INTERPRETATION OF STATISTICAL ANALYIS OF LV CABLE CONDITION

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ABSTRACT

In order to maintain a reliable LV distribution grid (an important building block in the energy transition) DSOs are looking into ways to investigate the condition of LV grid components. A survival analysis method – Cox Proportional Hazard regression – was used to investigate relations between variables and the failure probability of LV cables and joints. In this paper the results of this approach are interpreted. The results provide much insight and can be explained by experts and are supported by experts in the electricity distribution sector. The results can be used to rank individual assets on a relative failure probability, which is based on the values of the aforementioned variables. This study is a first step towards improved asset management strategies.

INTRODUCTION

Within the ongoing energy transition Low Voltage (LV) grids will become an even more crucial part in electricity distribution grids. Technologies such as electric heat pumps, electric vehicles and solar PV panels require a reliable electricity grid. Both generation and production will increase on LV level, resulting in increasing and fluctuating power flows.

The average interruption duration of underground LV grids in the Netherlands is generally well below limit [1]. However with most components ageing, DSOs (Distribution System Operators) want to know whether the current high reliability level can be maintained.

Financial aspects also play a role in the increased interest in LV grids and components. A typical interruption on LV level will cost less than on higher voltage levels. Also the consequences for the average interruption duration is generally lower (i.e. lower costs). However, due to the large amount of LV components, the total amount of interruptions on LV level is higher than on other voltage levels. Therefore the total costs of all LV interruptions add up to a significant amount – around €50-100M yearly for all DSOs in the Netherlands.

Currently only corrective maintenance is performed for underground LV assets. This is the most straightforward way of maintaining assets: repair or replace a component when it has failed. In order to reduce costs associated with interruptions and to gain more insight in the condition of assets (cables and joints) more information is required.

One of the ways to obtain this information is the combined use of historical data, asset data and environmental data. The following section will provide some background of the study. Thereafter the method is shortly introduced. This method attempts to assess the condition of LV cables (cables and joints), where the main topic of interest in this paper is the resulting relations found in the data sample. These relations will be presented and discussed in the results. These results will provide insight in failure mechanisms and condition estimates of LV assets. Finally a conclusion is drawn.

BACKGROUND

The first subsection will shortly describe the problem and the goal of this study. Subsequently the limitations which complicate the analysis are described. Finally some previous research is discussed.

Problem description and goal

As aforementioned the goal of DSOs is to obtain condition information of LV assets with the use of historical data, asset data and environmental data. More specifically, the problem can be described as a survival analysis. Ideally we would be interested in the exact time-to-event (here: time-to-failure). However due to some limitations – further explained in the following sub-section – predicting the exact time-to-event is a bridge too far. Therefore we focus on the relations between various covariates and the failure of LV cables and joints. In this paper we will present and explain these relations.

Limitations

Condition assessment of LV cables and joints is not a straightforward reliability study, because of some circumstances in this study. These are shortly described here, more can be found in [2].

First of all relatively few LV components actually fail (less than 0.2% per year). Therefore predictive models will most likely be biased towards the assets which do not fail – they will predict too few failures.

Another possible source of biasing is the fact that the dataset is right-censored and left-truncated. Right-censoring happens when analysing the survival of assets while a part of the assets is still functioning at the end of the observation window. Left-truncation happens when (older) assets have already failed before entering the dataset, which is the case when assets fail and are replaced before registration in the dataset started. Both phenomena may lead to bias.

Furthermore LV cables hardly exhibit internal degradation [2]. Most of the time LV cables fail due to excavation damage, either directly or indirectly. Indirect failure from excavation damage is caused by damages which develop into larger defects which finally cause failure of the cable. Monitoring or large-scale measuring is practically and economically not possible on LV level. The LV distribution grids are difficult to measure [3] and the vast amount of components will result in very high costs for large-scale measurements. Visual inspection is not possible due to the fact that almost all LV assets are located underground in the Netherlands.

The current situation regarding interruptions of LV cables and joints is thus best described as: a low-failure, right-censored, left-truncated, non-monitorable asset base. In this paper this asset base will be analysed in a survival analysis based on historical, environmental and asset data.

Previous research

In [3] a start was made with the investigation of failure mechanisms in LV cables and joints, and some first steps were made towards diagnostics. One of the most important conclusions in this study is that LV cables hardly degrade internally. Most failures originate from excavation damages, both direct and indirect.

This is further investigated in [4], where it is also shown that LV failures are generally not age-related. Therefore it is important to focus on other covariates which may predict a higher failure probability.

In [5] various methods are compared for the survival analysis of LV cables and joints. The Cox Proportional Hazard model turned out to be the best suitable method. This method is thus used in [6] where an overview is given of the complete condition assessment analysis of LV cables and joints. The prediction power of the models is average at best, therefore predicting the exact time-to-failure is not possible. However, the resulting models contain much information on relations between covariates and failure probability. These relations provide insight in failure mechanisms. In addition, although the exact moment of failure cannot be predicted, LV cables and joints can be ranked on failure probability based on the values of the covariates.

Where the previous publications [3-6] mainly focus on the method, this paper will focus more on the results of the survival analysis. The following section will shortly present the method, thereafter the results are presented.

METHOD

As aforementioned the problem in this study is analysed with a survival analysis. This analysis is performed with the use of the Cox Proportional Hazard (CPH) model [7]. In this section CPH is described.

The CPH model

CPH is a semi-parametric survival model, which is described by the hazard function, which is shown in equation 1.

$$h(t) = h_0(t) \times e^{(b_1x_1+b_2x_2+...+b_px_p)} \qquad (1)$$

A baseline hazard $h_0(t)$ is constructed from the survival data supplied to the model. This hazard is non-parametric as it only needs the data to be constructed.

The influence of the covariate values x_p is captured in the exponential part of the equation. The coefficients b_p denote the direction and size of the change in hazard. The values of the covariates of one LV cable thus produce an estimate of the failure probability of that cable.

Assuming proportionality

The resulting CPH models have to meet the proportionality assumption. This means that the effects of the covariates have to be multiplicative to the hazard rate – the effect of a covariate is to multiply the hazard by some constant. When they are multiplicative, the hazard rate of each of the observations is proportional to the baseline hazard.

Not every covariate will meet this proportionality assumption. In this case this covariate can be treated as a stratification variable (strata). When a strata is used, the hazard function is calculated for every value of the covariate. In this way the difference in survival probability between the values can be visually inspected.

Outcomes

In this study various outcome measures are important to evaluate. In the table I-III the resulting parameters related to the covariates are displayed. The value *Exp(coef)* is the exponential value of the coefficient. A value larger than 1 means an increase in hazard rate, a value smaller than 1 means a decrease in hazard rate. The *Lower .95* and *Upper .95* are the lower and upper boundaries of the confidence interval. The value *Pr(>|z|)* represents the significance of the covariate, where a value smaller than 0.05 means that the covariate has a significant influence. For stratified variables the outcomes are visually inspected.

Variables

The following variables are included as covariates in this study, with the reference value in italics:

- Soil type – *Buildings etc.*
- Former DSO (the current DSOs in the Netherlands originate from multiple former DSOs) – *DSO A*
- Construction – *GPLK*
- Excavation Notices (number of registered excavation actions in area of cable) – *0*
- Number of Interruptions Main Cable (number of interruptions in components connected to the corresponding main cable) – *0*
- Conductor Material (material used for conductor) – *Copper*
- Type of Joint – *Service Joint*

TABLE I. RESULTING MODEL PARAMETERS OF MAIN CABLE MODEL

Covariate	**Exp(coef)**	**Lower .95**	**Upper .95**	**Pr (>|z|)**
Soiltype: Light Clay	2.09	1.70	2.56	$9.1e^{-6}$
Soiltype: Peat	1.65	1.34	2.04	0.0042
Soiltype: Water	1.94	1.25	3.03	0.022
Soiltype: Heavy clay	1.41	1.09	1.82	0.046
Soiltype: Heavy sabulous clay	1.28	1.07	1.53	0.005
Number of interruptions main cable	1.50	1.44	1.55	$<2e^{-16}$
Number of excavation notices main cable	0.98	0.98	0.99	$<2e^{-16}$
Concordance	0.67			
R^2	0.093			

Other variables – such as length of a cable or total precipitation – were considered, however they were either not of significant influence or the quality of the data was not of the required level.

More on the method can be found in [6] and [5]. This method is used on three types of LV cable components: the main cables, the service cables and the joints. In the following section the resulting models and the relations found in these models are presented in detail.

RESULTS

In this section we will present the relations found in the models. For each covariate a sub-section is used, where the relation between covariate and failure is presented. The results have been discussed with experts on LV cables and joints and the explanations that are given in this section are formulated together with them.

Number of interruptions main cable

This covariate represents the number of interruptions reported in components connected to the same main cable. It is the most important covariate in the study. A CPH model with only this variable as covariate performs almost as good as the final model. Also in decision-tree based methods it comes out as most important in variable importance calculation methods.

TABLE II. RESULTING MODEL PARAMETERS JOINTS MODEL

Covariate	**Exp(coef)**	**Lower .95**	**Upper .95**	**Pr (>|z|)**
Soiltype: Light sabulous clay	0.70	0.53	0.93	0.015
Soiltype: Nutty on sand	0.19	0.05	0.77	0.020
Soiltype: Water	1.98	1.27	3.08	0.0027
Soiltype: Sand	0.53	0.45	0.63	$7.24e^{-13}$
Soiltype: Heavy sabulous clay	0.52	0.40	0.69	$3.76e^{-6}$
Number of interruptions main cable	1.43	1.37	1.48	$<2e^{-16}$
Joint type: Branch/End	1.56	1.20	2.04	0.0012
Joint type: Branch	1.21	1.02	1.44	0.030
Joint type: End	1.87	1.59	2.20	$6.32e^{-14}$
Joint type: Cable	1.65	1.45	1.87	$6.88e^{-15}$
Concordance	0.67			
R^2	0.091			

TABLE III. RESULTING MODEL PARAMETERS SERVICE CABLE MODEL

Covariate	**Exp(coef)**	**Lower .95**	**Upper .95**	**Pr (>|z|)**
Conductor Material: Copper	1.74	1.46	2.08	$<2e^{-16}$
Conductor Material: Unknown	1.50	0.96	2.36	0.00021
Number of interruptions main cable	1.42	1.37	1.48	$<2e^{-16}$
Number of excavation notices main cable	0.984	0.981	0.986	$<2e^{-16}$
Concordance	0.67			
R^2	0.088			

In table I, II and III it can be seen that the coefficient *Exp(coef)* is similar for all three types of components (1.42-1.50). A higher number of interruptions in components connected to the main cable results in a higher hazard – a higher failure probability for components connected to that main cable.

This can be explained by three phenomena. Firstly, a high number of interruptions may indicate a bad condition of the grid. Secondly, with each interruption a short circuit current may run which can damage components – leading to extra failures. Thirdly, the measurements to find the fault location in LV grids may use high currents which damage components.

Number of excavation notices

In table I and III it can be seen that the number of excavation notices in the area of the main cable to which the component is connected to, does not have a large influence on the hazard rate – with the coefficient almost equal to 1. The stratification plot for the joints model was not included as no relation could be derived from the plot. One would expect that the number of excavation notices in an area would increase the failure probability. Excavation notices are mandatory for contractors when performing excavation work. However to make sure they include everything in the excavation notices, they often include an area which is too large and inaccurate. This data is used in this study and therefore no clear increase in failure probability can be found.

Soil type

In table I and II the coefficients for the main cable and joint model can be seen. In figure 1 the stratified soil type for the service cable model can be seen. Each line represents the survival probability over time for each category of the covariate.

In all models, the soil type *Water* – which represents components located close or in water objects as ditches or ponds – increase the hazard rate, which is in line with the known relation between electrical components and water.

The reference category is *Buildings etc.* which denotes the built environment. In the main cable models *Buildings etc.*

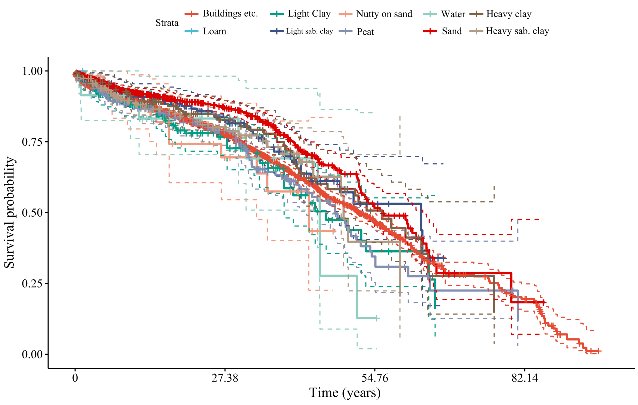

Figure 1: Survival plot of the CPH model for service cables, stratified for the variable *Soil type*

has a lower hazard rate than the other soil types. In the joints model *Buildings etc.* has a higher hazard rate than the other soil types – excluding water. In the service cable model *Buildings etc.* has one of the highest hazard rates (lowest survival probability), as can be seen in figure 1.

There is no clear explanation for these relations. Cable segments in the urban area are shorter, therefore relatively less main cables may fail than in other soil types – this could be further investigated by analysing cables per km. Also the density of joints and service cables is higher in urban areas, so more components are affected by short circuit currents. Therefore joints and service cables may have a higher failure probability in urban areas.

Former DSO

Due to page limits the plots for the former DSO are not published in this paper. However some conclusions from the stratification models can be drawn. One former DSO has the highest failure probability for each of the component types, another former DSO has the lowest failure probability for each of the component types.

This can be explained by a range of factors: installation practices, environmental factors, use of the grids, components used, etc.

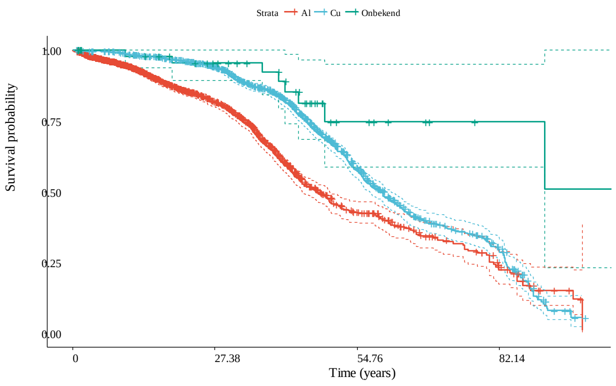

Figure 2: Survival plot of the CPH model for main cables, stratified for the variable *Conductor material*

Conductor material

Conductor material is a covariate in the service and main cable models. The reference value is *Aluminium*. The relations can be seen in table III and figure 2. For service cables *Aluminium* has the highest survival probability, for main cables *Copper*. According to [8] aluminium conductor cables should have a lower survival probability, because of severe corrosion originating from small defects. This is the case for main cables, but not for service cables. However for LV service cables aluminium is only used in long or large connections, which are only a small fraction of the total installed service cables. This may explain the unexpected high survival probability.

Construction

Construction is used as a stratification variable in the main and service cable models. The relation between this variable and the survival probability for main cables can be seen in figure 3. The figure for service cables is similar, and therefore not displayed here. In both models *GPLK*, also known as Paper Insulated Lead Cover (PILC), cables have the highest survival probability. Inquiries among experts confirm this findings, as they experience PILC cables as the most solid and reliable cables. Plastic variants as PVC have a lower survival probability.

The construction of PILC cables explain this difference. As described in [3] the cables consist of copper conductors which are insulated by seven layers of paper and oil. These are then protected by a lead sheath and a layer of jute or bitumen. The plastic variants consists of single layers of plastic and sometimes a metal (e.g. aluminium) screen.

Joint type

This covariate is used for joints only. The reference category is *Service joint* which has a lower hazard than the other categories. This can be explained by various factors. First of all the load on this type of joint is lower as they only supply power to one household. Also the main cable conductor does not get interrupted with service joints. Therefore the temperature rise due to short circuit currents through these joints will be lower than other joints.

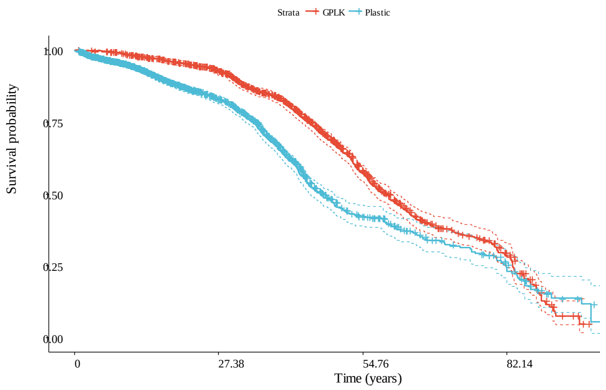

Figure 3: Survival plot of the CPH model for main cables, stratified for the variable *Construction*

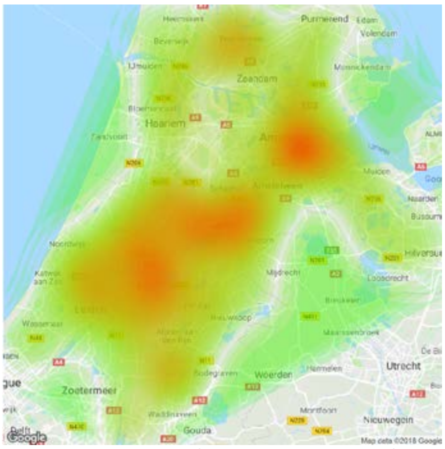

Figure 4: Heat map of high-risk LV assets for the Amsterdam Leiden region in the Netherlands

DISCUSSION

In this section we will discuss the interpretation of the results and the objectives for further research.

Interpretation of results

In the previous section some relations between several variables and the failure of LV assets are presented.

However these relations are still too general to base a whole replacement program of specific populations of assets, or even specific assets, on it. Although the failure probability increases for a certain combination of covariate values, still the uncertainty remains in the model.

The only relation which can be translated to policy directly is the increased failure probability with the number of interruptions on a main cable. When a certain number of interruptions has occurred the DSO may closely monitor this grid and perform a more extensive investigation. All of this in order to prevent repeated solving of interruptions. In that case it might be better to replace the complete cable.

Another option to use the relations that have been found is to rank components based on their characteristics and surroundings. Covariate values in combination with the coefficients from the CPH models are then used to calculate a relative failure probability. The highest ranked assets (highest relative failure probability) may then be selected for monitoring – for instance with an approach as described in [9]. It is then for example possible to make a geographical overview of the failure probability of LV assets. An example is given in figure 4, where a heat map of those assets in a region of a Dutch DSO is depicted.

Further research

In the previous subsection it was discussed that the relations presented in this paper provide some additional insight. However to translate this to a new strategy for more cost-effective maintenance, more research is needed. Amongst others material, labour and outage costs may be combined with the results from this study to investigate whether an optimal maintenance strategy can be found. The currently used corrective maintenance (‘run-to-fail’) may well be the current optimal solution, however it is also valuable to investigate in which scenario (better/cheaper measurement techniques, higher quality of data) a more optimal solution can be used.

Furthermore it is advised to investigate time-varying effects, such as metrological effects and the time between interruptions in the same grid. Experts expect a relation between such effects and the failure of LV components. An example of such a study is [10].

CONCLUSION

In order to maintain reliable and cost-effective LV grids DSOs are looking for ways to make well-thought investments. The results of a proposed method are presented and explained in this paper. The method focuses on finding relations between various variables and failures of LV cables and joints. Also relative failure probabilities are calculated to rank components in order to prioritize locations for monitoring tests.

The presented results in this paper provide insight in failure mechanisms in LV cables and joints. As they are agreed upon or proposed by experts in the field, the results provide a good overview of new and existing knowledge on LV failures.

Further research is needed on asset management, in order to investigate whether this knowledge can be translated to improved policy and strategy.

The results presented in this paper are promising and well-supported by experts in the field of LV distribution, but to achieve tangible improvements more research is needed.

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