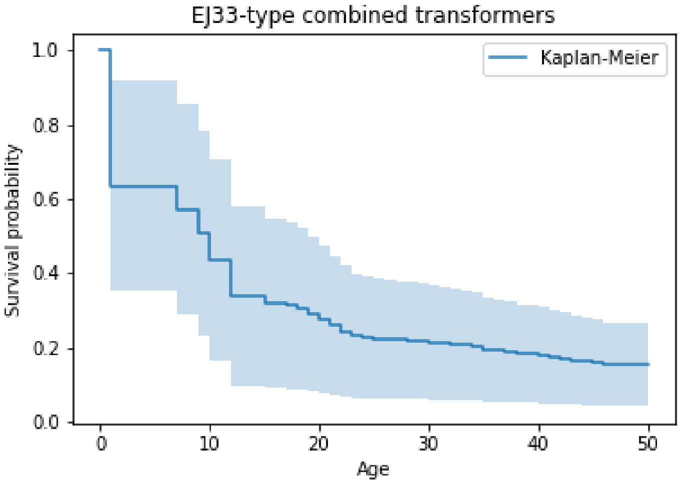

Figure 4 : Non-parametric estimation of the survival function for the EJ33 model of combined transformers.

6.2. Covariates

As we just saw, ageing models give the probability of failure as a function of the equipment age, but external factor such as weather pollutants or internal factors such as technology or materials can accelerate the ageing process. It is then necessary to take into account those covariates. To achieve this, the mechanisms of equipment destruction, and accumulation effects that can lead to it, must be precisely identified. The main causes of material destruction are breakdown due to too high undissolved water in the oil. Therefore, covariates that can lead to water accumulation have been studied: relative humidity, precipitation, pollutants that can accelerate corrosion. As well as the internal variables, oil type and oil compensation device technology.

As seen in the previous part, the univariate analysis of the EJ33 combined transformers “Current and Voltage transformers” leads to a superposition of different kind of ageing. Figure 5 shows the different survival function for the relevant covariates affecting EJ33 ageing. The analysis showed that the combination of the Shell diala D oil and the polyurethane bellow (top right) is the worst. Indeed, by the age of 20, less than 25% of the asset population is still alive, meaning that those materials have a pathological behavior. This result reflects the wave of failures that have occurred in the summers of 2005 to 2015. We also saw during this period a lot of equipment with Shell diala oil and neoprene bellow failing. This is reflected in the accelerated ageing around 30 years in their survival function in Figure 5 top left. The two others type of oil (Nynas nitro 4000a et Esso u64) have a behavior closer to what is expected for an IT, with at least 75% of the asset without hazardous event at 40 years.

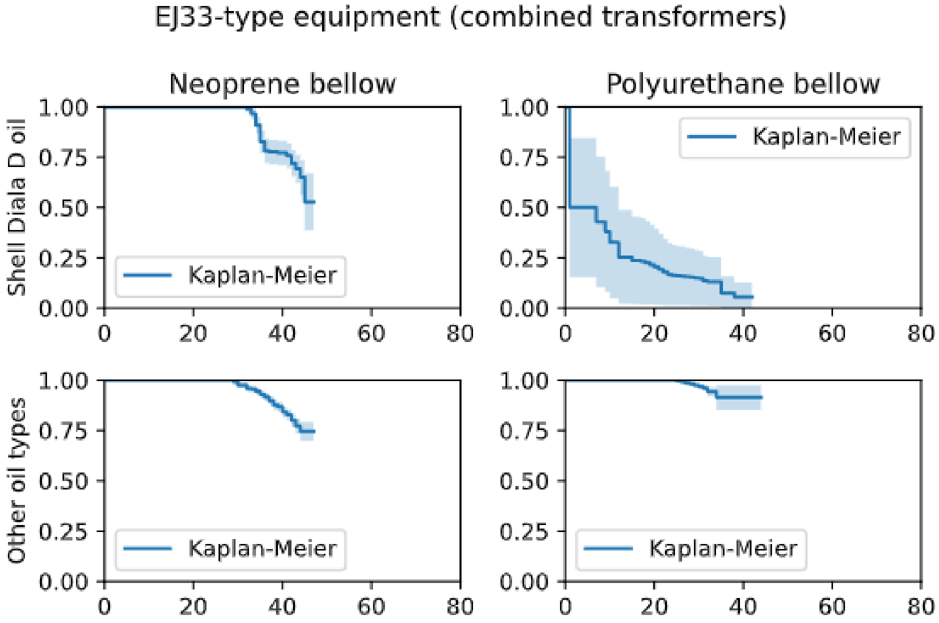

Figure 5: Kaplan-Meier curves for Combined Transformer (EJ33) taking the covariates into account.

We have seen how the material reliability study determined the ageing process of the material. The inclusion of covariates has allowed us to refine the models and to identify materials that age more rapidly. However, the optimal replacement age also depends on the consequences. Two equipment with the same type of ageing but with different consequences of failure would not have the same optimal replacement age. To protect oneself from the consequences, one will renew at a higher frequency an equipment whose consequences of a failure are more important.

7. IDENTIFICATION AND EVALUATION OF THE CONSEQUENCES OF FAILURE

It is first necessary to identify all the consequences following a failure (spectrum of consequences) by distinguishing, on the one hand, the replacement constraints after failure which imply additional costs and, on the other hand, the consequences on the three strategic challenges of the company (Operation, Environment and Safety of third parties), see Figure 5.

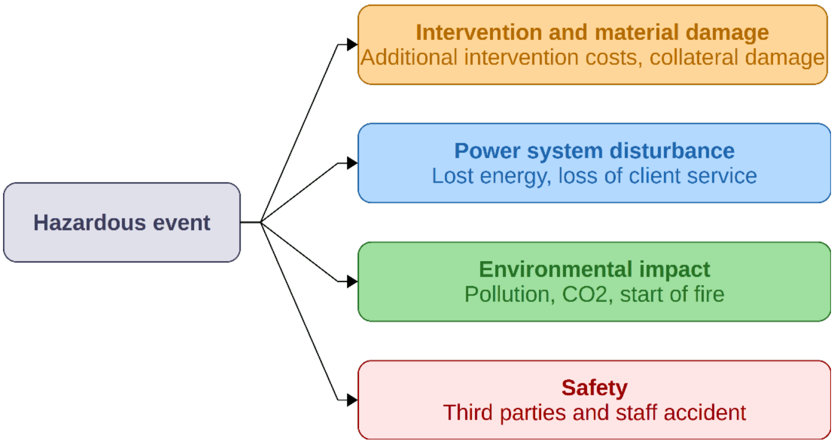

Figure 6: Identification of the consequences and strategic challenges of the company.

The assessment of the consequences of a failure takes into account the real additional costs of a maintenance operation as well as the collective costs related to the issues identified by each TSO (Operation, Environment, Safety). At RTE, these values are mentioned in a repository of the consequences, which guarantees the transparency and consistency of decisions. The results of the optimization for each asset depend on the data collected on the failures (type of equipment failure and its location in the network) and the assumptions made on the **valuation of the consequences**.

Some types of equipment failure can cause great harm to nearby company staff, as in the case of EJ33 failure. Ensuring the safety of operators weighs on the crafting of the policy. It is possible to account for it by using government-sanctioned studies that attribute an economic value to human life, based on [3]. It is then combined to the probability of having an operator working in the substation at any given time to produce a value for each asset.

8. OPTIMAL REPLACEMENT POLICY

The optimal replacement age of an equipment depends on its type of ageing and the valuation of the consequences on failure. Equipment that is renewed too often costs too much in terms of maintenance policy, and equipment that is not renewed often enough costs too much in terms of consequences. A balance must therefore be found between the probability of failure and the consequences. Different cost functions can then be derived depending on the decision horizon time [5]. When the function that the asset plays on the network is not intended to be stopped the decision horizon time can be assessed as infinite. When it is a patch for an equipment identified as pathological one can consider a one-cycle replacement policy. The expected equivalent annual cost function is an example of the cost function to be minimized for an infinite decision horizon time:

$$C(a) = \frac{c_f\, F(a) + c_p\, S(a)}{MTBR(a)} \qquad \text{(4) cost function}$$

This equation contains all the steps of the risk analysis. We optimize an age for a preventive replacement (step 1 and 2). C_f is the cost of a renewal after a failure (step 4). C_p is the cost of a preventive replacement. S(a) is the survival function (step 3). F(a) = 1-S(a) (step 3). MTBR(a), is the mean time between replacement and depend on the survival function (step 3).

The renewal of the pathological EJ33s must be considered as a corrective replacement. In fact, the entire fleet has to be replaced by new equipment whose ageing cannot be considered as close to the previous one. For all the other IT, the ageing of the renewed equipment can be considered similar or close. As the equipment function on the network is not expected to cease, it can be considered that it will be renewed over an infinite time horizon.

The evolution of the expected policy cost as a function of the replacement age of the EJ33 fleet can be seen in Figure 7 and Figure 8. The optimum is reached at the minimum of this function. In Figure 7 only the type of law changes and in Figure 8 only the consequences change. Thus, we can see that the more important the consequences are, the smaller the optimal replacement age is; and the faster the ageing, the smaller the optimal replacement age is.

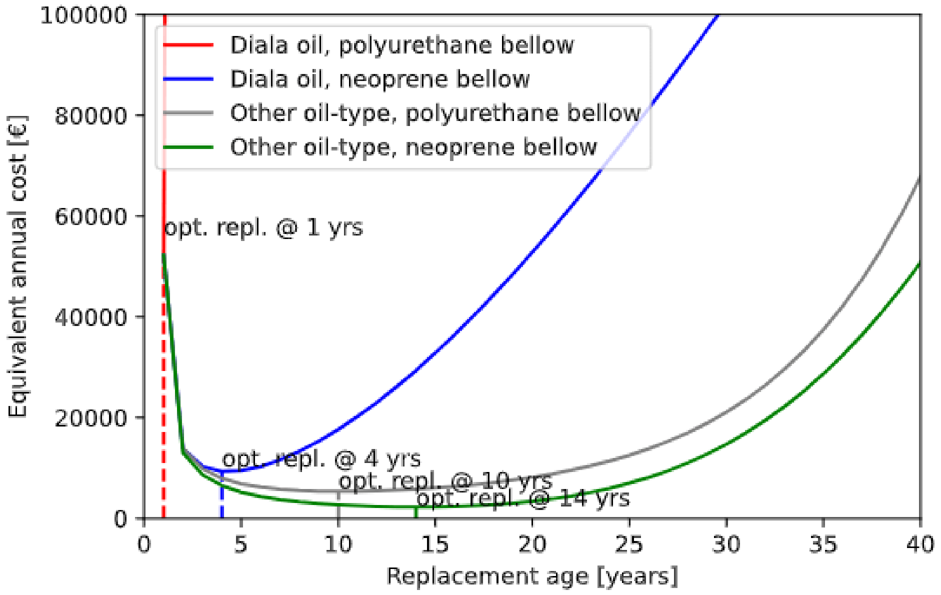

Figure 7: Equivalent annual cost for combined transformers EJ33 with 10M€ for the consequences.

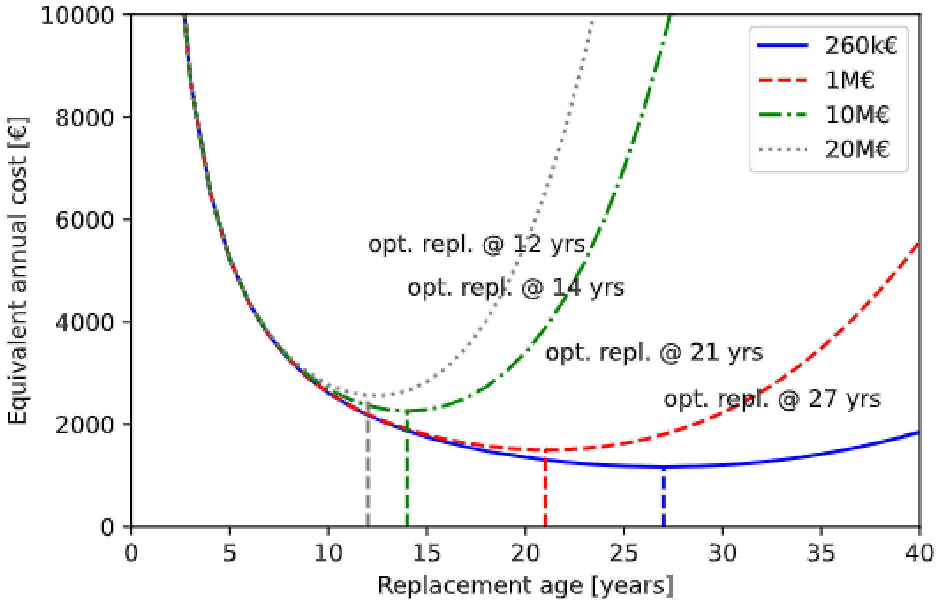

Figure 8: Equivalent annual cost of the policy as a function of replacement age for a combined transformer with different costs of consequences.

One can also notice that the optimal age for the very pathologic instrument transformers (EJ33 with Shell diala D oil & polyurethane bellow) the optimal age found is 1 year. This means that we should not install any pathological material on the network.

9. CONCLUSIONS

We have seen how to implement a risk-based policy by following the five steps of quantitative risk analysis. From the definition of the decision problem and the hazardous event, one can identify the data needed to construct the likelihood of the feared event. Data collection needs to be carried out rigorously, in particular to take into account possible censoring and truncation biases. By applying the theory of survival analysis one can then establish the survival function of the material that allows the probabilization of the occurrence of the hazardous event as a function of age. We have seen how taking into account covariates allows us to refine the survival functions and identify pathological equipment. For the policy to be risk-based, the consequences of a failure must also be taken into account. This is why the fourth step consists in evaluating the consequences of a failure in terms of network operation, environment and safety. Finally, once the failure law has been established and all the consequences have been evaluated, the cost function can be minimized to find the balance between preventive renewal and consequences.

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