Advanced replacement strategies for low voltage distribution grids

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Abstract

Low voltage distribution grids play an important role in the energy transition—both in generation and demand. In the coming decades the reliability of these grids may deteriorate due to asset ageing. Various maintenance (replacement) strategies are compared in order to mitigate this. For multiple scenarios, it is analysed under which circumstances and when alternative strategies are more profitable than current practice towards managing low voltage assets. Under all scenarios utilities are advised to actively seek collaboration with other utilities and institutions in order to increase efficiency, reduce nuisance, achieve future-proofness and minimise risks. Also, opportunities for condition-based approaches exist with the increasing application of distribution automation.

1 | INTRODUCTION

Electrical energy has become of major importance for modern societies. Nowadays people rely on electricity in every aspect of their lives: varying from personal hygiene to communication and transportation. Therefore the need for a robust and reliable electricity grid for modern societies is obvious. Reliability will become even more important with the ongoing energy transition as the share of electricity in the overall energy mix will increase. Especially the low-voltage (LV) distribution networks will be affected by the energy transition. LV grids can be based on overhead lines or cables. The reliability of LV cable networks tends to be high. For example the Dutch LV distribution grids (consisting of almost 100% underground cables) are very high. The overall system average interruption duration index (SAIDI) of less than 30 min, of which only 5 min result from outages in LV grids, corresponds to an availability of electricity of more than 99.99% [1]. These numbers indicate a reliable and robust electricity system. It is important to maintain these reliability levels in order to ensure robust distribution grids in the future. This might be difficult however.

First of all, distribution grids are ageing. Traditionally, distribution system operators (DSOs) are focused on the higher voltage levels, as the impact and costs of supply interruptions originating here are higher. However, recently also the LV level is receiving more attention, and LV grid the first steps towards condition assessment of LV grids have been taken. Fundamental research has been performed on failure mechanisms in LV assets [2]. Moreover, it has been shown that it is possible to make a ranking of LV assets based on relative failure probability. However, it is still not possible to determine the remaining lifetime of these assets accurately [3]. Also, LV grids cannot (yet) be monitored on a large scale in a cost-effective way [4]. Without information on the remaining lifetime of LV assets, it is challenging for a DSO to determine whether and when to replace or maintain them.

Secondly, the energy transition will result in increasing and more fluctuating energy flows due to the introduction of new technologies, such as, electric vehicles, heat pumps and PV systems. The majority of these technologies will be connected to LV grids. Currently, it is unknown what the impact of the resulting energy flows will be on the condition and lifetime of LV grids and components. However, it is known that the thermal cycles resulting from fluctuating power flows can have a negative impact on the condition and lifetime of MV grid components [5], therefore, similar effects might be expected in LV grids. Condition monitoring and maintenance and replacement strategies will therefore become increasingly important.

In the third place the availability of sufficient and adequate personnel may increasingly become problematic. Many DSOs face a shortage of technical staff to execute the energy transition. Such a shortage would also have consequences for other activities—for example, solving interruptions.

Currently LV grids are operated in a 'run-to-failure' (corrective maintenance, CM) way, in which an asset only is replaced or repaired when it has failed. Because of ageing and increasing loading of LV grids, this strategy may become increasingly costly and lead to strongly fluctuating volumes of work.
Therefore DSOs are interested in how, when and what kind of maintenance (including replacement) should be performed to avoid this scenario. In this paper we offer a perspective on the future of LV grid conservation.

Previous research has among others focused on systems subject to specific circumstances [6], overhead line systems [7] and transformers [8]. Currently, however, scientific research performed on maintaining underground LV grids is limited. This paper aims to address this research gap. The paper presents alternatives for the currently applied CM approach. The proposed, more advanced methods make use of more input data (for example condition data, measurement data, planning data of other utilities).

The first contribution of this paper is the proposed maintenance investment decision framework, which provides DSOs with a tool to make well-supported decisions regarding maintenance of underground cable networks. Comparing profitability of alternatives as such is not new; however this framework is a novel and structured way to support investment decisions, specifically tailored to LV grids. For LV grids no previous research exists on alternative (more advanced) maintenance strategies. The second contribution is the scenario analysis which provides an overview of possible future developments and their impact on the reliability and cost effectiveness of maintaining LV grids. The third contribution are the recommendations that are given for maintaining LV grids resulting in an overview of realistic alternatives for conventional CM approaches for LV grids. The presented method is an evidence based, integral approach, focusing on LV networks—something which is not yet known so far.

The paper is structured as follows. First the background of the research is given, the current situation regarding LV interruptions is presented and the current state of research on the condition of LV grids is summarised. Thereafter, we will introduce the proposed method for the comparison of maintenance strategies of ageing LV grids and evaluate the method both quantitatively and qualitatively. Finally the conclusions of this study are formulated and discussed.

2 | BACKGROUND

2.1 | Current situation

In this subsection important aspects of the current situation in LV grids are treated. First, the structure of an LV grid is described. Then, various aspects of reliability of supply are discussed. Thereafter the costs of interruptions are discussed. Finally, the strategy which is currently used to maintain these grids is described.

2.1.1 | Structure

A typical LV grid and its components are depicted in Figure 1. The substation has a MV/LV transformer to transform the voltage level from MV to LV. Power is then supplied to the customers via service cables, connected to the main cables via service joints. Sections of the main cable are connected via cable joints.

The (LV) distribution network of a typical Dutch DSO which is addressed in this study consists of underground cables and joints. These feeders are fed from MV/LV stations. Ages of the components range typically from 0 to 100 years, the average age is ∼35 years. Older cables (>40 years) are paper insulated lead covered cables (25,000 km), younger cables are equipped with plastic insulation (e.g. XLPE, ∼60,000 km). A total of ∼2,500,000 joints are placed in the LV grids. The DSO which owns this distribution network serves more than 2 million customers. A typical LV feeder is ∼250 meters long and serves ∼20 customers.

2.1.2 | Reliability

Reliability of supply is generally quantified using three metrics. First of all, the average interruption duration per customer per year (SAIDI). Secondly, the average interruption frequency per customer per year (system average interruption frequency index, SAIFI). And thirdly, the average interruption duration per interruption for a given year (customer average interruption duration index, CAIDI). The Dutch values for these metrics are presented in Figures 2,3,4 [1]. The figures show a low average interruption frequency for LV grids, a low average interruption duration per customer and a high average interruption duration per interruption. LV interruptions could thus be described as relatively rare for individual customers, but when an interruption occurs it takes a relatively long to restore power to the affected customers.

For the DSO under investigation there are 6000–8000 interruptions per year in LV grids, of which 1500–2000 interruptions per year are directly caused by excavation damages. Excavation damages are directly caused by human failure and are therefore not condition related—and therefore out of scope for this study. When these excavation damages are excluded, 4000–6000 yearly interruptions remain in scope for this study.
2.1.3 | Costs

As mentioned in refs. [3,9] solving all interruptions involves substantial costs. The costs of solving a typical LV interruption are €1300–1800. These costs roughly consist of labour (50%), services (office tasks, 15%), material (5%), surcharges (15%) and contractors (15%, as part of the works is executed by contractors).

So although the cost of solving a single interruption is relatively low, total costs are high because of the large number of LV interruptions, adding up to €10–15 M annually for a large DSO.

In this analysis we exclude the costs for solving interruptions in the public lighting grid, which is also partly the responsibility of DSOs but is outside the scope of this research.

2.1.4 | Maintenance strategy

The strategy for maintaining LV grids has been stable for a long time. It is best described as run-to-failure or CM. Basically components are replaced or repaired when they fail. CM is typically used for low-priority and low-value assets. However, as discussed before, the priority of LV grids increases with the energy transition. Therefore in this paper we will evaluate whether this strategy is still an optimal choice for DSOs.

There are some exceptions to the typical CM strategy in LV networks. Firstly, in grids with a very low performance (i.e. a high number of interruptions) preventive replacements may sometimes be performed to improve reliability. Furthermore, at large-scale renewal projects (sewage, natural gas or street works) sometimes also the electricity grid (LV and sometimes MV) is replaced. This decision may be made based on historical data (e.g. number of interruptions), or the cables and joints are visually inspected when excavation works have been performed. However for condition-based maintenance (CBM) a DSO would want not only to obtain condition information when carrying out large-scale replacements.

2.2 | Condition

In this subsection the current state of condition assessment for LV grids is presented. Condition in LV grids is a relatively new topic of research. DSOs of course register the cause of failure when registering interruptions. Also, manufacturers investigate failed components to improve their products.

The general idea is that failure of LV components is not due to intrinsic degradation or ageing. This is further investigated in several studies. In ref. [2] an overview is given of various failure mechanisms, and an exploration of perspectives for online condition monitoring of LV network components is presented. Aluminium corrosion and fault development initiated by water ingress are the failure mechanisms which are investigated. In ref. [4] these phenomena are further investigated and a pilot on online condition monitoring is presented. The ultimate goal is to predict and prevent failures before they occur. For MV distribution lines, such methods have already been developed [10].

Besides these physical phenomena and monitoring, historical data is also investigated in order to obtain condition information. In ref. [3] a method is described to analyse which parameters affect the reliability of LV grids. It was found that some parameters increase the probability of failure. The most important parameter is the number of historical interruptions in components connected to a given main LV feeder—a larger number of interruptions will lead to a higher failure probability for components connected to this feeder. However, the relations derived from the historical data do not contain enough information to accurately predict interruptions. It is also
investigated how this method could be used in an asset management (AM) environment. In AM multiple stages exist [11], in this study we only focus on the techno-economic comparison of various maintenance (replacement) strategies. This topic will be further explored in the research presented in this paper.

In summary, the studies described in this subsection show that some failure mechanisms are known, there is a proof of concept of online condition monitoring and relative failure probabilities can be derived from historical data. However a certain degree of uncertainty will remain. Therefore in this study a method which deals with this inherent uncertainty is presented.

3 | METHOD

The method proposed in this paper consists of a number of steps. First the scenario analysis is described. In this scenario analysis a set of scenarios is used. Each of those scenarios consists of a set of parameters of which the values are varied. Thereafter, alternative maintenance strategies are presented. These alternative maintenance strategies are then compared with the currently applied CM strategy, both quantitatively and qualitatively. The quantitative comparison of strategies is based on the proposed maintenance investment decision model, which is introduced in Subsection 3.3. Also the qualitative aspects, on which the qualitative evaluation is based, are introduced here.

3.1 | Scenario analysis

In this section, the parameters that characterise the scenarios will be discussed in detail. These parameters are chosen because they may differ for various scenarios, and they affect the costs of interruptions. In Section 4 the scenarios are evaluated.

3.1.1 | Parameters

In this subsection a detailed treatment of the scenario parameters is given. A structured overview of these parameters is given in Table 1. The third column of the table represents the assumed variation of the parameters.

First, the autonomous growth of the number of interruptions is described. With the increasing age of LV components, the cumulative probability that a given LV grid component gets damaged—but does not fail immediately—during excavation works increases. Also, the expectation is that the number of excavation actions will increase in the Netherlands. In many cities there are plans for the construction, renovation or removal of underground infrastructure—which may also affect LV grid components. Examples of this infrastructure are sewerage, optical fibre, natural gas grid renewal and urban heating networks. Also increasing the capacity of LV grids, by installing additional cables alongside existing feeders, may affect existing LV grids. An increase of excavation actions will most likely cause an increase in interruptions.

Secondly, it will become increasingly difficult for DSOs to find enough skilled and qualified personnel. To retain skilled and experienced personnel, higher salaries may have to be paid. Less experienced and skilled personnel will also increase costs. Another cause of this labour scarcity is the expectation that the energy transition will induce a lot of work. This will result in a high demand for personnel. The costs to make adequate personnel available in order to solve an interruption will therefore increase.

Finally, DSOs can decide to attach a financial value to the CML caused by an interruption in order to reflect the consequence of an outage for their customers, depending on their company values and strategy. These costs add up to the financial compensation DSOs may have to pay customers directly when an interruption occurs and the costs for restoring supply after an outage.

### Table 1 Parameters which influence costs of interruptions in LV grids

| Parameter | Description | Variation assumed |
|-----------|-------------|------------------|
| 1. Autonomous growth of number of interruptions | Cumulative probability components get damaged | Growth of 0–2% per year |
| 1. Labour costs increase | Technical specialists may become more valuable and thus more expensive | Increase of labour costs up to 400% |
| 1. Available man hours decrease | Energy transition requires labour. Less (and thus more expensive) hours for interruptions. | Costs increase interruptions up to 400% |
| 1. CML costs increase | DSOs decide to value CML higher | Increase of CML costs up to 400% |

3.1.2 | Scenarios

How the number of interruptions and the associated costs and labour for DSOs will develop in the future is uncertain. Therefore, possible futures are explored by varying the parameters mentioned in the previous subsection, thus defining a set of scenarios. Scenarios enable covering a variety of possible futures, by varying the parameters. In this paper four scenarios are developed.

The scenarios are based on expert opinions and represent futures varying from small growth to very large growth. The scenarios have been developed using a structured approach involving experienced experts from different large DSOs in the Netherlands, who have thorough knowledge of and vast experience with management of LV grids and their components, including reliability and failure analyses.
The scenarios define the growth of the aforementioned parameters towards the year 2050. The growth over time towards 2050 is described via an s-curve, which is often used in scenario analysis [12].

The scenarios are summarised in Table 2. For each of the parameters (1–4) the growth in 2050 is given. The first scenario is ‘Conservative.’ In this scenario parameter changes are limited, compromising a relatively small increase in the number of interruptions and costs of labour. Also, the available man hours will only slightly decrease towards 2050. This scenario could happen when the effects of the energy transition would be marginal. Moreover personnel would be well available over the coming decades.

The next scenario is called ‘Active government.’ In this scenario the government actively intervenes in the energy system. The regulator will increase the penalties for interruptions by a factor four. However through subsidies and encouraging actions, financed by the government, more personnel can be recruited. Therefore only the costs for CML will heavily increase.

The third scenario is called ‘Energy transition max.’ In this scenario the energy transition will strongly accelerate. Technologies such as heat pumps and PV systems are widely installed, causing many potential capacity and condition problems. Therefore we expect that the number of interruptions and the labour costs increase. The largest change will happen in the available man hours, as most personnel will be deployed in energy transition related activities. As a reliable LV grid is even more important when the LV grid is as heavily used as in the scenario energy transition max, it is expected that CML will be valued higher in this scenario.

The fourth and final scenario is called ‘Scarcity of personnel.’ In this scenario the availability of (technical) staff of DSOs would be heavily decreased. Therefore the number of interruptions will increase, as maintenance, replacements and upgrades of the grid will be difficult to execute. These four scenarios are expected to cover the largest part of the range of possible futures. In the following section various maintenance strategies are evaluated for these scenarios, in order to give insight in the possible ways of handling these possible futures.

### Table 2 Values of parameters of future scenarios for interruptions in LV grids

| Scenario                  | Description                                      | Parameter growth in 2050 |
|---------------------------|--------------------------------------------------|--------------------------|
| 1. Conservative           | Relatively few changes                           | 50% 20% 20% 0%           |
| 1. Active government      | Government active in increasing reliability      | 40% 20% 0% 400%          |
| 1. Energy transition max  | Energy transition completely taking place         | 200% 200% 400% 200%     |
| 1. Scarcity of personnel  | Very large decrease of available (technical) personnel | 100% 20% 250% 0%        |

The maintenance investment decision model, which will be introduced in Section 3.3, is flexible. Therefore also other alternative strategies could be investigated. The strategies discussed here are illustrative. In this paper, maintenance implies replacement. Currently no other maintenance action exists for underground LV components. In the case of CM, replacement is only performed on the section of the cable which has failed.

### Table 3 Maintenance strategies which can be used in LV grids and their change on the costs of one replacement

| Alternative strategy       | Description                                      | Change costs replacement |
|----------------------------|--------------------------------------------------|--------------------------|
| Corrective maintenance (CM)| No change in costs                                | —                        |
| Preventive maintenance (PM)| Decrease in number of interruptions, increase in costs | 0%                       |
| Condition-based maintenance (CBM)| Decrease in number of interruptions, increase in costs | 10%                      |
| Joint utility works (JUW)  | Decrease in costs                                | -50%                     |

As aforementioned, the strategy of CM—that is, run-to-failure—has been used since the first underground LV grids were installed. Because the failure rate is relatively low and only few customers are affected by an interruption, this has so far been an adequate strategy. However, the importance of LV grids increases due to the energy transition. Also, technical personnel is hard to find and keep. In this section various alternatives to the currently applied CM strategy are given. These alternatives are evaluated for various scenarios in the following section, in order assess their benefits for various possible futures. The alternative maintenance strategies are given in Table 3 and will be described and characterised on the aspects of costs and applicability in the following subsections. The values for the change in costs of replacement are based on expert opinions using the above mentioned structured approach, acquired from the DSO that was a partner in the research presented in the paper.

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### 3.2 Alternative strategies

#### 3.2.1 Corrective maintenance

The first strategy is already mentioned before, namely CM. This is the strategy that has so far been applied by DSOs. Basically the oldest form of maintenance, in CM a component is replaced or repaired only when it fails.
The costs of CM can be described very directly. As aforementioned, the costs of solving an average interruption (thus performing CM) vary between €1300 and €1800. More than half of this amount consists of direct labour costs. Some feeders do not any endure interruptions in their complete lifetime, whereas others might endure multiple interruptions in one year. Combining the costs per interruption with ~1–2 interruptions per feeder during the lifetime and a lifetime of more than 50 years, the average maintenance costs per feeder are in the range of tens of euros per year.

The only main requirement for the application of CM is the availability of personnel and a sufficient maintenance budget. When one of these is not sufficient anymore, for instance due to a large increase of the number of interruptions, the applicability decreases and the costs increase.

### 3.2.2 Preventive maintenance

Preventive maintenance (PM) means that components are replaced before they fail. Preferable this is done shortly before the moment of failure. Generally PM strategies are based on lifetime or loading of the component.

The costs of preventively replacing an average LV-feeder including connections (length of 220 m, ~17 serviced connections) lay between €200 and €300 per meter. This amount depends on the number of connections and local circumstances. Replacing a connection includes the replacement of the service cable and joint. The costs of replacing an LV main cable are €110–140 per meter, where the costs of replacing a typical connection (service cable and joint) is €1000–1500 per connection. However, a complete replacement of feeder including connections rarely happens. Therefore, when preventive replacement would be applied on a larger scale, these costs will probably decrease.

Also, the costs of planned preventive replacement are much lower than the costs of replacements during outage restoration. Restoration after an interruption costs between €1300 and €1800, where a preventive replacement of main cable only costs €110–140 per meter.

The first difficulty with applying PM is whether to base the maintenance on age or on loading. From previous research it is concluded that failure of LV components generally is not age-related. Also, the effect of a higher current on the condition of an LV-feeder is not known.

The lifetime is often assumed to be ~50 years [13]. The component is amortized within this period, however the DSO ‘makes’ money by the absence of amortization payments after this period when the component is still operational. Therefore choosing a fixed age for which to replace components is both financially suboptimal and technically unjustified. However, when a moment in time to replace components is chosen, PM is easy to apply as it is planned maintenance. Therefore man hours and budget can easily be made available.

It is unknown to which extent the loading of LV components affects their. Therefore it is currently impossible to determine the moment of replacement based on, for example, the total energy supplied by a component. When research would point out that there is a relation between loading and condition or remaining life, this could be an effective method. However, overloading of components can happen in LV grids. It might also be an option to determine the moment of replacement on the amount of overloading that has occurred. However, currently the largest part of data on cable loading is based on average load profiles and overloading is not monitored and registered. Concluding, although PM would be easily applicable for LV grids, currently only time-based is a viable option.

### 3.2.3 Condition-based maintenance

CBM is maintenance based on the condition of assets. The reasoning behind CBM is that maintenance is only performed when it is necessary. Therefore, at least in theory maintenance and interruption costs could be saved by using this method.

As maintenance or replacement can be reasonably planned in advance, costs will be lower than interruption costs and more comparable to the costs of preventive replacement. However, large investments are required to obtain accurate and sufficient condition information. The monitoring method introduced in Section 2.2 may be used to discover malfunctioning components, however each feeder has to be measured separately. However, measurement devices may be necessary for the energy transition anyway—enabling market orientated functionality such as demand side management or monitoring power quality [14]. It may be beneficial for condition monitoring when these devices could also be used for obtaining condition information.

The price of one measuring and communication unit is currently relatively high. Therefore, application to hundred thousands of feeders seems infeasible. However combining monitoring approaches with data-driven condition assessment might increase the effectiveness and feasibility, so that devices could be installed in substations where many interruptions occur (or which have a high probability on future interruptions).

Distribution automation is increasingly applied in LV (smart) grids, and in the long term it is plausible to incorporate aforementioned monitoring functionality in monitoring hardware [15,16]. This would enable large-scale condition monitoring, which would enable CBM. As mentioned in ref. [17] substation automation can increase efficiency in operation and maintenance, and thus reduce costs.

In the current situation the availability and accuracy of data is too limited to select assets which should be replaced, based on a condition assessment. However a condition assessment method could still be applied to select which (limited amount of) feeders should be monitored to prevent interruptions, thus increasing the efficiency of CBM.

### 3.2.4 Joint utility work

Currently DSOs replace LV grids when the capacity is not sufficient any more. These capacity problems originate mainly from
technologies which are installed in the context of the energy transition.

Also, there are ongoing works on other underground infrastructure such as natural gas networks, drinking water, sewerage and telecom networks. Moreover, streets are renovated too. The resulting excavation works provide an opportunity to inspect and/or replace LV components at lower costs (up to 50% reduction). For other excavation works, the fact that the cables trenches are easily accessible would be used. Moreover, in some locations excavation works may be performed only once per given time period (up to 25 years) to reduce nuisance for public and enterprises, and repaving costs. Therefore there are limited opportunities to replace assets.

The process for utilities to eventually execute these excavation works is long and costly. Permits are needed, calculations have to be performed, and the work has to be planned. When utilities cooperate to make this process more efficient, a significant cost reduction can be achieved. Therefore this strategy is called ‘joint utility works’ (JUW). As aforementioned, JUW can reduce costs up to 50 percent. This cost reduction is caused by higher efficiency and a sharing the workload and cost of the preparation efforts. This strategy is already applied by some DSOs. Components may be inspected when the cable trench is excavated, sometimes it is planned beforehand to replace (old) LV feeders. However, no clear defined and widely applied strategy is used. For JUW to be applied, it is necessary to gain more insight in excavation and renovation projects from other utility companies and from municipalities. A unified approach of multiple utilities and instances would enable greater synergy and efficiency. An additional advantage is that the public nuisance of excavation works is reduced by applying JUW.

### 3.3 | Maintenance investment decision framework

In order to provide DSOs with a structured method to make investment decisions on maintenance and replacements in LV grids, in this section a supporting framework is presented. The framework is based on economic optimization and can therefore be extended with other (monetized) parameters. First the parameters will be explained, thereafter the objective function will be presented.

#### 3.3.1 | Decision parameters

Investments in distribution grids typically have a long lifetime. Therefore these investments are capitalised, which results in annual depreciation payments for an investment instead of one large payment in the year of investment. These investments result in capital expenditure (CAPEX) costs. The annuities method is used to convert the CAPEX into a series of annual payments [18], which is also mentioned in ref. [19] as reliable option for asset depreciation and valuation. The annual payment is defined as:

\[
AN_{\text{asset}}(a) = \text{CAPEX}_{\text{asset}}(a) \times \frac{i}{1 - (1 + i)^{-T_{\text{life}}(a)}}, \tag{1}
\]

where \(i\) is the discount rate, \(T_{\text{life}}\) is the economic lifetime of the asset and \(\text{CAPEX}_{\text{asset}}\) the initial cost of the asset. The cost of this asset \(a\) in year \(t\) then becomes:

\[
\text{Cost}_{\text{asset}}(a, t) = \begin{cases} 
AN_{\text{asset}}(a) & \text{if } t_{\text{inst}} \leq t < t_{\text{inst}} + T_{\text{life}}(a) \\
0 & \text{else}
\end{cases}, \tag{2}
\]

where \(t_{\text{inst}}\) is the year of installation of asset \(a\). After the economic lifetime, no more depreciation of an asset occurs.

Besides the CAPEX, also operational expenditure (OPEX) has to be taken into account. In this paper we focus on underground assets. Underground assets typically only have OPEX related to an outage—as no other maintenance than outage restoration is performed. The outage costs consist of labour, services (office tasks), surcharges and contractors as part of the work is executed by contractors. The material which is used to solve an outage only accounts for 5% and is therefore not activated as CAPEX, so that OPEX remain as direct costs for an interruption. However, also a financial value for the resulting CML could be included when determining the costs of outages, representing the impact on affected customers. Therefore the \(\text{Cost}_{\text{outage}}\) is here defined as the sum of OPEX and monetized CML. The total costs are now defined as:

\[
\text{Cost}_{\text{total}}(t) = \sum_{c=1}^{C} \text{Cost}_{\text{cable}}(c, t) + \sum_{f=1}^{F} \text{Cost}_{\text{outage}}(f, t), \tag{3}
\]

where \(c\) is the number of cables and \(f\) is the number of interruptions (failures). The parameter \(\text{Cost}_{\text{cable}}\) is based on Equation (2). The costs of outages increases over time according to the scenarios in Section 3.1. The costs of replacing cables change according to the alternative strategies in Section 3.2.

#### 3.3.2 | Objective function

The defined parameters enable the formulation of an objective function. The goal for the DSO is to reduce costs. Therefore the net present value (NPV) of the total costs has to be minimised:

\[
\min \text{NPV} = \sum_{t=t_0}^{t_{\text{horizon}}} \frac{\text{Cost}_{\text{total}}(t)}{(1+i)^{t-t_0}}, \tag{4}
\]

where \(t_{\text{horizon}}\) is the time frame for which the NPV is minimised. By minimizing the NPV, the total cost of ownership of an asset is minimised. This will lead to minimizing the cost of maintenance of LV grids. The interest rate \(i\) in this study is chosen at 5%.

For assets which are still before the end of their economic life, a replacement would mean that the remaining CAPEX annuity payments still have to be paid for. From a financial view this is
undesirable. Therefore assets which still have to be amortized are excluded in this study and only amortized assets are taken into consideration. Because of the sensitivity of the NPV for the chosen time interval, the yearly costs are evaluated. OPEX of the current asset should be lower than the annuitized CAPEX of a replacement, under the condition that the replacement does not endure interruptions—as this will increase OPEX. This translates into the following definition:

\[
\text{replacement if } \frac{\text{AN}_\text{cable}(\theta)}{(1 + \delta)^t} \leq \frac{\text{AN}_\text{outage}(\theta)}{(1 + \delta)^t},
\]

where AN\text{cable} and AN\text{outage} are defined via the annuities method, as defined in Equation (1). The yearly cost of outages is calculated via the annuities method because the number of interruptions during the lifetime is one of the variables. As the yearly cost varies because of the unpredictability of interruptions, it is annuitized via the method in Equation (5). This leads to a fair comparison between outage and replacement costs.

### 3.4 Qualitative evaluation parameters

Besides the quantitative (financial) aspects of maintenance strategies, other aspects have to be taken into account as well. Often, in AM in DSOs, multiple business values are taken into account to evaluate possible risks and to decide on and optimise policies. The business values that are taken into account may differ amongst individual DSOs. Therefore in this study we present some qualitative aspects which may be used as, or translated into, a quantitative score on business values. The qualitative aspects taken into account here are the applicability, efficiency, nuisance and future-proofness. The qualitative evaluation parameters, as well as the qualitative evaluation itself, are again based on expert opinions, gathered in structured workshops involving a number of experienced experts from different large DSOs in the Netherlands, who have thorough knowledge of and vast experience with management of LV grids and their components.

The applicability is important because the maintenance strategy has to be relatively easily applied, due to the vast amount of LV assets. Otherwise the complexity and amount of work would be unmanageable for an average DSO and costs of applying the strategy will quickly outweigh its benefits. It is ever more important to work efficiently, to achieve high productivity so that better results can be achieved with relatively limited effort. Maintenance on the electrical infrastructure can be a nuisance for the public. Therefore the amount of nuisance each strategy causes is also taken into account, as well as, regulations on excavation works.

In Section 4.1, a quantitative evaluation of maintenance strategies is carried out, to determine the most profitable strategy for different situations. However, the most profitable solution may no longer be the most profitable when circumstances change. The presented scenarios try to cover all possible futures. As the future is uncertain, the strategies are also qualitatively judged on how future-proof they are.

### 4 RESULTS

In this section the alternatives will be evaluated for the different future scenarios. The total costs of maintenance are quantitatively assessed in Section 4.1.1. Therefore CM is quantitatively compared against the alternative strategies, searching for the optimal strategy depending on the moment of time. The evaluation is performed on the LV system of a large DSO in the Netherlands. In Section 2 some background is given on the current situation for Dutch LV networks. Typically those LV grids have a low failure rate and planned replacements are cheaper than replacements due to failures. In the final subsection the scenarios and strategies are qualitatively evaluated—looking at various aspects.

#### 4.1 Quantitative evaluation results

##### 4.1.1 Total costs

In order to give an overview of potential costs regarding interruptions in the future, various scenarios were developed and described in Section 3.2. In Figure 5 the total costs for interruptions per large DSO per year are presented for each of the four scenarios, including the costs for CML by attaching a financial value to reliability of supply. The costs are calculated using the current maintenance strategy—CM. For these calculations we considered a starting point of 5000 interruptions per year—in Section 2.1.2 it was mentioned that for a large DSO 4000–6000 interruptions occur every year. Interruptions directly caused by excavation works account for 1500–2000 incidents each year. Therefore taking 5000 interruptions is a valid starting point.

In Figure 6 the same overview of costs is given, but then with costs of CML excluded. As aforementioned, the CML can be used internally to compare and prioritize, for example, strategies and locations. Excluding CML in the evaluation shows the comparison between strategies on the basis of actual ‘direct,’ accounting costs. The total costs are lower than when CML
is included for every scenario. For scenario 2, active government the decrease is very high, because this scenario assumes a large increase in the price of CML.

In Figures 5 and 6 it can be seen that large differences are expected between the various scenarios. When no alternative strategy will be applied, costs of interruptions will increase with tens to hundreds of millions of euros. Eventually these costs must be recovered from society. As many other costs regarding the energy transition will also be recovered from society, it may be necessary to reduce costs related to interruptions. In the following subsection the potential cost reduction by using alternative maintenance strategies is evaluated.

4.1.2 | Optimal strategy versus time

As mentioned in Section 3.2, various maintenance strategies exist throughout utilities and industry. They are generally not directly applicable to this specific problem, however we derived four potential strategies for the maintenance and replacement of underground LV distribution cables and joints. Each strategy has its specific advantages and disadvantages. In this subsection the strategies are compared in a quantitative way. The alternative strategies are compared to traditionally applied CM. For each scenario the moment in time is calculated for which an alternative strategy is more profitable than CM. These calculations are based on the decision framework introduced in Section 3.3.

The costs of CM depend on the number of interruptions during the lifetime of the feeder. As was found in ref. [3], the probability of recurring interruptions increases with every interruption in either main cable, service cable or joint. Therefore in this study, the complete main cable including service cables and joints is replaced. So for a given number of interruptions the costs of CM is compared to the costs of replacing the complete feeder (and accessories) using alternative strategies.

In Figure 7 the results of the aforementioned calculations are given, with the cost of monetized CML included. In Figure 8 the cost of CML is excluded. On the horizontal axis the number of interruptions during the lifetime of an asset is given. On the vertical axis the moment of replacement is given—in years from now. The curves represent the moment in time for which replacement using an alternative strategy induces lower annual costs than using CM. This moment in time is given for each combination of scenario (separate plots), alternative strategy (colour of curve) and number of interruptions during lifetime of asset (x-axis). For the area below the curves CM is more profitable, for the area above the curves the alternatives are more profitable.

This can be further explained by an example. In Figure 7, scenario 3 energy transition max, one of points of the curve of JUW is at the combination of 1 interruption, 50 years. This means that JUW is more profitable than CM when a replacement prevents one (or more) interruption(s) and the feeder is replaced at least 50 years from now.

In every scenario JUW is the most profitable alternative strategy. This is easily explained by the cost-reducing effect of combining multiple utility projects. As one may expect, including CML causes alternative strategies to be profitable for lower ages and numbers of interruptions.

Furthermore, in scenario 3 energy transition max, it can be seen that the profitable age of replacement is lower than in other scenarios. Scenario 3 energy transition max is the scenario in which it is expected that costs of interruptions will increase extremely.

In every figure the variable on the x-axis is the number of interruptions that is assumed during the lifetime of a feeder. The expected technical lifetime of a feeder is 70 years. On average, in these 70 years, the number of interruptions endured by a feeder is 1.5–3. However, when an interruption occurs and is solved by CM, the costs related to this interruption are already made and cannot be prevented any more by an alternative strategy. The number of interruptions on the x-axis has to be prevented by timely replacement of assets, in order to make the alternative strategy more profitable than CM.

The consequences of these quantitative outcomes are further discussed in Section 5. In the following subsection we will evaluate the various maintenance strategies on a qualitative basis.

4.2 | Qualitative evaluation results

In Table 4 the resulting qualitative evaluation of the maintenance strategies is given. For every strategy a short explanation is given. The qualitative evaluation is based on expert opinions from the DSO that is the research partner and that were gathered in a structured workshop involving a number of experienced experts, who have thorough knowledge of and vast experience with management of LV grids and their components. First, the alternatives were scored individually, thereafter through a discussion a common view was formulated.

4.2.1 | Corrective maintenance

This is the most simple (applicability ++ ) of all strategies. A downside of this strategy is that it requires a rapid and

FIGURE 6  Expected yearly costs of all interruptions for an average large distribution system operator in the Netherlands for all scenarios, excluding costs for CML.
unplanned response to interruptions (efficiency $-$), making it less efficient. It is however advantageous that only failed assets are replaced. For customers it is disadvantageous that interruptions may happen spontaneous from time to time (nuisance $-$), but still the average household only endures less than 2 outages caused by LV interruptions during the lifetime of a feeder. Although CM is currently the most profitable, low-quality assets will remain in operation. This leads to potential higher failure probabilities, thus making it less future-proof (future-proofness $-$).

4.2.2 Preventive maintenance

Due to the vast amount of LV assets, PM is practically impossible to carry out (applicability $-$). It will take tens of years and large sums of money to preventively replace assets. This leads to an inefficient strategy (efficiency $-$). However, as maintenance is planned, the nuisance can be reduced although it will certainly remain with preventive replacements on a large scale (nuisance $+/-$). The big advantage of PM is the fact that the complete asset base of the LV level can be made ready for the future, by using new components, materials and techniques and increasing capacity (future-proofness $++$).

4.2.3 Condition-based maintenance

One of the requirements for CBM is the availability of an approach towards condition assessment. Currently, options exist via data analysis [3] and measurement devices [4]. Where data analysis is not accurate enough, measurement devices are
FIGURE 8  Moment of replacement and number of interruptions for which alternative strategies are more profitable than corrective maintenance for each scenario, excluding CML.

expensive or not yet available on a large scale. Therefore the applicability is not as good as other strategies (applicability +/−). However when a DSO can discover and replace/repair malfunctioning LV assets by using condition assessment, efficiency would increase by exchanging unplanned outage restoration for planned activities (efficiency +). As only malfunctioning cables are replaced and thus the amount of unexpected outages decreases, the nuisance of CM will decrease (nuisance ++). However, as only cables are replaced that (almost) failed already, this strategy is not explicitly future-proof (future-proofness +/−).

4.2.4 Joint utility works

Replacing or repairing LV assets in combination with other planned excavation works decreases costs, because the excavation works can be combined for multiple types of assets and utilities (efficiency ++). This will also lead to less excavation works in total (nuisance ++). In the cases where it can be applied, JUW is easily applied, because the actual work is comparable (applicability ++). However, the benefits of combining only exist when excavation works are needed for multiple utilities/companies. Therefore, not all low-condition or malfunctioning assets can be replaced or repaired, and many interruptions will still occur (future-proofness +/−).

5 DISCUSSION

Currently, LV assets are widely maintained in the traditional form; CM. When a component fails, it is replaced or repaired. Nowadays, and possibly in the (near) future as well, this approach will be sufficient. However, as shown in Section 3 and Figure 2 various futures are possible which incur a range of possible financial consequences. In Section 3.2 the alternative strategies are presented. In Section 4.1 those strategies are quantitatively compared with the currently used CM using the decision framework presented in Section 3.3. Each of them have their advantages and disadvantages, which are evaluated in Section 4.2.

5.1 Quantitative evaluation

From the quantitative evaluation it can be concluded that preventively replacing LV feeders (based on either PM, CBM or JUW) is often not profitable. When an extreme scenario as scenario 3 energy transition max will occur, older feeders for which at least 1–2 future interruptions are expected can be replaced—especially when the replacement may be combined with other works (JUW). In all other cases (scenarios, alternatives) a higher number expected and hence avoided of interruptions would be needed to make alternative strategies more profitable than CM.
More insight is needed to accurately determine these expected interruptions, which could be achieved by using measurement devices as in CBM. So, when the strategies are quantitatively evaluated, it is confirmed that CM is still an optimal solution for DSOs.

Furthermore, including CML in the calculations results in earlier profitability of alternative strategies. Therefore monetizing and incorporating CML in the decision framework may be used as an incentive to invest in the maintenance of LV grids.

The use of various different scenarios for the quantitative analysis gives insight in the sensitivity of the study. As the parameters are varied over the different scenarios, the impact on the outcomes can be seen in the various scenarios. However, to be prepared for the future, as well as to reduce nuisance for customers and comply with regulations, it may be relevant to look into other business values than costs. The strategies were therefore also evaluated qualitatively.

5.2 Qualitative evaluation

First of all, JUW is a strategy which can be combined with other strategies. Besides its financial benefits, it also scores well on qualitative criteria. Because of the synergy, nuisance is reduced and efficiency is increased. Therefore DSOs are advised to actively seek collaboration with other utilities and instances such as municipalities.

Furthermore, CBM can be a viable option as well. The initial investment in measurement devices etc. may not be profitable at first sight, but when malfunctioning components can be found accurately there will be an increase in efficiency and a reduction in nuisance. Also, as aforementioned, measurement devices might be widely applied (developing LV grids into smart(er) grids) to enable the energy transition anyway. When a DSO could integrate measurement functionality in substation automatization, interruptions can be prevented by preventively replacing components based on those measurements. Another possibility is to combine CBM and JUW. This can be done by measuring feeders in areas where excavation works are planned. When malfunctioning assets are found, the feeders can be replaced.

The last strategy, PM, showed to be unprofitable in almost all cases. Often the age or the loading during the lifetime is used to determine which assets to replace using PM. However for LV assets age is not an appropriate indicator for condition and loading is often unknown for LV assets due to lack of adequate measurement equipment.

Moreover, certain developments may make other strategies more profitable. For instance CBM would benefit heavily from widely introduced cost effective measurement devices. If the needed functionality would be incorporated in distribution automation or smart grid equipment and be employed throughout the whole network, this would enable a CBM strategy much more cost-effectively.

Another possible development may be caused by the energy transition. The power flows expected from the technologies used in this transition may accelerate degradation phenomena in LV assets.

Developments may also occur on ageing assets. Currently, the first cables with plastic insulation approach the age of 50 years. These cables were designed to last around 50 years. After this lifetime, plasticizers may evaporate and the insulation becomes brittle – increasing the risk of damages due to external forces. When such a phenomenon indeed occurs—on a large scale—a DSO might want to switch to PM (initiating a much debated “replacement wave”) to prevent a large number of interruptions. Therefore it is necessary to be alert on signals which may indicate that a certain component is very likely to fail at a certain age (or other circumstance/characteristic than age).

To apply the proposed framework and maintenance strategies in other real-world systems, it is important to keep in mind their specific characteristics. For other failure rates and replacement costs, the business case will be different. This can be incorporated in the presented maintenance decision framework, in order to be able to make adequate decisions. Also, other scenarios and parameters can be defined depending on the situation, system or country.

The qualitative evaluation is performed based on expert opinions. A recommendation for further research would be to perform a more thorough and broad qualitative evaluation. The final important consideration is the fact that we do not take into account capacity-based replacements. It is expected that LV assets will be replaced because their capacity is not sufficient—due to higher loads as a result of the energy transition. Therefore, new assets will replace old assets, which may decrease the number of interruptions and the need to replace assets on the basis of condition.

6 Conclusion

In this paper the present and the future of maintaining LV distribution grids is discussed. With a large and ageing LV asset base which may be not sufficient anymore both from the perspective of capacity and condition due to the energy transition, DSOs want to optimally manage these assets. For the Netherlands, on which the analysis focuses, the LV distribution grids perform well but are relatively costly to maintain. The currently used practice is CM, which turns out to be a sound choice—at least for the time being.

In the paper CM is compared to alternative strategies. Promising strategies are JUW and CBM. PM in its purest form makes no sense for LV distribution grids, due to low failure frequencies and the vast amount of assets.
It is recommended to DSOs to—even more than already done—seek collaboration with other instances and utilities to enable JUW to achieve an efficiency gain and decrease nuisance. It is also recommended to actively explore options for CBM, as every interruption which can be prevented leads to a decrease in nuisance and costs. If a reliable and cost effective condition assessment method can be introduced, the field of LV AM will never be the same again.

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**REFERENCES**

1. Netbeheer Nederland: Betrouwbaarheid van elektriciteitsnetten in Nederland Resultaten 2018 (2019). https://www.netbeheernederland.nl/dossiers/betrouwbaarheid-23/documenten

2. Kruizinga, B.: Low Voltage Underground Power Cable Systems: Degradation Mechanisms and the Path to Diagnostics. PhD Thesis, Dept. Elect. Eng., Eindhoven University of Technology (2017)

3. Klerx, M., Morren, J., Slootweg, J.G.: Analyzing parameters that affect the reliability of low-voltage cable grids and their applicability in asset management. IEEE Trans. Power Deliv. 34(4), 1432–1441 (2019)

4. van Deursen, A., Wouters, P.A.A.F., Steennis, F.: Corrosion in low-voltage distribution networks and perspectives for online condition monitoring. IEEE Trans. Power Deliv. 34(4), 1423–1431 (2019)

5. Di Sante, R., et al.: Effects of thermal cycles on interfacial pressure in MV cable joints. Sensors (Basel) 20(1), 169 (2020)

6. Carnero, C., Gomez, A.: Maintenance strategy selection in electric power distribution systems. Energy 129, 255–272 (2017). https://doi.org/10.1016/j.energy.2017.04.100

7. Salman, A.M., Li, Y., Bastidas-Arteaga, E.: Maintenance optimization for power distribution systems subjected to hurricane hazard, timber decay and climate change. Reliab. Eng. and SystemSafety 168, 136–149 (2017)

8. Markert, M., Polster, J., Muhr, M.: Maintenance strategies for distribution networks. In: Proceedings of the XIVth International Symposium on High Voltage Engineering, Tsinghua University, Beijing, China, August 25–29, 2005 (2017)

9. Klerx, M., Morren, J., Slootweg, J.G.: Patterns in failure rate of LV distribution components. In: Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, 2018-April (2018)

10. Russell, R.D., Benner, C.L.: Intelligent systems for improved reliability and failure diagnosis in distribution systems. IEEE Trans. Smart Grid 1(1), 48–56 (2010)

11. Hoskins, R.P., Brint, A.T., Srirac, G.: A structured approach to asset management within the electricity industry. Util. Policy 7(4), 221–232 (1999)

12. Kovacs, I.Z., et al.: Mobile Broadband Traffic Forecast Modeling for Network Evolution Studies. In: 2011 IEEE Vehicular Technology Conference (VTC Fall), pp. 1–5 (2011). https://doi.org/10.1109/VETECF.2011.6092960

13. Council of European Energy Regulators: Report on Regulatory Frameworks for European Energy Networks (2019). https://www.ceer.eu/report-on-regulatory-frameworks-for-european-energy-networks-2019

14. Morren, J., Slootweg, H.: Investments in distribution automation as a foundation for smart grids. In: CIRED Workshop 2016, pp. 1–4 (2016). https://doi.org/10.1049/cp.2016.0656

15. de Groot, R.W., Morren, J., Slootweg, J.G.: Reliable and efficient operation of closed-ring distribution grids supported by distribution automation. Sustain. Energy, Grids Networks 15, 53–62 (2018)

16. Balakrishna, P., Rajagopal, K., Swarup, K.S.: Application benefits of distribution automation and AMI systems convergence methodology for distribution power restoration analysis. Sustain. Energy, Grids Networks 2, 15–22 (2015)

17. Thomas, M.S., McDonald, J.D: Power System SCADA and Smart Grids. CRC Press, Boca Raton, Florida (2017)

18. Grond, M.O.W.: Computational capacity planning in medium voltage distribution networks. Eindhoven University of Technology (2016)

19. Kipper, H.U., Pedell, B: Which asset valuation and depreciation method should be used for regulated utilities? An analytical and simulation-based comparison. Util. Policy 40, 88–103 (2016)

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