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Maintenance Planning of Electric Distribution Systems—A Review

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Abstract
Electric distribution systems have the objective of supplying electricity with quality and reliability to the final consumers. In order to meet both criteria, efficient maintenance programs have a vital importance mainly due to the actual increase in the requirements for distribution service quality and in technologies related to electrical networks. In this sense, the number of options and criteria for developing effective programs makes the related decision-making process a complex task. This paper presents a comprehensive review on maintenance planning in electrical distribution systems covering different criteria such as economic and reliability. More specifically, this work summarizes contributions up to now through a holistic framework that comprises the premises of predictive, preventive and corrective maintenance. The work is organized by relevant aspects of researches in the field, as criteria, probability functions, constraints and methods that have been applied, within a comprehensive classification.

Keywords Distribution system · Maintenance · Planning · Reliability · Economy

1 Introduction

The maintenance planning assumes a strategical role within technical and financial feasibility scenarios (Li and Brown 2004). These criteria are conflicting with each other requiring effective tools for the decision-making related to the maintenance actions (Abbasi et al. 2009) over a given planning horizon. These actions comprise asset management and maintenance scheduling planning.

Maintenance consists of a set of actions that seek to maintain the system in a suitable functioning condition (Caballé et al. 2015) and extends the lifespan of equipment or the average time to failure. It means reduction in interruption frequency and failure probability (Li and Brown 2004), and the system reliability is directly affected by the type and level of maintenance (Endrenyi et al. 2001). Each maintenance type depends on the equipment feature and function in the system, besides its accessibility, network configuration and climatic condition (Beaumont and Geary 1944).

In the past, the maintenance tasks were based on regulation requirements, utility criteria or experience. Afterward, mathematical models were developed aiming at defining maintenance plans focused on economic and technical criteria (Caballé et al. 2015). In face of scheduled interruptions costs, maintenance actions should be optimized by utilities through a suitable cost–benefit analysis (Endrenyi et al. 1998) and can be classified as predictive, preventive and corrective.

Given the importance of the maintenance planning in EDS, as well as the fact that it has not been found works on the literature that organize contributions about this subject, this paper discusses the main publications on this topic since 1944. In particular, this work summarizes contributions up to now through a comprehensive framework that comprises predictive, preventive and corrective maintenance. The present review is organized by relevant aspects of researches in the field, such as criteria and probability functions that have been used, constraints and applied methods within a comprehensive classification.

The remainder of this paper is organized as follows: Sect. 2 addresses the maintenance planning in EDS and Sect. 3 encompasses the reliability criterion regarding this topic. Section 4 presents the main contributions covering their

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objective functions (OBF), constraints, as well as programming and optimization methods. Finally, Sect. 5 gives some conclusions and remarks about the present review.

2 The Maintenance Planning of Distribution Systems

The maintenance planning of EDS consists of a complex problem since it involves decision-making processes in environments of multiple options related to the definition of plans that include diverse actions over a planning horizon (Dashti and Yousefi 2013; Lopez et al. 2017; Miloca et al. 2015; Pang et al. 2016). Although these actions fall under the scope of predictive, preventive or corrective maintenance type, there are different levels for a given type (Mohammadnezhad-Shourkaei et al. 2011; Salman et al. 2017; Yumbe et al. 2016).

Traditionally, unlike generation and transmission systems, EDS utilities choose corrective actions having lower immediate costs, rather than predictive and preventive plans. However, a portfolio having only corrective tasks cannot be a good option under the criterion of total cost over a planning horizon. Thus, a trend for more planned maintenance actions is emerging for EDS due to contemporary management premises and operative requirements, as greater reliability of service. In this sense, the maintenance planning with focus on reliability, which is known as reliability-centered maintenance (RCM), is a concept found in works and researches from the literature, such as in (Endrenyi et al. 2001, 1998; Heo et al. 2011, 2014; Mirsaeedi et al. 2017a, 2017b).

The RCM policy can be considered as an improvement over traditional preventive maintenance policies known as time-based maintenance (TBM) and condition-based maintenance (CBM) (Li and Brown 2004), since RCM considers both the probability of equipment failure and its consequences, which are not covered by CBM. CBM depends on technologies for sensors since it is based on monitoring. However, besides the advances in such technologies, this policy is not necessarily the best cost–benefit option (De Jonge et al. 2015b) due to its related costs. TBM, in turn, has still been shown to be attractive for most companies (Zhang et al. 2013), but it may not minimize the annualized equipment cost (Li and Brown 2004).

In general, both TBM and CBM may lead to suboptimal solutions regarding the annualized cost that should be minimized (Li and Brow, 2004), which justifies the concept of RCM policy (Yumbe et al. 2013). RCM provides a more flexible schedule by monitoring conditions and data, failure effect analysis, requirements, priorities and flowcharts for decision-making processes. However, the RCM application requires experience and a step-by-step decision-making by using heuristic approaches that can result in large amount of time to collect the required data (Endrenyi et al. 1998).

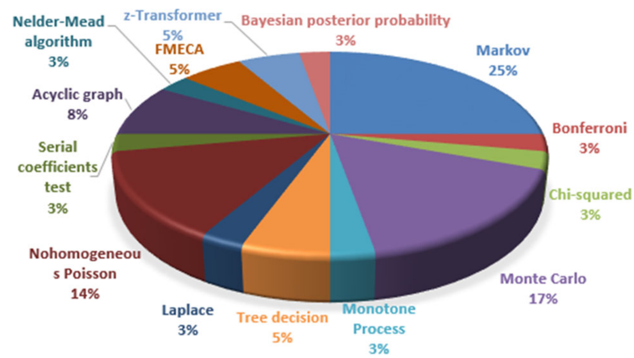

Fig. 1 Overview of reliability methods for EDS maintenance planning

The RCM policy is applied to evaluate maintenance plans for EDS in Afzali et al. 2019, where an importance level is defined for main distribution feeders through a weighting index. An importance level is also assigned to equipment in feeders. Aspects on the reliability criterion have utmost importance for the maintenance planning and thus are covered in the next section.

3 The Reliability Criterion in the Maintenance Planning of EDS

The maintenance planning with focus on RCM seeks to make decisions on actions that improve some reliability indexes and consequently the distribution service quality. Billinton and Grover (1975) formulate reliability indexes for EDS. This section presents works that addressed the reliability issue in the maintenance planning of EDS and comprises the main methods, reliability indexes and variables that have been used.

3.1 Methods for Reliability Analysis

The reliability criterion has been investigated in most recent works that address the task of maintenance planning of EDS. Several methods have been applied to the reliability analysis. The Markov chain (Billinton and Grover 1975) and the Monte Carlo methods are the most commonly found in the literature for the purpose at hand. Other techniques can be considered evenly distributed among the works. A comprehensive overview of the reliability approaches that are most used in the literature is shown in Fig. 1, which presents the percent usage of each one. Table 1 associates the methods for reliability analysis with the respective references.

The Markov method is based on system states and their transition rules. Several failure modes can be considered to evaluate reliability of maintenance planning (MP), as done in Yin et al. (2013). Continuous-time model is applied in

Table 1 Reliability methods for EDS maintenance planning

Method	Reference
Markov	Abiri-Jahromi et al. (2009), Billinton and Grover (1975), Carnero and Gómez (2017); Cormen et al. (2001), Dhople et al. (2013), Endrenyi et al. 1998, 2001, Nourelfath et al. (2012), Ruiz-Castro (2014), Yin et al. (2013) and Yssaad and Abene (2015)
Monte Carlo	Briš et al. (2003), Endrenyi et al. (1998), Hanai et al. (2013), Hilber et al. (2007), Melchor-Hernández et al. (2015), Mollahassani-pour et al. (2014), Salman et al. (2017), Yssaad and Abene (2015) and Wang et al. (2016)
Acyclic graph	Briš et al. (2003), (2017) and Briš and Byczanski (2013)
Bayesian	De Jonge et al. (2015a)
Bonferroni	Yumbe et al. (2016)
Chi-squared	Yumbe et al. (2016)
FMECA	Yssaad and Abene (2015) and Yssaad et al. (2014)
Laplace	Adoghe et al. (2013)
Monotone process	Dehghanian et al. (2013)
Nelder-Mead algorithm	Moradkhani et al. (2014a)
Nonhomogeneous Poisson	Caballé et al. (2015), Chen (2012), Doostparast et al. (2014), Melchor-Hernández et al. (2015) and Wang and Pham (2011)
Serial coefficients test	Adoghe et al. (2013)
Tree decision	Abbasi et al. (2009) and Cormen et al. (2001), Mohammadnezhad-Shourkaei et al. (2011)
z-transformer	Nahas et al. (2008) and Nourelfath et al. (2012)

Carnero and Gómez (2017) to obtain the expected availability.

The Monte Carlo (MC) technique is a well-known approach to evaluate reliability of systems that is based on a probabilistic sample process of system states. In Endrenyi et al. (1998), MC is associated with Markov chain to evaluate maintenance plans; in Wang et al. (2016) it is used to identify critical components that affect the preventive maintenance; and in Salman et al. (2017) MC is applied to model the weakness of electricity distribution poles and the hurricane risks.

Another type of reliability analysis is based on acyclic graphs, which is associated with MC in Briš et al. (2003) for maintenance planning and in Briš and Byczanski 2013, Briš et al. 2017) to model the system unavailability. There are still methods based on decision tree, i.e., a binary tree that provides comparisons between MP decisions through a classification algorithm (Abbasi et al. 2009; Mohammadnezhad-Shourkaei et al. 2011; Cormen et al. 2001).

In Yumbe et al. (2016), a two-step approach is presented where the first step carries out a correlation analysis between equipment failures and historical maintenance data by using the Chi-squared test and the Bonferroni method. This step seeks to find causes of faults and provides the input parameters of the second step whose purpose is to forecast future failures. In Adoghe et al. (2013), the Laplace method is used to identify the system's tendency to change reliability over time, and the serial correlation coefficient is used to identify whether the times between faults are independent of each other. A monotone process (Yeh 2005) is presented in (Zhang et al. 2013) to model deterioration processes, and in (De Jonge et al. 2015a), the weakest generating units are identified by applying Bayesian inference. The Nelder–Mead algorithm (Nash and Varadhan 2011) is applied in Moradkhani et al. (2014a) to optimize the occurrence probability of failures, having the advantage of not requiring derivative computations.

The FMECA (failure modes, effects and criticality) software is presented in (Yssaad et al. 2014) to evaluate failures modes and their causes and effects. In Yssaad and Abene (2015), FMECA is used to obtain reliability indexes through Markov graphs, Petri networks and MC technique. A function named as universal moment generating function or z-transform is presented in (Hilber et al. 2007) to define the system availability in a multi-state approach. In Nourelfath et al. (2012), z-transform is combined with Markov chain.

Finally, the nonhomogeneous Poisson process has also been used to assess reliability. In Wang and Pham (2011), it is considered to define the rate of random system failures. The work presented in (Doostparast et al. 2014) applies nonhomogeneous Poisson process to define failure modes. In Caballé et al. (2015) and in Melchor-Hernández et al. (2015), the Poisson is associated with the gamma process to model the degradation of systems and to evaluate failures patterns, respectively.

3.2 Reliability Indexes

Reliability indexes have been used as metrics to determine the system adequacy under the reliability requirement and different perspectives, as the social standpoint by using frequency and duration indexes, or under the light of economics through the energy not supplied. Such indexes can be obtained from historical data, mathematical expressions that model the system behavior or probability distributions. Several indexes are distributed among the papers of literature, but it can be pointed out that few works consider diverse indexes in a comprehensive manner to plan maintenance actions in EDS (Afzali et al. 2019; Mirsaeedi et al. 2017a, 2017b; Mohammadnezhad-Shourkaei et al. 2011; Yssaad et al. 2014; Wang et al. 2014).

Some reliability indexes are introduced hereinafter (Allan and Billinton 1996; Brown 2008; Chowdhury and Koval 2009,2001; IEEE 2012; ANEEL 2018; Da Silva et al. 1997):

- average energy not supplied (AENS);
- customer average interruption duration index (CAIDI) (IEEE 2012);
- energy not supplied (ENS);
- expected interruption cost (ECOST);
- failure rate;
- loss of load cost (LOLC);
- mean time between failures (MTBF);
- mean time to failure (MTTF);
- mean time to repair (MTTR);
- momentary average interruption frequency index (MAIFI);
- service availability index (ASAI);
- service unavailability index (ASUI);
- system average interruption duration index (SAIDI);
- system average interruption frequency index (SAIFI).

Commonly used units for SAIDI and SAIFI are hours and failures by year, respectively. The ASUI, ASAI and LOLC are used in the context of maintenance planning policies. There are indexes defined in Brazil that are equivalent to others previously defined as:

- frequency of interruption per consumer unit (FIC)—it is equivalent to failure rate for a larger set of equipment at a point or consumer units;
- individual interruption duration per costumer unit (DIC)—it can be related to MTTR when a repair is associated with the restoration of supply for a consumer unit.

Figure 2 and Table 2 summarize the application of reliability indexes in the literature and their association with the respective references. Table 3 lists the works that use the equivalent Brazilian reliability indexes.

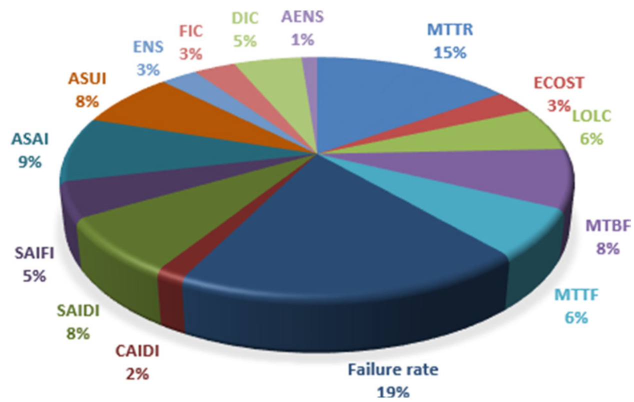

Fig. 2 Reliability index application

It can be highlighted the connection of very common indexes among the previously described with the maintenance planning problem: LOLC and ENS. LOLC is similar to the expected reliability cost, ECOST, but does not depend on the costumer type, being therefore a general cost index useful to evaluate maintenance plans under the economic criterion. ENS, in turn, is an important metric to evaluate maintenance plans under the energy standpoint, which is important to obtain plans that avoid or minimize electricity shortage and penalization for utilities as well as to maximize the social welfare.

There are other less used indexes to define reliability of a system, such as the health index of Ma et al. (2017), the maximum continuous interruption duration of Da Silva et al. (2005), the interrupted energy assessment rate of Goel and Billinton (1991) and the operational vulnerability indicator of Schmitz et al. (2018).

3.3 Variables

Some variables are handled in studies that involve the reliability criterion in the maintenance planning of EDS. Several indexes use a given distribution of probabilities and random variables to model their randomness, as the failure rate, MTTR, MTBF, MTTF, ASAI and ASUI. Other parameters are also random variables as the lifespan, renewable generation and inspection time (IT) (comprises the time to select a device and perform its inspection). The distribution functions model the probabilities of a random variable that can be discrete, whose values are defined in a finite and countable space, or continuous having innumerable possible values. Notice that a same random variable can be handled by different distribution functions. In this sense, the failure rate can be highlighted for having been modeled by several functions in the literature, as shown in Table 4. The adequacy of the distribution function determines the effectiveness in modeling the random variable. Figure 3 summarizes the application of distribution functions.

Table 2 Reliability index by reference

Index	Reference
AENS	Afzali et al. (2019), Bertling et al. (2005) and Velasquez-Contreras et al. (2011)
ASAI	Abbasi et al. (2009), Afzali et al. (2019), Briš et al. (2003), Caballé et al. (2015), Carnero and Gómez (2017), Chan and Shaw (1993), Dhople et al. (2013), Doostparast et al. (2014), Lin and Wang (2012), Liu et al. (2014), Marquez et al. (2013), Mohammadnezhad-Shourkaei et al. (2011), Nahas et al. (2008), Nourelfath et al. (2012), Piasson et al. (2016), Salman et al. (2017), Xu and Hu (2013), Zhang et al. (2013), Yin et al. (2013), Wang and Pham (2011), Wang et al. 2016 and Yumbe et al. (2016)
ASUI	Briš and Byczanski (2013), Chang (2014), Chen (2012), Dhople et al. (2013), Endrenyi et al. (1998), (2001), Estava (1987), Marquez et al. (2013), Melchor-Hernández et al. (2015), Mohammadnezhad-Shourkaei et al. (2011), Piasson et al. (2016), Ruiz-Castro (2014), Salman et al. (2017), Sim and Endrenyi (1988), Yssaad and Abene (2015), Yssaad et al. (2014), Wang and Pham (2011) and Wang et al. (2016)
CAIDI	Aravinthan and Jewell (2013), Bertling et al. (2005), Canizes et al. (2015) and Velasquez-Contreras et al. (2011)
DIC	Adoghe et al. (2013), Afzali et al. (2019), Bertling et al. (2005), Billinton and Grover (1975), Canizes et al. (2015), Dehghanian et al. (2013), Hilber et al. (2007), Mirsaeedi et al. (2017b), Moraes et al. (2017), Narimani et al. (2018), Piasson et al. (2016) and Velasquez-Contreras et al. (2011)
ECOST	Bertling et al. (2005), Hanai et al. (2013), Hilber et al. (2007), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a) and Moraes et al. (2017)
ENS	Afzali et al. (2019), Bertling et al. (2005), Dehghanian et al. (2013), Mohammadnezhad-Shourkaei et al. (2011), Velasquez-Contreras et al. (2011) and Wang et al. (2014), (2016))
Failure rate	Abbasi et al. (2009), Abiri-Jahromi et al. (2009), Adoghe et al. (2013), Afzali et al. (2019), Bertling et al. (2005), Billinton and Grover (1975), Briš and Byczanski (2013), Briš et al. (2003), Caballé et al. (2015), Chan and Shaw (1993), Chang (2014), Dehghanian et al. (2013), Dhople et al. (2013), Doostparast et al. (2014), Endrenyi et al. (1998), Endrenyi et al. (2001), Hanai et al. (2013), Hilber et al. (2007), Li and Brown (2004), Lin and Wang (2012), Marquez et al. (2013), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a)Moradkhani et al. (2015), Moraes et al. (2017), Nahas et al. (2008), Narimani et al. (2018), Nourelfath et al. (2012), Piasson et al. (2016), Salman et al. (2017), Sim and Endrenyi (1988), Sittithumwat et al. (2004), Velasquez-Contreras et al. (2011), Xu and Hu (2013), Zhang and Gockenbach (2011), Yssaad and Abene (2015), Yssaad et al. (2014), Yumbe et al. (2013), Yumbe et al.(2016), Wang and Pham (2011), Wang et al. (2014), Wang et al. (2016), Canizes et al. (2015) and Wu and Clements-Croome 2005)
FIC	Afzali et al. (2019), Aravinthan and Jewell (2013), Arya (2016), Billinton and Grover (1975), Dehghanian et al. (2013), Hilber et al. (2007), Mirsaeedi et al. (2017b) and Moraes et al. (2017), Piasson et al. (2016)
LOLC	Abbasi et al. (2009), Abiri-Jahromi et al. (2009), Afzali et al. (2019), Caballé et al. (2015), Campelo et al. (2016), Dehghanian et al. (2013), Doostparast et al. (2014), Liu et al. (2014), Moradkhani et al. (2015), Ruiz-Castro (2014), Zhang et al. (2013), Yssaad et al. (2014), Wang and Pham (2011), Wang et al. (2014) and Wu and Clements-Croome (2005)
MAIFI	Li and Brown (2004)
MTBF	Adoghe et al. (2013), Briš and Byczanski (2013), Briš et al. (2017), Canizes et al. (2015), Chang (2014), Dehghanian et al. (2013), Endrenyi et al. (2001), Hilber et al. (2007), Lin and Wang (2012), Marquez et al. (2013), Melchor-Hernández et al. (2015), Narimani et al. (2018), Ruiz-Castro (2014), Salman et al. (2017), Zhang et al. (2013), Xu and Hu (2013), Yin et al. (2013), Yssaad and Abene (2015), Yssaad et al. (2014) and Wang and Pham (2011)

Table 2 continued

Index	Reference
MTTF	Aravinthan and Jewell (2013), Briš and Byczanski (2013), Briš et al. (2017), Chan and Shaw (1993), Dehghanian et al. (2013), Endrenyi et al. (2001), 1998, Estava (1987), Hilber et al. (2007), Lin and Wang (2012), Melchor-Hernández et al. (2015), Velasquez-Contreras et al. (2011), Zhang et al. (2013), Yin et al. (2013), Yssaad and Abene (2015) and Yssaad et al. 2014)
MTTR	Abbasi et al. (2009), Adoghe et al. (2013), Afzali et al. (2019), Billinton and Grover (1975),, Briš and Byczanski (2013), Briš et al. (2017), Canizes et al. (2015), Chan and Shaw (1993), Carnero and Gómez (2017), Dehghanian et al. (2013), Dhople et al. (2013), Doostparast et al. (2014), Endrenyi et al. 1998, Estava (1987), Hilber et al. (2007), Marquez et al. (2013), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Moraes et al. (2017), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a), Narimani et al. (2018), Nourelfath et al. (2012), Piasson et al. (2016), Ruiz-Castro (2014), Salman et al. (2017), Sim and Endrenyi (1988), Sittithumwat et al. (2004), Silva et al. (2014), Velasquez-Contreras et al. (2011), Yin et al. (2013), Xu and Hu (2013), Yssaad et al. (2014), Yssaad and Abene (2015), Wang et al. (2014), Wang et al. (2016) and Wu and Clements-Croome (2005)
SAIDI	Abiri-Jahromi et al. (2009), Afzali et al. (20190, Aravinthan and Jewell (2013), Arya (2016), Bertling et al. (2005), Canizes et al. (2015), Chen (2012), Endrenyi et al. (1998), Li and Brown (2004), Lin and Wang (2012), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2015), Narimani et al. (2018), Silva et al. (2014), Sim and Endrenyi (1988), Velasquez-Contreras et al. (2011), Wang and Pham (2011) and Wang et al. 2014
SAIFI	Abiri-Jahromi et al. (2009), Afzali et al. (2019), Aravinthan and Jewell (2013), Arya (2016), Bertling et al. (2005), Canizes et al. (2015), Li and Brown (2004), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Sittithumwat et al. (2004), Velasquez-Contreras et al. (2011) and Yssaad et al. (2014)

Table 3 Brazilian equivalent reliability indexes

Index	Reference
DIC	Adoghe et al. (2013), Afzali et al. (2019), Arya (2016), Bertling et al. (2005), Billinton and Grover (1975), Canizes et al. (2015), Dehghanian et al. (2013), Hilber et al. (2007), Mirsaeedi et al. (2017b), Moraes et al. (2017), Narimani et al. (2018), Piasson et al. (2016), Velasquez-Contreras et al. (2011)
FIC	Afzali et al. (2019), Aravinthan and Jewell (2013), Billinton and Grover (1975), Dehghanian et al. (2013), Hilber et al. (2007), Mirsaeedi et al. (2017b), Moraes et al. (2017) and Piasson et al. (2016)

Among the discrete distributions, the geometric and Poisson functions have been used. Regarding continuous distributions, the exponential (Elmakis and Levy 1987), Erlang, gamma, normal, Rayleigh, uniform, Weibull, lognormal, phase-type and Student's t-distribution can be mentioned. There are also works that model random variables by applying fuzzy logic to assign a quantitative value to qualitative and subjective quantities. This can be pointed out as a recent trend found in (Piasson et al. 2016) and allows representing complex features with more precision and reality.

3.4 Equipment

Works on maintenance planning of EDS that include the reliability criterion consider different equipment in the system, as transformers (Koksal and Ozdemir 2016), breakers (Abbasghorbani and Mashhadi 2013; Abbasghorbani et al. 2014), switches and distribution branches. Figure 4 and Table 5 summarize the equipment in works from the literature. The majority of papers consider equipment in MP, around 56.6%.

It can be highlighted that transformers and breakers are the equipment most commonly considered in approaches to plan the EDS maintenance, due to their vital function in the distribution grid. Distribution network branches are also grid elements widely included in planning methods from the literature since they are subject to severe operating conditions and faults. Few works cover diverse equipment through a comprehensive approach, which can be pointed out as a lack for future developments. In this sense, some works stand out for covering much equipment as (Piasson et al. 2016; Yssaad and Abene 2015; Yssaad et al. 2014; Yumbe et al. 2013).

3.5 Uncertainties

An important aspect of the maintenance planning in EDS is related to the uncertainties over quantities that affect this task. In the literature, uncertainty parameters have been classified

Table 4 Probability distribution by reference

Distribution	Variable	Reference
Erlang	MTTR	Sim and Endrenyi (1988)
Exponential	Failure rate	Abbasi et al. (2009), Briš et al. (2003), Lin and Wang (2012), Mohammadnezhad-Shourkaei et al. (2011), Sim and Endrenyi (1988), Xu and Hu (2013) and Wang and Pham 2011
	Deterioration rate	Sim and Endrenyi (1988)
	ASUI	Briš and Byczanski (2013) and Chen (2012)
	ASAI	Marquez et al. (2013)
	MTTR	Yin et al. 2013
	MTTF	Zhang et al. (2013) and Yin et al. (2013)
Fuzzy	Failure rate	Bao et al. (2018), Canizes et al. (2015) and Piasson et al. (2016), Sittithumwat et al. (2004
	MTTR	Canizes et al. (2015)
	Unavailability	Canizes et al. (2015)
	Renewable	Bao et al. (2018)
Gamma	Failure rate	Caballé et al.(2015)
Gaussian	Load demand	Bao et al. (2018)
Geometric	Lifespan	Wu and Clements-Croome (2005)
Lognormal	ASUI	Salman et al. (2017)
	Lifespan	Campelo et al. (2016)
Normal	MTTR	Adoghe et al. (2013)
	Failure rate	Yumbe et al. (2013), (2016)
	ASUI	Estava (1987)
	ASAI	Liu et al. (2014)
Phase-type	TMEF, IT, MTTR, MTTF	Ruiz-Castro (2014)
Poisson	Failure rate	Doostparast et al. (2014), Moradkhani et al. (2015) and Xu and Hu (2013)
Rayleigh	Failure rate	Chan and Shaw (1993)
Student's t	Failure rate	Moradkhani et al. (2014a)
Uniform	MTTR	Chan and Shaw (1993)
	Lifespan	De Jonge et al. (2015b)
Weibull	MTTR	Chan and Shaw (1993)
	Lifespan	Chan and Shaw (1993), De Jonge et al. (2015a), (2015b), Doostparast et al. (2014), Salman et al. (2017) and Zhang et al. (2013)
	ASAI	Caballé et al. (2015, Doostparast et al. (2014 and Nahas et al. (2008)
	Deterioration rate	Abbasi et al. (2009 and Mohammadnezhad-Shourkaei et al. (2011)
	Failure rate	Abiri-Jahromi et al. (2009, Aravinthan and Jewell (2013), Briš et al. (2017), Chang (2014), Chen (2012), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), (2017b), Salman et al. (2017), Xu and Hu (2013) and Wang et al. (2014), (2016)

and addressed by different methods (Catrinu and Nordgård 2011).

According to Sittithumwat et al. (2004), the quantification of reliability parameters that are required in RCM is a difficult task because, even when available, they are subject to uncertainty for being inaccurate. In this sense, the prediction of equipment future behavior can be unfeasible from only historical records. Moreover, manufacturing issues, age as well as adverse operating conditions can affect equipment in different manners. Therefore, in the absence of accurate data, which is common in EDS, uncertainties must be considered,

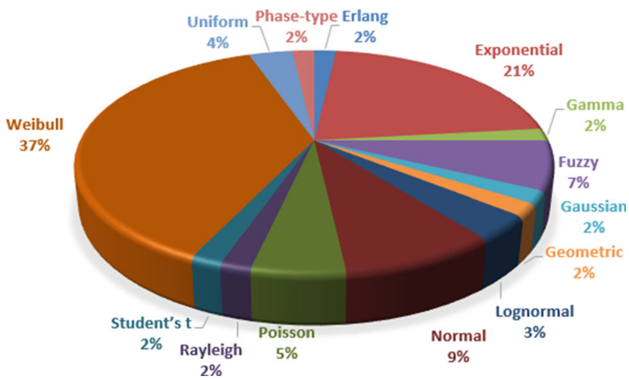

Fig. 3 Probability distribution application

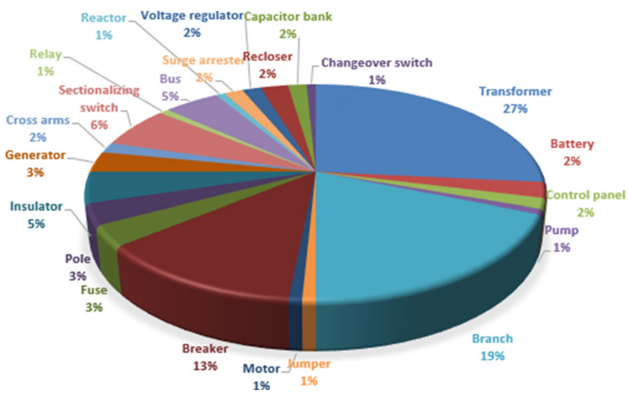

Fig. 4 Equipment distribution

as in Bao et al. (2018), Piasson et al. (2016), Sittithumwat et al. (2004).

In the previous works, fuzzy sets are used to handle uncertainties over failure rate. In (Sittithumwat et al. 2004), the value of additional information is investigated aiming at defining a trade-off between the expense of financial resources for this information and the assertiveness of the decisions, which is subject to more uncertainties when less information is provided. The uncertain variable in this case is the failure rate, which has an expected value and a standard deviation directly proportional to the uncertainty level.

In Dhople et al. (2013), the uncertainty over equipment repair time is represented through a version of the parallelogram method. Notice that the ASAI and LOLC reliability indexes are used in Dhople et al. (2013) as objective functions to be maximized and minimized, respectively. Fuzzy logic is applied in Bao et al. (2018) to represent uncertainties over photovoltaic generation and failure rate in MP, by using historical data and Gaussian distribution for loads.

Sensitivity analyses have been presented, as in Wang and Pham (2011) for maintenance time and in De Jonge et al. (2015b) for lifespan probability distribution. Heuristic methods are applied in De Jonge et al. (2015a) to include uncertainties over equipment lifespan due to different kinds of maintenance policies. Moreover, in (Salman et al. 2017), the MC method is applied to represent uncertainties over the initial reliability condition of poles and their degradation due to climatic condition. Table 6 shows the papers that consider uncertainties with the respective quantities and methods to handle them. Figure 5 shows the percent of occurrence of each quantity being handled with its uncertainty in the maintenance planning of EDS.

Although diverse variables have been considered with their uncertainties, there is a gap in the literature regarding the investigation of alternative or complementary methods, as the interval mathematics or neural networks, which have also potential for application to improve the assertiveness of maintenance decisions under uncertainties. Another gap is the lack of studies considering electric vehicles and their load stations with the related uncertainties.

4 Main Contributions in the Subject of Maintenance Planning of EDS

As previously described, research and development efforts to provide tools that can support the decision-making on the maintenance planning of EDS have been found in the literature because of the increasing relevance of this subject in the context of distribution networks (Briš et al. 2017; Carnero and Gómez 2017; Mazidi and Bobi 2017; Arya 2016; Piasson et al. 2016; Wang et al. 2016; Yumbe et al. 2016). Factors that can contribute to the definition of maintenance type were already raised in Beaumont and Geary (1944), as atmospheric condition, electrical and mechanical resistance, accessibility and physical layout of the system. Also in this sense, efforts to identify the system status as support to maintenance planning are presented in Endrenyi et al. (2001), Estava (1987). These efforts include survey to give an overview about equipment.

In Billinton and Grover (1975), equations are formulated to model system reliability indexes. Most recently, a weighting index is proposed by Afzali et al. (2019) to obtain priority levels for main distribution feeders and equipment under the RCM policy. Moreover, a decision-making process on maintenance of distribution branches to improve reliability is presented in (Arya 2016), by applying a weighted importance factor that classifies branches under their failure severity including load and distributed generation effects.

The MP problem has high dimension due to the number of alternative plans, as well as due to several options of preventive, predictive and corrective actions in short, medium and long term (Briš et al. 2017; Salman et al. 2017; Piasson et al. 2016; Yumbe et al. 2016; Wang et al. 2016). Considering that the MP decision must be made within a suitable time, for instance on a monthly base, this decision must be supported by computational tools. The next subsections describe relevant aspects on mathematical programming and optimization

Table 5 Equipment by reference

Equipment	Reference
Transformer	Adoghe et al. (2013), Aravinthan and Jewell (2013), Bao et al. (2018), Beaumont and Geary (1944), Bertling et al. (2005), Briš and Byczanski (2013), Briš et al. (2017), Campelo et al. 2016, Carnero and Gómez (2017), Dhople et al. (2013), Endrenyi et al. (1998), Endrenyi et al. (2001), Hanai et al. (2013), Hilber et al. (2007), Li and Brown (2004), Marquez et al. (2013), Melchor-Hernández et al. 2015, Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a), Moradkhani et al. (2015), Moraes et al. (2017), Narimani et al. (2018), Piasson et al. (2016), Sim and Endrenyi (1988), Sittithumwat et al. (2004), Velasquez-Contreras et al. (2011), Zhang and Gockenbach (2011), Yssaad and Abene (2015), Yssaad et al. (2014), Yumbe et al. (2013), Yumbe et al. (2016) and Wang et al. (2014)
Breaker	Adoghe et al. (2013), Aravinthan and Jewell (2013), Beaumont and Geary (1944), Bertling et al. (2005), Endrenyi et al. (1998), (2001), Hanai et al. (2013), Hilber et al. (2007), Li and Brown (2004), Melchor-Hernández et al. (2015), Piasson et al. (2016), Sim and Endrenyi (1988), Zhang and Gockenbach (2011), Yssaad and Abene (2015), Yssaad et al. (2014) and Wang et al. (2014)
Branch	Abiri-Jahromi et al. (2009), Adoghe et al. (2013), Aravinthan and Jewell (2013), Bertling et al. (2005), Briš and Byczanski (2013), Briš et al. (2017), Canizes et al. (2015), Carnero and Gómez (2017), Hanai et al. (2013), Hilber et al. (2007), Li and Brown (2004), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Moraes et al. (2017), Moradkhani et al. (2014a), Moradkhani et al. (2015), Narimani et al. (2018), Piasson et al. (2016), Sittithumwat et al. (2004), Yssaad and Abene (2015), Yssaad et al. (2014), Yumbe et al. (2013), Wang et al. (2014) and Wang et al. (2016)
Battery	Beaumont and Geary (1944), Masteri et al. (2018) and Narimani et al. (2018)
Bus	Adoghe et al. (2013), Bertling et al. (2005), Hilber et al. (2007), Yssaad and Abene (2015), Yssaad et al. (2014) and Wang et al. (2014)
Capacitor	Canizes et al. (2015), and Piasson et al. (2016)
Changeover switch	Yumbe et al. (2016)
Cross-arms	Moradkhani et al. (2014a) and Yumbe et al. (2013)
Control panel	Beaumont and Geary (1944) and Yumbe et al. (2016)
Fuse	Aravinthan and Jewell, (2013), Hilber et al. (2007), Yssaad and Abene (2015) and Yssaad et al. (2014)
Generator	Bao et al. (2018) and Endrenyi et al. (1998), (2001), Mirsaeedi et al. (2017a)
Insulator	Adoghe et al. (2013), Moradkhani et al. (2014a, Moradkhani et al. (2015), Yssaad and Abene (2015), Yumbe et al. (2013) and Yumbe et al. (2016)
Jumper	Moradkhani et al. (2014a)
Motor	Sittithumwat et al. (2004)
Pole	Salman et al. (2017), Moradkhani et al. (2014a, Yumbe et al. (2013) and Yumbe et al. 2016)
Pump	Endrenyi et al. (1998)
Reactor	Melchor-Hernández et al. (2015)
Recloser	Aravinthan and Jewell (2013), Sittithumwat et al. (2004) and Yumbe et al. (2013)
Relay	Beaumont and Geary (1944)
Sectionalizing switch	Adoghe et al. (2013), Aravinthan and Jewell (2013), Briš and Byczanski (2013), Mirsaeedi et al. (2017b), Piasson et al. (2016), Yssaad and Abene (2015), Yssaad et al. (2014) and Wang et al. (2016)
Surge arrester	Yssaad and Abene (2015), Yumbe et al. (2013)
Voltage regulator	Piasson et al. (2016) and Yumbe et al. (2013)

Table 6 Uncertain parameter by reference

Parameter	Model	Reference
Failure rate	Fuzzy	Bao et al. (2018); Piasson et al. (2016) and Sitthithumwat et al. (2004)
	Parallelogram	Dhople et al. (2013)
Climatic condition	Monte Carlo	Salman et al. (2017)
Initial reliability	Monte Carlo	Salman et al. (2017)
Lifespan	Heuristic	De Jonge et al. (2015a)
	–	De Jonge et al. (2015b)
	Monte Carlo	Salman et al. (2017)
Load demand	Gaussian distribution	Bao et al. (2018)
Maintenance time	–	Wang and Pham (2011)
Renewable generation	Fuzzy	Bao et al. (2018)
Repair time	Parallelogram	Dhople et al. (2013)

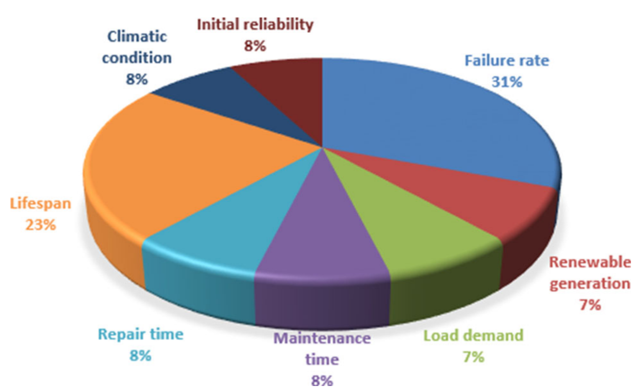

Fig. 5 Distribution of uncertain parameters

methods, as their merit or objective functions, constraints and approaches have been developed to the matter at hand.

5 4.1 Objective Function.

In general, an objective function is required when it is needed to maximize or minimize a given performance index. An optimization problem can be mono- or multi-objective. Moreover, multi-objective problems, i.e., that have two or more indexes to be optimized, can be solved by mono-objective approaches when different indexes can be merged in a unique function. On the other hand, when different objectives cannot be merged due to unit conflict or difficulty to define weighting factors, multi-objective approaches must be used to handle each quantity with the proper relation between quantities. The following notation is used to describe some contributions to the field in the literature:

- P_MO: Mono-objective problem, i.e., problem with a unique objective;
- P_MU: Multi-objective problem, i.e., problem with two or more objectives;
- A_MO: Mono-objective approach, which can be applied to P_MO or P_MU;
- A_MU: Multi-objective approach for multi-objective problems.

Among the mono-objective MP problems, some have focus on reliability, as (Nourelfath et al. 2012; Yin et al. 2013; Dhople et al. 2013), where the ASAI index is proposed to be maximized, and (Wang et al. 2016), (Sitthithumwat et al. 2004), where SAIFI and ENS are minimized, respectively. Costs are also focus of some studies, expressed in terms of Preventive Maintenance (PvM) costs in (Aravinthan and Jewell 2013; De Jonge et al. 2015a; Lin and Wang 2012), LOLC in (Zhang et al. 2013), Preventive (PvM), Predictive (PdM) and Corrective Maintenance (CM) costs and ECOST in (Hanai et al. 2013). Other relevant parameters have been also defined as performance index to be optimized, as the maintenance time of crews in service (Silva et al. 2014) and the equipment criticality (Carnero and Gómez 2017). Table 7 presents the classification of works found in the literature according to the notation previously introduced.

From Table 7, it can be verified that about 38% of the papers consider a unique merit function as OBF. The percentage of papers that use mono-objective approaches is about 75%, whereas the Pareto method is applied in the works that consider multi-objective approach. Given the conflicting nature of the core objectives in the EDS maintenance planning problem, i.e., the lowest cost with the highest reliability, multi-objective algorithms will be highly demanded in the future. Despite their computational cost, multi-objective methods can provide a set of maintenance plans that can be assessed with other studies considering the grid such as expansion planning, increasing the range of possibilities for the maintenance planning crew.

Table 8 and Fig. 6 present the distribution of objective functions among references from the literature. It can be verified that most references consider at least one reliability index as OBF, whereas some consider even more than one index: SAIFI, SAIDI and MAIFI in (Li and Brown 2004); LOLC and ASAI in (Mollahassani-pour et al. 2014). This shows the relevance of the reliability criterion in studies on MP of EDS. Another conclusion is that almost all references consider reliability or cost index as OBF, proving the higher importance of these criteria for the problem at hand.

Some remarks can be made:

Table 7 Optimization type by papers

Type	Reference
P_MO	Aravinthan and Jewell (2013), Briš and Byczanski (2013), Briš et al. (2003), (2017), Carnero and Gómez (2017), De Jonge et al. (2015a), (2015b), Dhople et al. (2013), Hanai et al. (2013), Lin and Wang (2012), Liu et al. (2014), Nourelfath et al. (2012), Silva et al. (2014), Sittithumwat et al. (2004), Zhang et al. (2013), Yin et al. (2013) and Wang et al. (2016)
P_MU	Abbasi et al. (2009), Abiri-Jahromi et al. (2009), Bao et al. (2018), Bertling et al. (2005), Caballé et al. (2015), Campelo et al. (2016), Chang (2014), Chen (2012), Dehghanian et al. (2013), Doostparast et al. (2014), Hilber et al. (2007), Li and Brown (2004), Masteri et al. (2018), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2015), Moraes et al. (2017), Nahas et al. (2008), Piasson et al. (2016), Ruiz-Castro (2014), Salman et al. (2017), Yumbe et al. (2013), (2016), Wang and Pham (2011) and Wang et al. (2014)
A_MO	Abbasi et al. (2009), Abiri-Jahromi et al. (2009), Bertling et al. (2005), Caballé et al. (2015), Chang (2014), Chen (2012), Dehghanian et al. (2013), Doostparast et al. (2014), Li and Brown (2004), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2015), Moraes et al. (2017), Nahas et al. (2008), Ruiz-Castro (2014), Yumbe et al. (2013) and Wang et al. (2014)
A_MU	Bao et al. (2018), Campelo et al. (2016), Hilber et al. (2007), Masteri et al. (2018), Piasson et al. (2016), Salman et al. (2017) and Wang and Pham (2011)

- The papers classified as A_MU apply the Pareto method to provide the proper trade-off between the reliability and cost criteria, and the considered indexes can be found in Table 8—for instance, CM, PvM and ASAI are optimized in (Piasson et al. 2016);
- Approaches that minimize the LOLC index seek to obtain the minimum cost independently of the customer type, unlike others that take into account this type using ECOST;
- Most studies consider preventive, or preventive and corrective costs, but few works (Briš et al. 2017; Dehghanian et al. 2013; Hanai et al. 2013) optimize in a comprehensive manner all the planning maintenance types, i.e., corrective, predictive and preventive.

4.2 Constraints.

Most mathematical programming and optimization approaches applied to the maintenance planning of EDS have constraints that can be equality or inequality, linear or nonlinear, or related to limits for decision variables. Among the main constraints, financial and reliability-based are the most commonly found. Some works consider both, as (Doostparast et al. 2014; Wang et al. 2014; Aravinthan and Jewell

Table 8 OBF by paper

Function	Reference
ASAI	Dhople et al. (2013), Nourelfath et al. (2012), Piasson et al. (2016), Salman et al. (2017), Yin et al. (2013) and Wang and Pham (2011))
ECOST	Bertling et al. (2005), Hanai et al. (2013), Hilber et al. (2007), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a)and Moraes et al. (2017)
ENS	Wang et al. (2016)
LOLC	Abbasi et al. (2009), Abiri-Jahromi et al. (2009), Bao et al. (2018), Caballé et al. (2015), Campelo et al. (2016), Dehghanian et al. (2013), Doostparast et al. (2014), Liu et al. (2014), Moradkhani et al. (2015), Ruiz-Castro (2014), Zhang et al. (2013), Wang and Pham (2011) and Wang et al. (2014)
MAIFI	Li and Brown (2004)
SAIFI	Li and Brown (2004) and Sittithumwat et al. (2004)
SAIDI	Li and Brown (2004) and Masteri et al. (2018)
CM Cost	Abbasi et al. (2009), Abiri-Jahromi et al. (2009), Bertling et al. (2005), Briš and Byczanski (2013), Briš et al. (2017), Caballé et al. (2015), Chang (2014), Chen (2012), De Jonge et al. (2015b), Dehghanian et al. (2013), Doostparast et al. (2014), Hanai et al. (2013), Hilber et al. (2007), Masteri et al. (2018), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b),, Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a), Moradkhani et al. (2015), Moraes et al. (2017), Nahas et al. (2008), Piasson et al. (2016), Ruiz-Castro (2014), Salman et al. (2017), Zhang et al. (2013), Wang and Pham (2011) and Wang et al. (2014)
PdM Cost	Briš and Byczanski (2013), Briš et al. (2003), (2017), Caballé et al. (2015), Campelo et al. (2016), Dehghanian et al. (2013), Hanai et al. (2013) and Yumbe et al. (2013), (2016)
PvM Cost	Abbasi et al. (2009), Aravinthan and Jewell (2013), Bao et al. (2018), Bertling et al. (2005), Briš and Byczanski (2013), Briš et al. (2003), Briš et al. (2017), Caballé et al. (2015), Chang (2014),, Chen (2012), De Jonge et al. (2015a), De Jonge et al. (2015b), Dehghanian et al. (2013), Doostparast et al. (2014), Hanai et al. (2013), Hilber et al. (2007), Lin and Wang (2012), Liu et al. (2014), Masteri et al. (2018), Melchor-Hernández et al. (2015), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a), Moradkhani et al. 2015, Moraes et al. (2017), Nahas et al. (2008), Piasson et al. (2016), Ruiz-Castro (2014), Salman et al. (2017), Zhang et al. (2013), Wang and Pham (2011) and Wang et al. (2014)
Crew	Silva et al. (2014)
Criticality	Carnero and Gómez (2017)
Lifespan	Salman et al. (2017)

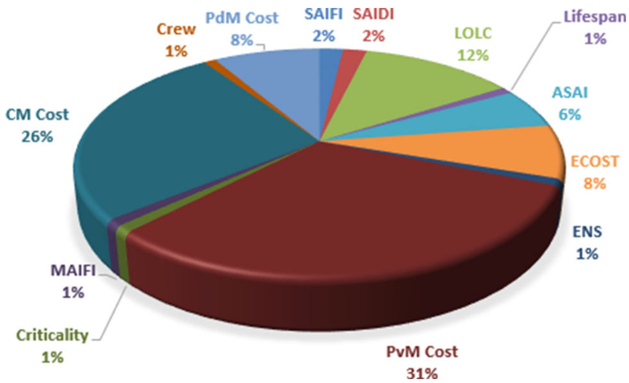

Fig. 6 OBF distribution

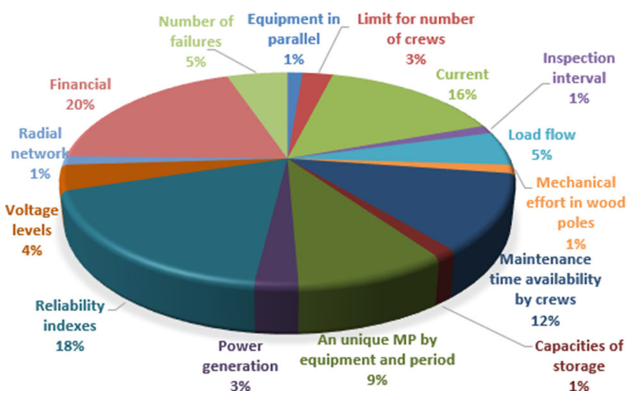

Fig. 7 Constraint distribution

2013; Wang and Pham 2011; Abiri-Jahromi et al. 2009). On the other hand, other works, as (Mirsaeedi et al. 2017a, 2017b), do not consider both constraints, but consider one of them as OBF instead of constraint, which leads to a similar covering of the trade-off issue. Mirsaeedi et al. (2017a) and Mirsaeedi et al. (2017b), for instance, consider financial constraints, whereas the reliability criterion is modeled as OBF. The modeling of a given criterion as objective function or constraint can be decided in function of the approach or software available to solve the MP problem. Constraints considered in the problem at hand are listed and summarized in Fig. 7 and Table 9.

It can be highlighted that Piasson et al. (2016) use monthly, quarterly and yearly limits for DIC and FIC while maximizing ASAI (Table 8). When this mix occurs, constraints impose hard limits, in general for frequency and duration indexes according to current regulation, whereas OBF makes other indexes as optimal as possible, in general, availability indexes.

Few papers consider the time for crew displacement in their models, despite the importance of such constraint for the MP problem. Notice that there are constraints needed to ensure a practical solution for the maintenance planning over the considered horizon taking into account that it must be defined a unique action per equipment and period.

4.3 Applied Programming and Optimization Approaches.

Mathematical programming and optimization approaches can be classified as dynamic (DP), linear (LP), nonlinear (NP), mixed-integer linear (MILP) or mixed-integer nonlinear programming (MINP), as well as heuristic or metaheuristic. Notice that heuristic and metaheuristic have as premise computational efficiency for problems that are difficult to treat by classical mathematical methods, in particular the mixed-integer ones. In general, metaheuristics are based on some behavior of well-known systems.

Figure 8 and Table 10 present an overview on approaches that have been applied to the maintenance planning of EDS, whereas Fig. 9 relates to only metaheuristic methods for the same purpose: genetic algorithm (GA), particle swarm optimization (PSO), tabu search (TS); simulated annealing (SA), artificial immune system (AIS) and great deluge (GD). Figure 8 highlights the prevalence of heuristics and metaheuristics proposals in the literature for the distribution system maintenance planning. This can be related to the capacity of these methods to handle nonlinear optimization problems considering decision variables from different natures (real, binary, integer).

Another advantage of metaheuristics is its capacity to deal with objective functions and constraints that cannot be written as an analytical expression. For instance, GA can easily interact with a distribution system simulator, i.e., the OpenDSS (ANEEL 2018), aiming at considering grid aspects in the optimization problem. Linear programming algorithms like simplex and interior point require a full mathematical formulation of the optimization problem, which can be a very difficult task for some objectives (grid-related indexes) or constraints (reliability indexes). Notice that a single reference using LP was found (Campelo et al. 2016) because the planning analyses are limited when neither nonlinear behavior nor discrete decision is considered.

Hybrid algorithms can be highlighted for combining good features of different optimization approaches, as in Bao et al. (2018), where heuristic is used to model load transfer, failure modes and their effect analysis defining priority equipment, and the PSO metaheuristic optimizes the maintenance plans. The algorithm of Piasson et al. (2016) is derived from GA for multi-objective problems, and their nonlinear model is solved by using DP for the decision-making in each period over a planning horizon. Lin and Wang (2012) also propose a hybrid method that combines heuristic and genetic algorithm. Finally, other works combine the advantages of two metaheuristics, as (Nourelfath et al. 2012) (GA and TS) and (Wang et al. 2014) (PSO and TS).

Table 9 Constraint by paper

Constraints	Reference
Financial	Abbasi et al. (2009), Abiri-Jahromi et al. (2009) , Aravinthan and Jewell (2013), Bao et al. (2018), Chen (2012), De Jonge et al. (2015a), Doostparast et al. (2014), Li and Brown 2004, Mirsaeedi et al. (2017a), (2017b), Nourelfath et al. 2012, Sittithumwat et al. (2004, Yumbe et al. (2013), Wang and Pham (2011) and Wang et al. (2014)
Reliability	Abiri-Jahromi et al. (2009), Aravinthan and Jewell (2013), Briš and Byczanski (2013), Briš et al. (2003), (2017), Doostparast et al. (2014), Lin and Wang (2012), Liu et al. (2014), Moraes et al. 2017, Nahas et al. (2008), Piasson et al. (2016), Zhang et al. (2013) and Wang and Pham (2011), Wang et al. (2014)
Storage capacity	Masteri et al. (2018)
Current	Bao et al. (2018)
Equipment in parallel	Nourelfath et al. (2012)
Inspection interval	Yumbe et al. (2013)
Load flow	Masteri et al. (2018), Mirsaeedi et al. (2017b) and Wang et al. (2014), (2016)
Maintenance time availability by crew	Abbasi et al. (2009), Mohammadnezhad-Shourkaei et al. (2011), Moradkhani et al. (2014a), Moradkhani et al. (2015), Moraes et al. (2017), Piasson et al. (2016), Silva et al. (2014), Sittithumwat et al. (2004) and Wang et al. (2014)
Mechanical effort in wood poles	Salman et al. (2017)
Number of crews	Bao et al. (2018), Wang et al. (2014)
Number of failures	Caballé et al. (2015), Chen (2012), Ruiz-Castro (2014) and Wang and Pham (2011)
Power generation	Bao et al. (2018) and Masteri et al. (2018)
Radial network	Bao et al. (2018)
Unique MP per equipment and period	Chang (2014), Doostparast et al. (2014), Mohammadnezhad-Shourkaei et al. (2011), Moraes et al. (2017), Nourelfath et al. (2012), Piasson et al. (2016), Sittithumwat et al. (2004))
Voltage level	Bao et al. (2018), Masteri et al. (2018) and Mirsaeedi et al. (2017b)

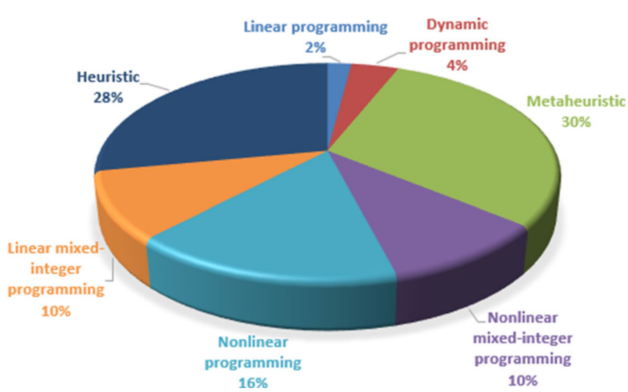

Fig. 8 Approach distribution

6 Conclusions and Remarks

This paper presented an overview of the main EDS maintenance planning proposals since 1944. This review comprises works involving predictive, preventive and corrective maintenance, and it was organized by relevant aspects as indexes and probability functions, objectives, constraints and applied approaches within a comprehensive classification.

The reliability analysis showed as being essential for the problem, and the Markov chain is the most used technique. The Monte Carlo and Poisson methods have also been frequently used. About the reliability indexes, the failure rate is the most used, followed by the mean repair time. Moreover, it could be concluded that most papers use more than one index for reliability assessment. Probability distributions have been applied to represent uncertain parameters, and the Weibull distribution is the most used, followed by the exponential.

Several methods have been proposed for EDS maintenance planning, being heuristic and metaheuristic the most commonly applied due to the nonlinear and combinatorial features of the problem at hand. Maintenance costs or reliability indexes are widely used as objective functions or

Table 10 Approaches for EDS maintenance planning by reference

Approach	Reference
Heuristic	Aravinthan and Jewell (2013), Bao et al. (2018), Bertling et al. (2005), Carnero and Gómez (2017), Chen (2012), Dehghanian et al. (2013), Li and Brown (2004), Lin and Wang 2012, Melchor-Hernández et al. (2015), Salman et al. (2017), Yssaad and Abene (2015), Yssaad et al. (2014) and Yumbe et al. (2013), (2016)
Metaheuristic	Bao et al. (2018), Briš et al. (2003), Doostparast et al. (2014), Hilber et al. (2007), Lin and Wang (2012), Mirsaeedi et al. (2017a), Mirsaeedi et al. (2017b), Moradkhani et al. (2014a), Moradkhani et al. (2015), Moraes et al. (2017), Nahas et al. (2008), Nourelfath et al. (2012), Piasson et al. 2016, Wang and Pham (2011) and Wang et al. (2014))
DP	Abbasi et al. (2009) and Zhang et al. (2013)
LP	Campelo et al. (2016)
MILP	Abiri-Jahromi et al. (2009), Briš and Byczanski (2013), Mohammadnezhad-Shourkaei et al. (2011), Silva et al. (2014) and Sittithumwat et al. (2004)
MINP	Briš et al. (2017), Liu et al. (2014), Masteri et al. (2018), Yin et al. (2013) and Wang et al. (2016)
NP	Caballé et al. (2015), Chang (2014), De Jonge et al. (2015a), (2015b), Dhople et al. (2013), Hanai et al. (2013), Ruiz-Castro (2014) and Xu and Hu (2013)

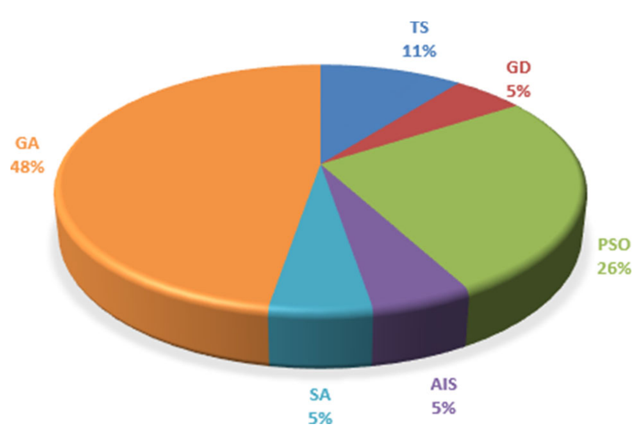

Fig. 9 Metaheuristics distribution

constraints. It could be concluded that most works have focused on costs with priority to the preventive ones, followed by corrective and predictive maintenance costs.

Although most papers consider more than one objective, most approaches can be classified as mono-objectives because they handle different merit functions within a unique function by using weighting. Few papers have applied more proper approaches for multi-objective problems as, for instance, the Pareto method, which points out a lack of accurate methods in the literature and a promising research field.

Most models are unconstrained, which outlines another lack of proper modeling in the literature, since the problem at hand is actually constrained. The works that consider constraints include mainly the financial and reliability criteria. Finally, the need for developing more accurate approaches is reinforced by the fact that most papers do not consider multiple equipment' or crew's displacement.

Some gaps were identified, and from them some future developments can be performed as:

- Development of comprehensive approaches that can consider several reliability indexes, random variables and equipment that are complementary for obtaining good trade-off EDS maintenance plans;
- Given the low number of references that consider a suitable trade-off between different criteria, mainly cost and reliability, by using a proper multiobjective approach, it can be pointed out as a lack and opens a range of possibilities for future investigations. The same is applicable for future developments that can consider in a comprehensive manner all the maintenance types—corrective, predictive and preventive—which tends to provide holistic optimal solutions;
- Investigation of alternative or complementary methods, as the interval mathematics or neural networks whose potential can also be assessed to improve the assertiveness of maintenance decisions;
- Investigation of the impact of electric vehicles and their load stations, with the related uncertainties, in the maintenance planning of EDS, since these devices modify the network load condition and thus the lifespan of grid equipment.

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