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Visualization of distribution system planning for engineers and decision-makers

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Abstract: Planning of an electric distribution network is a complex task, requiring a comprehensive approach that includes collecting and analyzing large amounts of technical and nontechnical data. In addition, the outcome of the planning procedure needs to be supported by economic analysis that provides pathways for future investments. In order to present the planning results to various groups of people, such as technical staff, managers, and politicians, different visualization techniques are used. Data visualization, as a branch of descriptive statistics, is important to understand and present information in an effective manner. The basic idea of visualization is to present data in a visual form, allowing a person to get a quick insight into the data, draw conclusions, and directly interact with the data. Some traditional methods, such as graphs, histograms, 2D column and line charts, single line diagrams, and 3D surfaces with contours, are mandatory for visualizing power data. However, in the electric power system business there is a growing need for geographically referenced visualization. While there is a lot of research being done on visualizing data in transmission power systems, the number of studies on display methods in distribution power systems is limited. The focus of this paper is the visualization of data used during the distribution network planning process.

Key words: Data visualization, distribution network planning, geographical referencing

1. Introduction

Distribution network planning is an ongoing task that needs to be conducted systematically in order to support the long-term goals. The main challenge is to strive towards long-term goals in an effective manner, simultaneously solving all current and short-term problems appearing in the network.

The initial and the most important step in distribution system planning is gathering all the data relevant for both short- and long-term planning. This includes technical data (load curves and information on all the distribution system elements) and population data, as well as foreseen investments in both demand and generation facilities. The next step is the identification of current problems and issues that need to be fixed in the shortest time frame. However, these solutions need to be compatible with the long-term goals, as otherwise they represent an unnecessary investment. Although there is no *perfect* distribution system planning solution, good distribution system planning studies are able to reach long-term goals while seamlessly incorporating solutions to current and short-term problems.

There is a fair amount of both scientific and technical literature available on the topic of distribution system planning. Most of the older work was focused on increasing reliability, e.g., [1–3]. Although reliability is still an important issue in distribution system planning [4–6], the focus has recently moved towards an effective integration of distributed generation [7–10] and demand response [11]. An elaborate review of distribution power

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system planning methods is presented in [12]. However, all of these papers present mathematical formulations accompanied by theoretical case studies. Although planning studies are technically very demanding, practical experience has shown that the representation and interpretation of results to the technical staff and especially to the decision makers is of vital importance for the proposed plan to be accepted and followed. This paper presents various visualization techniques in distribution network planning developed over the years based on feedback from the Croatian national distribution system operator (DSO) and ideas extracted from the available literature [13]. While some of them are suitable for strictly engineering purposes, others are intended to be used in executive summary reports prepared for decision makers. The visualization techniques presented in the following sections bring some relevant contributions to the field of distribution system planning:

- *Comprehensive and systematic way of summarizing input data.* While the available literature offers theoretical background on methodologies for distribution network planning, practical experience shows that up to 50% of the data needed are not systematically collected and available for planning studies. In this sense, this paper analyzes different data sources and formats that can be used as inputs into a planning procedure. In the absence of detailed measurements (usually very few measurements in distribution networks are available beyond secondary substations), different sources can be used to create a more detailed representation of the current, and consequently future, state of a distribution network.
- *Visualization of planning results suitable for engineers.* This paper recognizes the need to visualize the planning results to the planning personnel, the maintenance personnel, and other engineering personnel as each of them perceives distribution grid problems from a different perspective. This means that the current distribution network states and layouts, but more importantly future distribution network plans, need to be visualized in both geospatial and schematic representations. These visualizations should indicate areas close to the borders of technical constraints, indicating critical points for maintaining reliability of supply for the final consumers.
- *Visualization of planning results to financial decision makers.* The paper proposes several solutions to bridge the gap often present between the engineering and financial sectors. While the engineering implementation is the essential part of planning, without a clear visualization of the required investments the planning process is almost futile. Without a clear financial background supporting planning decisions, the needed investments are often reduced if not cut back entirely. The planning proposals are thus presented in a clear manner giving insight to decision makers on the pros and cons of making a specific investment decision. In this context, the proposed visualization relies on existing indicators, intuitive to the DSO, for planning and monitoring of quality of electricity supply, such as system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI).

The rest of the paper is divided into five sections as follows: Section 2 elaborates the distribution system planning procedure, proposing a concept shown in Figure 1 and explaining in detail the benefits of creating a unified framework for input data and their visualization. Section 3 provides an insight into distribution system planning issues and different methods for visualization of the results to utility engineers. In Section 4 we propose several solutions for visualizing results and the need for investments to the decision-makers. Finally, Section 5 provides the relevant conclusions.

The overview of the visualization methods presented in this paper is the result of the authors' experience in conducting a number of distribution system planning studies in Croatia. The Distribution network of Croatia is divided into 21 distribution control areas (DCAs), each with its specifics in terms of size, spatial load density,

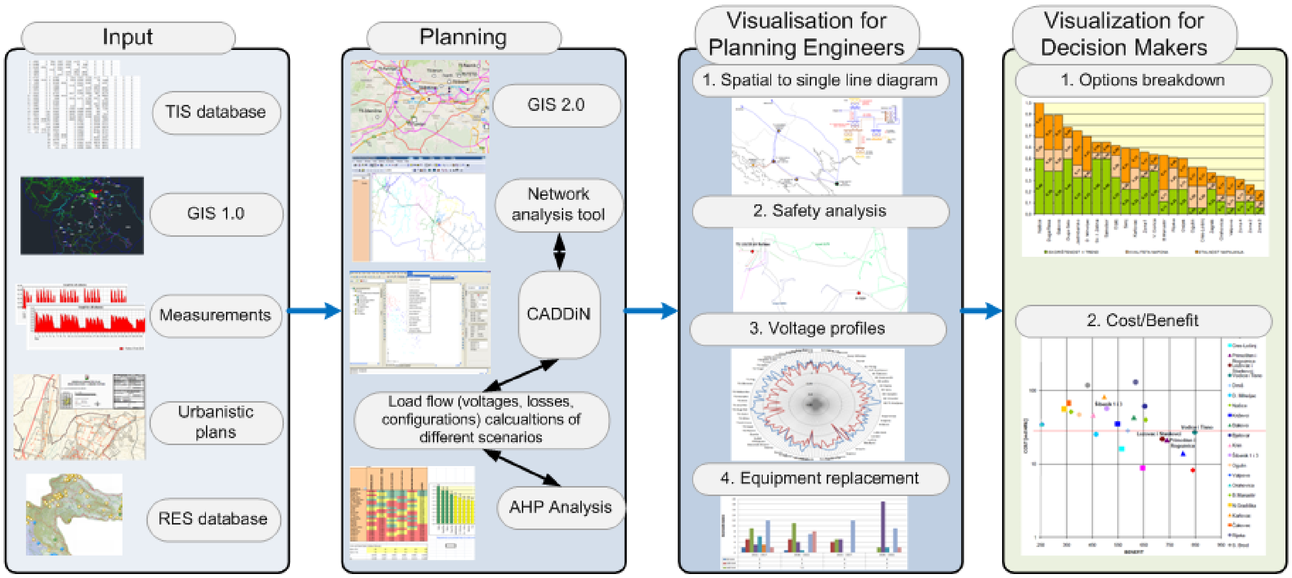


Figure 1. Multilayer concept of different stages of distribution network planning.

consumption profiles, age of the equipment, and unique operating issues. The Croatian DSO is constantly conducting distribution network planning studies, recognizing each the specifics of each DCA, but insisting on a universal approach when it comes to technical and economic analyses.

2. Visualization concepts for planning a distribution grid

In a deregulated and competitive environment the key parameter in planning distribution networks is the investment costs. One of the main goals is to reduce losses and operational costs while maintaining the quality of service keeping the investments as low as possible. Therefore, economic parameters, such as costs of undelivered energy and cost/benefit analysis, are gaining more attention in the planning process and becoming a dominant factor when making decisions.

In general, the technical component of the planning process can be broken down to these tasks, as shown in Figure 2:

- Acquisition of all the parameters of the distribution grid;
- Data preparation and adjustment;
- Development and validation of the initial model of the grid;
- Analysis of the demographic data;
- Load and consumption forecasts;
- Detailed network analyses including but not limited to power-flow calculation, voltage profiles calculation, reliability analysis, short circuit analysis, losses calculation;
- Definition of the optimal network configuration;
- Contingency analysis;
- Analysis of transitions to desired voltage levels.

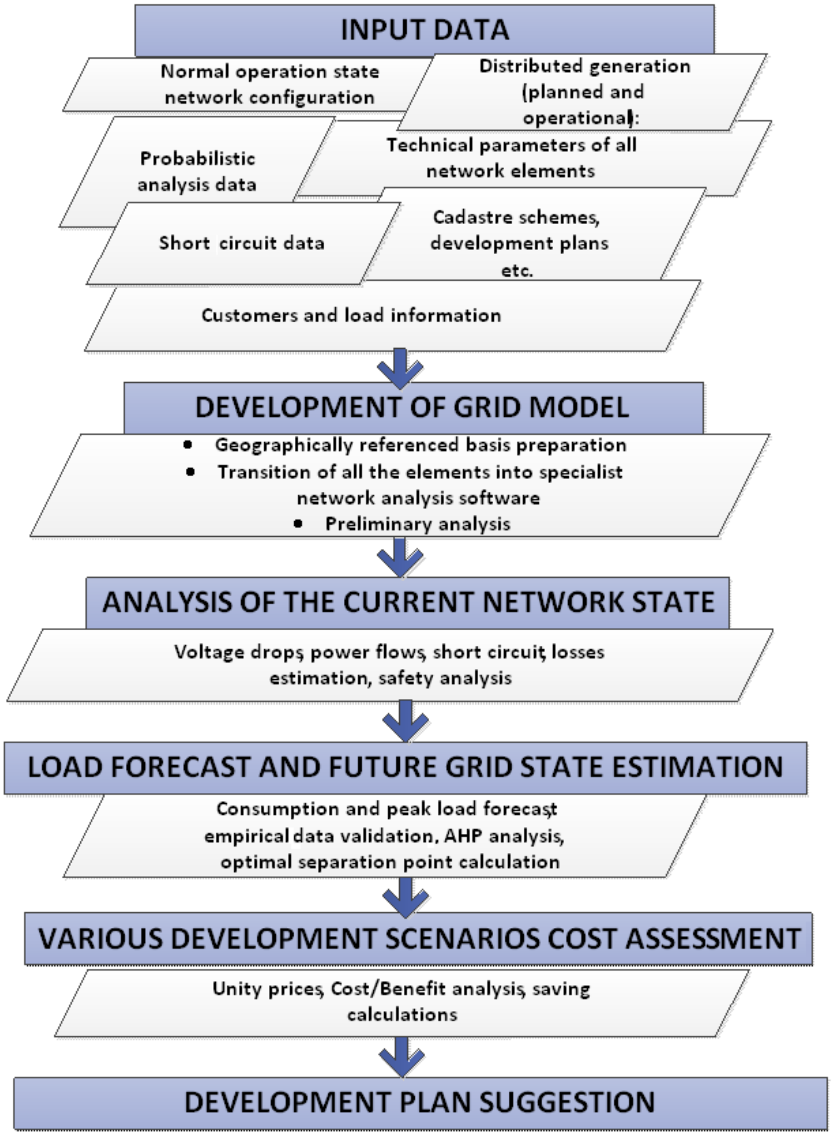


Figure 2. Flow diagram of the technical aspects of the distribution system planning process.

The planning process begins with collection and processing of a large amount of data available for a distribution area. The quality and quantity of these data vary depending on the planning area and, although the DSO makes a preliminary quality check of the data, it is difficult to argue there is a universal starting point when it comes to the input information.

2.1. Geographical referencing of all distribution grid elements

The available literature indicates that the geographical information system (GIS) is a prerequisite for distribution system planning [14–17]. A presentation of the NREL's GIS-based real-time state estimation model is available in [18]. The authors of [18] confirm that, although this seems quite straightforward and logical, even these days there is surprisingly little digital information that enables GIS. Unfortunately, in reality very few distribution areas have their network elements georeferenced. Even if georeferenced data exist, they are usually not integrated with the data warehouse containing equipment characteristics, age, or any other relevant planning and maintenance data. In Figure 1 this is called GIS 1.0: a simplified version of georeferenced lines and dots without any additional information. The initial step in the planning process is creating a useful GIS system. To increase the quality of the planning results, in particular the visual presentation of the results, additional tools have been developed. Even though these tools are primarily developed as planning and calculation tools, additional benefits can be recognized in creating a unified method for data collection and processing particularly valuable for future planning needs.

The initial step is to create a connection between the existing, if any, geographical information system (GIS 1.0 in Figure 1) and the belonging database of the grid elements (TIS database). This creates the so-called GIS 2.0. There are several methods of visualization of the distribution grid among which the most commonly used is Google Earth base with added distribution network units locations, as shown in Figure 3. A connection with the network analysis software is needed in order to provide valuable information on demand trends in various parts of the network. Usually, GIS applications contain a spatial analysis tool and feature statistics and geo-processing tools enabling a statistical analysis and breakdown structure of geo-referenced elements by their type, age, capacity etc. giving further insights into which locations require investments [19]. Creating a GIS platform should also be considered one of the most important steps in integrating alternative options to “more copper” in both distribution network operation and planning. The importance of GIS lays not only in visualization of the parts of the network operating close to their technical limits, but also as a central tool and a unified database for multiple advanced modules to assist in operation and planning.

Figure 3. Geographical representation of 110 and 35 kV network of a Croatian DCA (green – 110 kV lines; blue – 35 kV lines; red – 35 kV cables).

Optimization software, CADDiN, has been developed at the Faculty of Electrical Engineering and Computing, University of Zagreb, to determine the optimal grid layout for ”green” and ”brown” field problems [20]. This software visualizes the results in the GIS 2.0 environment.

Each planning process begins with the input data collection and processing. Although visualization is not of vital importance at this level, the concepts presented in this section can be regarded as a framework for future planning. A good planning process requires repeated review of the planning results, usually every 5 years, and adjustments in accordance with the realization of the previous plans. Having a unified input data collection methodology increases the quality of the planning process.

3. Visual presentation of the planning results to the utility engineers

Power system analyses, which involve handling of large data, inevitably imply using effective visualization methods to facilitate analysis and assist the user in obtaining a clear understanding of the present state of the system. Using analytical and nonanalytical methods for modeling the range of input data for present and future years can help determine the most probable and the worst case development scenarios. While this is a common technical problem when it comes to modeling and power flow simulations, power/energy losses, voltage drops, and other network analyses, the visualization and presentation of results must be done in a unified and easily understandable way.

The process of visualization for engineers is tightly correlated with the technical analyses conducted and it is impossible to elaborate on visualization techniques without discussing the analytical process that precedes them. The rest of this section discusses basic analyses in the planning process, but focuses on the methodology for presenting the results.

3.1. Load and consumption representation

Available data on load and consumption largely depend on the number of advanced meters installed in a specific DCA [21]. Although the idea of installing advance meter reading (AMR) infrastructure in every household is emerging, in reality these are installed in industrial facilities, small and medium enterprises, and only a portion of households. Consequently, exact consumer profiles for households are usually not available when planning a distribution system. On the other hand, consumption profiles from the interface with the transmission network are available, which helps approximate the missing household loads. As a starting point, consumer types are defined, as shown in Figure 4. Load modeling of small consumers is performed using replacement curves of standardized consumer types depending on their location and behavior. We created seven replacement curves for urban and rural areas, residential and commercial objects, public lighting, households with electric and district heating, weekend houses, and small industry, approximating their consumption for the work day and for each day of the weekend. The share of each of these seven types is then defined for each 10(20)/0.4 kV substation. The sum of all load profiles results in the overall load, which is balanced to the total consumption profile collected at the interface point with the transmission system. Smaller adjustments are made to fit the results with an acceptable level of error. While bar and pie charts are one of traditional techniques to visualize static or dynamic data, a 3D surface with contour visualization of load profiles at the interface with transmission is shown in Figure 5.

Load and consumption forecasting methods can roughly be divided into two main groups:

- Independent methods are based on the actual consumption data from the past and are defined only as a function of time. Each of the methods for load and consumption forecasting is fitted to the available historical data; the one having the smallest deviation in correlating to the data in the past is selected for future load and consumption forecast.
- In dependent methods, load and consumption in the future are determined as a function of various factors, which are characteristic for the area of interest. While these methods tend to give a better insight into

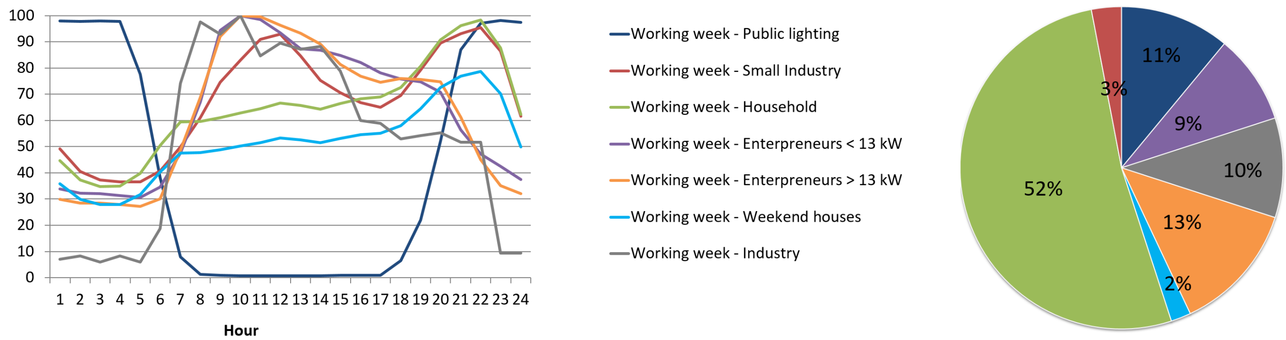


Figure 4. Bar chart of the number and the installed capacity of the 10(20)/0.4 kV transformers.

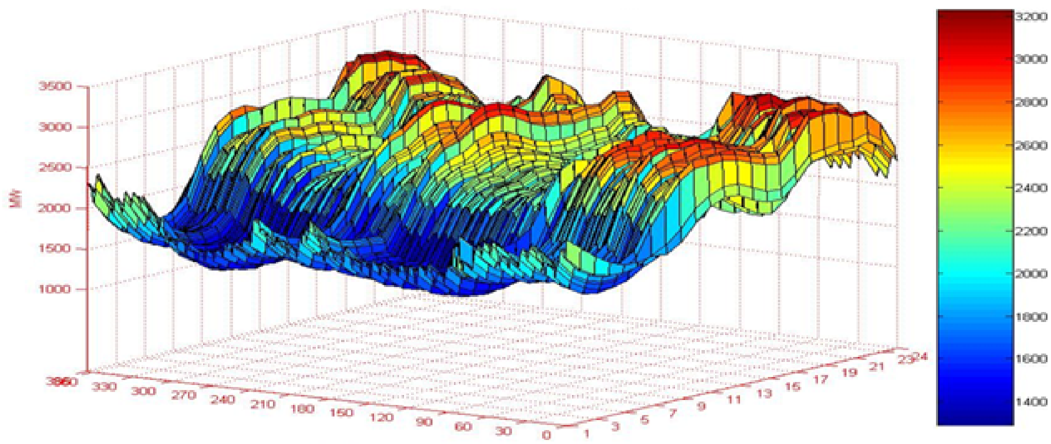


Figure 5. Load diagram of all DCAs in Croatia in 2012.

trends of the observed area (economical, population growth, land usage), they require a larger set of input data. Although the availability of these data is increasing as the centers for statistics include more data and higher resolutions into their questionnaires, in practice these methods have been inapplicable, especially when making load and consumption forecasts for smaller areas.

Regardless of the selected method, the shorter the forecast horizon is, the more accurate the forecast will be. Long-term planning studies are conducted for a period of at least 20 years in the future and the planners need to take into account the uncertainties of the load and consumption estimates they make today. The entire complex process of forecasting as accurately as possible is usually of little interest to the utility engineers. Figure 6 provides an example of a forecasting method, including the historical consumption data points.

3.2. Network analyses visualization

Starting from the initial reference scenario, which should present the current state of the grid as accurately as possible, these analyses are conducted for each planning horizon, usually in 5-year increments. Results obtained by these analyses serve as the initial indicator of problems in the grid, but also as a confirmation that the investments suggested to correct these are appropriate. These results need to be clear and useful to a number of specialty engineers ranging from maintenance to field engineers at the utility company. While maintenance engineers will prefer visualization of different supply directions to the final consumer in a geographically referenced network model, on-field personnel prefer a traditional "unbundled" block scheme of the network

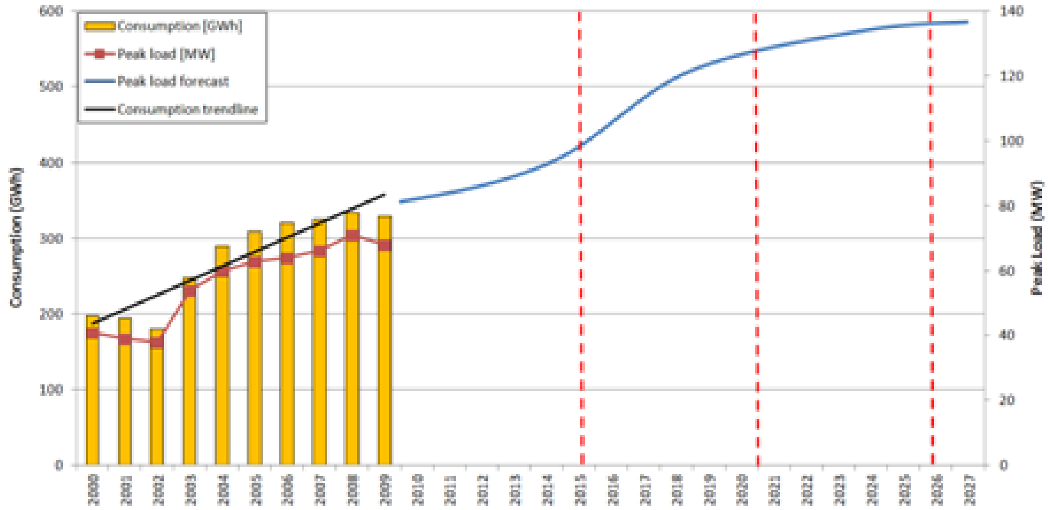


Figure 6. Presentation of the forecasting results with best fitting method.

highlighting potential problems. The reasons for these preferences are mostly historical as distribution grid planning predates computer technology. In addition, the "unbundled" or single line schemes were the backbone of the old supervisory control and data acquisition (SCADA) systems and on-field engineers base their education on these concepts and understanding of the grid.

A compressive approach is achieved by combining a single line diagram coupled with a geographically referenced map, as shown in Figure 7.

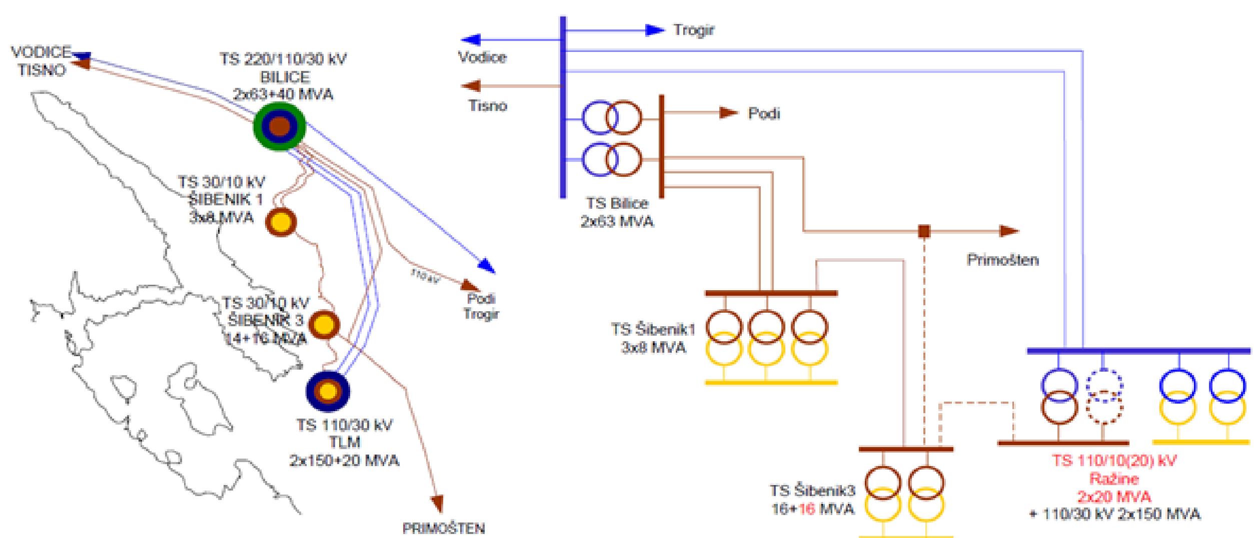


Figure 7. An example of geo-referenced map and single line scheme of 110–30 kV distribution level.

In practice, it is difficult to present the results of a network analyses with a large number of network elements and summarizing results of each element in a table is not useful. In Figure 8, two different concepts are shown: the first one shows the values for each line, node, and substation while the second one presents contour visualization of the same results [22,23]. Contour visualization is a method of connecting points of equal elevation and although it needs to be supported with tables containing element results, it is an excellent way of indicating initial problems in the distribution grid [24]. Presenting results in such a way is particularly useful when presenting contingency, or $N-1$, analyses showing an alternative way of supplying the demand when grid values are near the values of violating security constraints. Dynamic pie charts are an alternative solution to visualize the magnitude of line loading [22]. The idea is to have a pie chart appear on the line if it is overloaded or is close to overload. This will draw the operator's attention to the problem. When comparing two methods of visualization in Figure 8, it becomes rather clear that the contour presentation in combination with pie chart presentation gives a clearer insight into current or planned distribution network status.

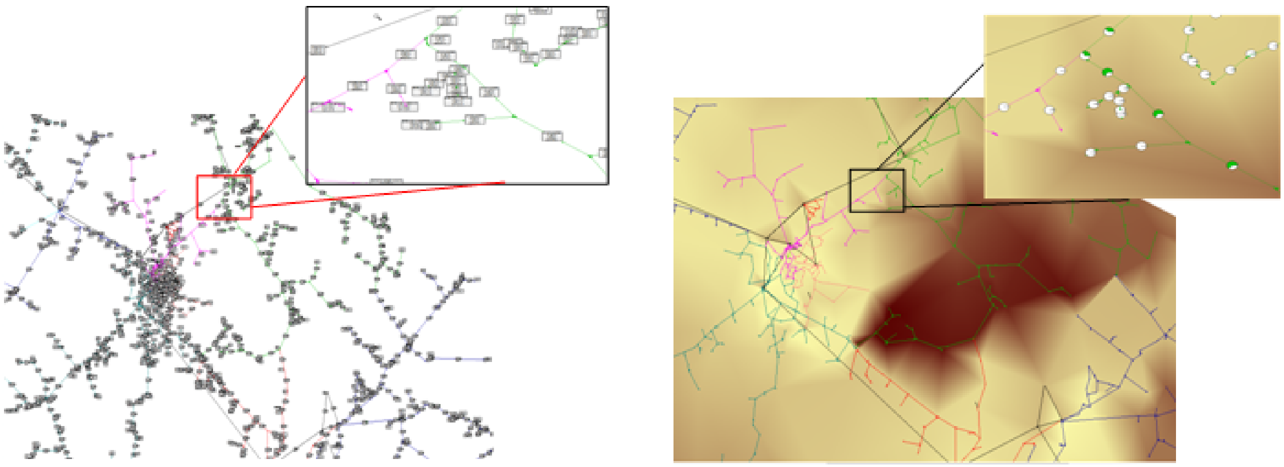


Figure 8. Different visualization concepts of distribution network analysis results.

An interesting way to present voltage profile through the network is the radar chart shown in Figure 9. In a clear and straightforward way extreme voltage values over all buses are summarized in a single figure.

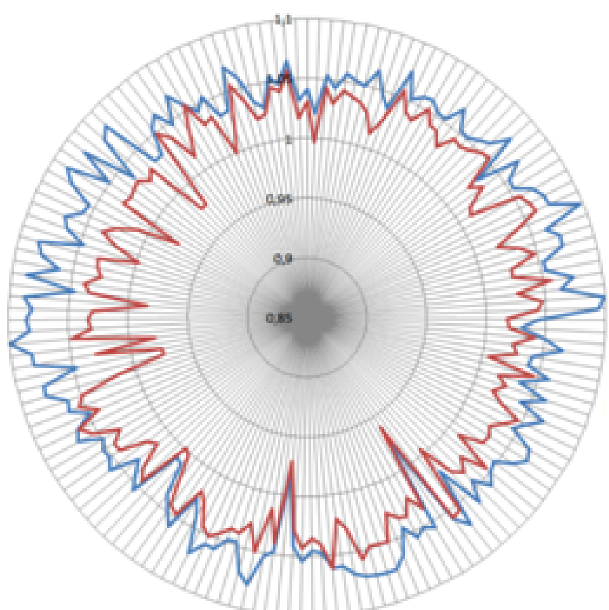


Figure 9. Voltage rose visualizing node voltages during peak and off-peak conditions in a distribution network.

4. Visualization of planning results for strategic decision-makers

Regardless of the quality of the planning procedure and the results visualization for engineers, visualization of the suggested future investments is the one that provides a framework to the management and financial structures for the required short- and long-term investments into the grid. For this reason, a structural graphical representation is developed showing planning costs and investment distribution for each planning phase presenting the results in a transparent way. Alongside time distribution, the proposed structure descriptively elaborates the investments by voltage levels, pieces of equipment, and technology.

4.1. Strategic planning decisions

One of the key strategic goals of the Croatian DSO is to replace the current three-level distribution voltage system, namely 110 kV, 35 kV and 10 kV, with a two level system, namely 110 kV and 20 kV, which will result in lower maintenance cost, improved voltage levels, lower losses, and other benefits. However, it is not possible to simply eliminate a voltage level, as this is a process lasting for decades. While some locations of the present 110/35 kV substations will simply be substituted by 110/20 kV substations, most will require a technically more demanding analysis. The decisions are supported by the proposed analytic hierarchy process (AHP) method. The benefits of transition to the two-voltage level system have been calculated and are shown on the left-hand side of Figure 10. The benefits are scaled to the maximum value 1.0 and are calculated based on 5 indicators:

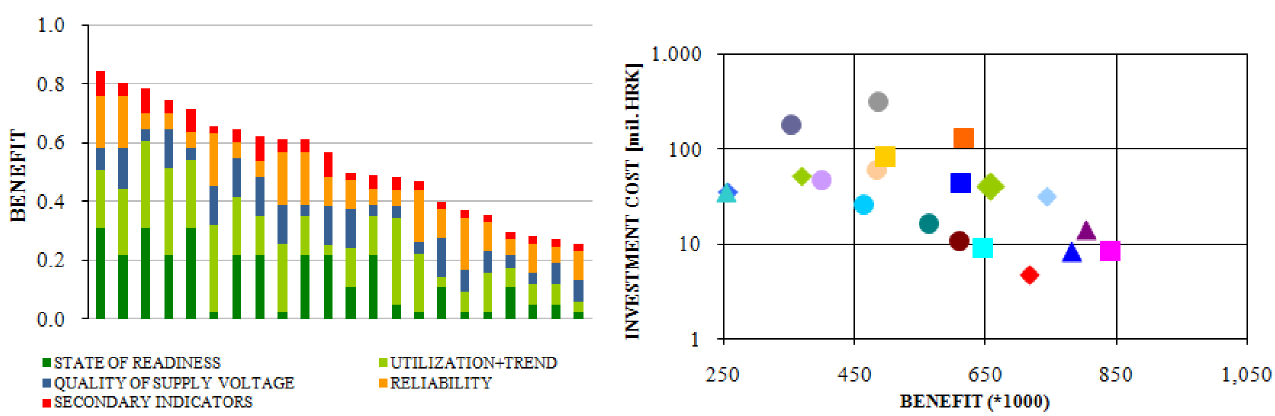


Figure 10. Breakdown structure on 20 kV distribution systems planning and investment priority visualization.

- Readiness of the network for the transition to the two-voltage level system – represents the portion of equipment already prepared to run at 20 kV;
- Utilization of the current network and trend of the consumption – represents the need for upgrades of the network with respect to the current and expected loadings;
- Voltage quality – quantifies the parts of the network with too low or too high voltage;
- Reliability of supply – represents reliability indicators explained in the following subsection;
- Secondary indicators – show if the surrounding networks are already operating at 20 kV and if there are investors willing to contribute to 20 kV equipment, e.g., investors in distributed energy sources or in industry facilities.

Comparing investment cost needed to achieve these benefits results in visualization as on the right-hand side of Figure 10.

4.2. Reliability indictors

The quality of costumer supply is best described using reliability indicators providing the information on the system average interruption duration (SAIDI), system average interruption frequency (SAIFI), and customer average interruption duration (CAIDI).

These factors are used to calculate energy not supplied (ENS) for a specific area. Equations for calculating these indices are given in (1) to (4):

$$SAIDI = \frac{\sum_{i=1}^{N_{SSN}} UV_i \cdot N_i}{\sum_{i=1}^{N_{SSN}} N_i} \tag{1}$$

$$SAIFI = \frac{\sum_{i=1}^{N_{SSN}} \lambda_{Fi} \cdot N_i}{\sum_{i=1}^{N_{SSN}} N_i} \tag{2}$$

$$CAIDI = \frac{\sum_{i=1}^{N_{SSN}} UV_i \cdot N_i}{\sum_{i=1}^{N_{SSN}} \lambda_{Fi} \cdot N_i} \tag{3}$$

$$ENS = \sum_{i=1}^{N_{SSN}} UV_i \cdot P_{sri}, \tag{4}$$

where

T total period used for calculations (usually one year = 8760 h),

N_i total number of consumers at node i,

U_{Vi} unavailability of supply at node i expressed in hours,

λ_{Fi} frequency of interruptions at node i (faults/year),

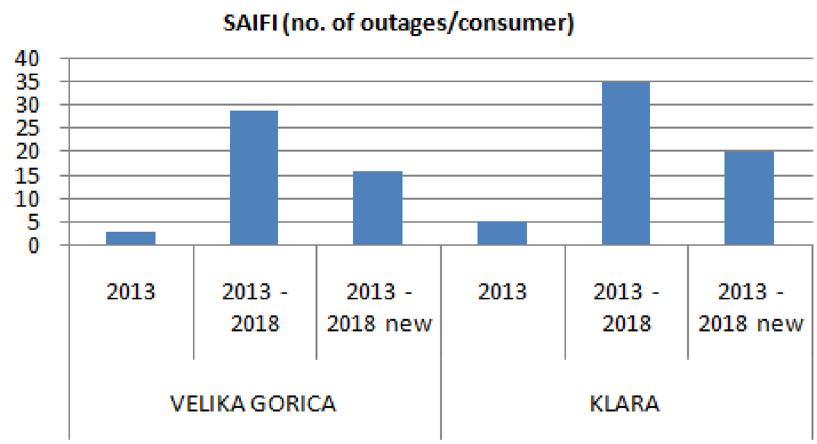
N_K total number of customers with at least one interruption over a period of one year,

N_{SSN} total number of nodes in the analyzed part of the distribution grid,

P_{sri} average load at node i.

The reliability indicators are calculated for the current network state and for the following 5-year period. An example of these values is shown in Figure 11. Values for the planned period, years 2013 to 2018, are shown as twofold: first for the "business as usual" case and second with the proposed investments and increased reliability. These investments are usually focused on remote switchgear and finding alternative supply points, closing as many feeders as possible in the so-called loop layouts. Increasing the reliability and quality of supply indices is in fact of major concern for the DSO. Insufficient SAIDI and SAIFI values are considered key indicators for further investments. Recent research is focused on increasing the reliability of supply and enhancing the quality of electricity through novel technologies such as storage or services such as demand response [25,26].

While both have shown promising results, the majority of DSOs have not yet adopted these technologies in their planning approaches and do not consider their utilization when creating future plans. For this reason, the idea presented here is not to propose new methodology for estimating SAIDI and SAIFI but rather to emphasize their value for distribution network planners. Visual representation of the results as in Figure 11 is a clear and efficient way of analyzing effects and potential investments for decision makers.



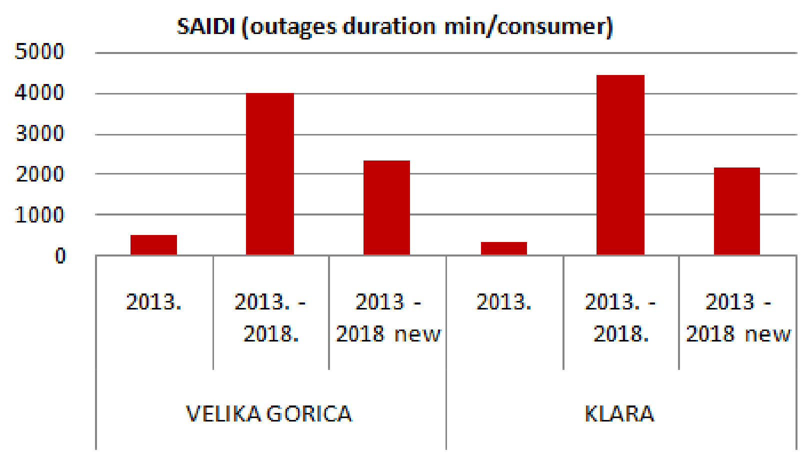


Figure 11. Reliability indicators calculations without and with suggested investments.

5. Conclusions

The goal of this paper was to present and elaborate practical solutions in planning DCAs, with emphasis on visualization of the results. Lack of quality visualization solutions may be a critical issue when seeking for financing in order to improve distribution network reliability and efficiency. The paper identifies these insufficiencies and brings additional value to the future network planners. The benefits are threefold:

1) A presentation of a comprehensive and unified method for defining input data into the planning process and visualization of the same. The proposed method can be of significant value for more detailed representation of the current distribution networks, which are characterized by scarce data from a number of different

format sources. In addition, the proposed methodology focuses on creating visual representation through GIS as a central point for developing advanced modules that should be of high relevance in planning future low carbon distribution networks.

2) The proposition of a framework for unified visualization techniques for utility engineers, taking into account their field of expertise. Again, this contribution emphasizes the aspect of developing advance GIS platforms but also focuses on traditional ways of network layout representations.

3) Development of the concept of visually presenting results in a simple to understand way to the decision makers, elaborating the need for investments into future distribution system development. This aspect is usually the most neglected one, often preventing realization of good distribution plans due to insufficient funds. The paper demonstrates a simple way of visualizing the effectiveness of investments for the proposed distribution network plan to the decision makers in utility companies.

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