

A Reference Network Model: the PECO model

Jesús Pascual Peco González
Instituto de Investigación Tecnológica
Universidad Pontificia Comillas, Madrid, Spain
<http://www.iit.upco.es>

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1 Introduction

The traditional distribution function actually comprises two separate activities: distribution network and retailing. Retailing, which is also termed supply, consists of trading electricity at the wholesale level and selling it to the end users. The distribution network business, or merely distribution, is a natural monopoly and it must be regulated. Increasing attention is presently being paid to the regulation of distribution pricing.

Distribution pricing comprises two major tasks: global remuneration of the distribution utility and tariff setting by allocation of the total costs among all the users of the network services. In this paper, the basic concepts for establishing the global remuneration of a distribution utility using the incentive based revenue cap scheme is presented.

Revenue cap regulation is able to promote an adequate level of: investment and operation costs, network losses, as well as quality of service. In order to assess and achieve these targets, a special type of distribution planning model called Reference Network Model is presented. This special type of model is being used both in Spain and Chile as an aiding tool for distribution regulation.

This paper is divided into two sections. The former is an introduction to the main features of reference network models and their role in distribution regulation. The latter describes the reference network model developed by IIT, including some execution examples, a graphical tour, and finally the list of projects where the model has been and is being used.

2 Reference Network Models

The main goal of distribution Regulators is the achievement of an objective, transparent and non-discriminatory remuneration of distribution utilities, considering both the economic viability of utilities and the net social welfare.

In Spain, an incentive-based regulation of electricity distribution companies, based on revenue caps, was introduced in 1997. The revenues are computed annually, and the new revenue cap is determined on the basis of last year's revenue cap adjusted for inflation, productivity improvement, and load growth. The idea behind the load growth compensation term is that the grid companies should be compensated for increased costs due to grid expansion. The formula of the proposed revenue cap is as follows:

$$R_{t+1} = R_t \cdot (1 + CPI - X) + Y_t + Q_t \pm E_t$$

Where:

| | |
|-----------|------------------------------|
| R_{t+1} | revenue in year t+1 |
| R_t | revenue in year t |
| Y_t | load growth compensation |
| Q_t | quality of service incentive |
| E_t | forecast errors compensation |

From a regulator's point of view, it is a hard task to determine the above terms due to an information asymmetry and an inherent complexity in assessing large size distribution networks. In order to make this task easier, Reference Network Models have been developed. These types of models are suitable tools for estimating the initial revenue cap (R_t), the load growth compensation (Y_t) and the quality of service incentive (Q_t), as well as the technical efficiency of distribution networks.

A Reference Network Model characterizes distribution service areas and designs a distribution network that connects final customers of electricity represented by their geographic locations, load peaks load and voltage levels. The methodology to determine the reference network should consider criteria of optimal network planning taking into account both technical and reliability constraints, investment, network losses and also O&M costs. Therefore, it may be used as an accurate benchmark of real networks.

2.1 General Features of Reference Network Models

In order to obtain an adequate benchmark of actual networks, a Reference Network Model should design large scale electricity distribution networks optimally, considering all the technical features imposed to actual distribution networks. The main variables that should be considered in the objective function are:

Total Cost = f (investment, O&M, quality of service, network ohmic losses)

Reference Network Models may have two different ways of designing the network:

- From scratch. In this case, the model should be able to design distribution networks, comprising hundreds of thousands of customers using a database of normalized equipment and several technical constraints imposed by the user using a set of parameters. The model should provide detailed results in order to perform sensitivity analyses.
- Expansion planning. In this case, the model should be able to load actual distribution networks from the utilities databases or reference networks obtained beforehand, and design their optimal expansion in order to satisfy an expected future demand increase or supply additional customers.

2.2 Input data, standardized equipment database and parameters

A Reference Network Model should design distribution networks considering these two key issues: (i) the distribution service areas should be modelled accurately, and (ii) the ideal reference networks given by the model should be as optimal as possible in order to obtain an appropriate benchmark.

According to these two key issues, input data can be classified into three categories:

Customer' data and transmission substations

The customer's database of distribution utilities and transmission substations (sources of the distribution networks) are the basic input data of the Network Reference Model.

Customer data should include at least: GPS coordinates, contracted power and annual energy consumption. Once audited, this data has to be loaded in the model as it is.

Distribution service areas modelling parameters

The objective of this set of parameters is to achieve an accurate modelling of the distribution service areas. Notice that if the service areas are not loosely modelled, the reference networks obtained cannot be used as an objective benchmark of actual networks. The main parameters that belong to this category are:

- Parameters associated with the *identification of settlements* and selection of *aerial or underground network* areas within settlements.
- *Simultaneity coefficients* to obtain system peak load from customer's contracted power.
- *Load and loss factors* used to compute energy and network losses in the different network voltage levels. These parameters have a great impact on network sizing.
- Historical *network voltage levels*.
- The *price of energy losses*, which has also a significant impact on network sizing.

Most of these parameters are out of control of distribution utilities. Other parameters, such as historical network voltage levels, should whenever possible be kept the same in the reference model because replacement costs of existing assets (transformers) are uneconomical. Therefore, these parameters cannot be part of the model's optimization objective function.

This set of parameters should be tuned so the Reference Network Model models the service areas accurately. Notice that the results obtained by the model and the actual network should match in: (i) the settlements identified, (ii) the percentage of LV, MV and HV aerial/underground network kilometres, and (iii) the peak load and annual energy of the service area.

Optimization and efficiency promoting parameters

The role of these parameters is setting the basis for an optimal network design from the regulator's viewpoint considering current and future demand. This design has adequately to take into account the lumpiness of distribution investment and its economies of scale, the network losses and the quality of service. The main parameters belonging to this category are:

- The *rate of return* used to compute the present value of network losses and O&M costs. This parameter has a great impact on network sizing.
- The *reserve factors* used to size assets are a key issue in promoting a long-term stable investment signal to distribution utilities.
- The regulated *quality of service* indexes that should be satisfied by both the actual and the reference network.
- The *standardized equipment database* (lines, cables, distribution transformers, distribution substations, protective devices...) used to design the network.

These parameters have a dramatic impact on network sizing, and determine the key features of the efficient network needed to supply a service area. Therefore, these parameters should be set by the regulator in order to promote an efficient utilities performance both in the short and long-term taking into account social welfare.

3 The Peco Model: main features

The PECO model is a planning tool capable of designing large distribution networks comprising hundreds of thousands of customers within hours. The main features of the model are:

- The model considers the **GPS coordinates** of customers and transmission substations to build the whole distribution network, that is: (i) MV/LV transformers, (ii) HV/MV substations, y (iii) and LV, MV and HV networks.
- The model determines automatically the settlement's outlines and their corresponding street maps from the aforementioned GPS coordinates.
- Additionally, **orography raster maps**, forbidden ways through... given by the user, are taken into account by the model during the design of the network (modifying the line routes).

- The optimization of both urban networks (constrained by the **street map**) and rural networks (considering orography and forbidden ways through...) networks are performed simultaneously.
- **The electric hardware** (lines, cables, HV/MV substations, MV/LV transformers, capacitors, manual sectionalizer, maintenance teams, fault indicators, circuit reclosers, voltage regulators...) used by the model can be customized very easily with a graphic interface.
- The network is sized by: (i) minimizing investment, operation & maintenance, losses subject to capacity, voltage and reliability constraints, and (ii) taking into account present demand and an estimation of its future growth.
- The network reliability assessment is computed **simulating the real process after a network failure has taken place**: (i) fault detection, (ii) fault location, (iii) fault clearance, and (iv) service restoration. This is a key point for designing both rural and urban areas in an unbiased way.
- The reliability assessment is computed using the parameter "cost of non-supplied energy", which can be different for each customer. The results of the model (specially the size and number of HV/MV substations and the MV network) depend on this parameter, allowing the user to obtain the optimal network investment vs reliability curve of a large service area.
- The results of the model may be exported to the **Arc/View's Shape format**, which allows an unbeatable display of: (i) power flows, (ii) number and duration of interruptions, (iii) location of electric hardware, (iv) network topology...

4 Three possible ways of running the model

The PECO model can be run in three different modes:

- Greenfield planning (without considering the existing network) of a large distribution network, given the size and location of transmission substations and the GPS coordinates of LV, MV and HV customers. In this case, the aim of the model is: (i) to design an optimal distribution network to electrify an area, or (ii) to compute the new replacement cost of an existing distribution network¹.
- Planning the distribution network given the location of HV/MV substations and/or the MV/LV transformers.

¹ The distribution of electric energy is a natural monopoly, therefore it has to be regulated. The goal of any regulation is to remunerate electric utilities in an objective, transparent and non-discriminatory way, as well as setting fair tariffs to consumers. In order to perform both tasks, the regulator may use the ideal network obtained using the "new replacement costs" methodology as a suitable indicator of the "efficient" costs of the distribution activity. The new replacement cost of a distribution network of a service area is the cost of an optimal and ideal network designed from scratch that electrifies that area.

- Given the topology of the LV or MV network, optimize conductor sizing, losses and/or reliability of supply. This running mode is especially suited for assessing the MV network cost and its impact on reliability of supply, as well as performing sensitivity analysis.

5 Implementation Details

The PECO model has been tested under Linux, Unix, Windows NT, Windows 2000 and Windows XP. It consists of two independent modules that exchange information during the execution:

- **A graphical user interface (programmed in wxWidgets)**, used for: giving the data to the model, and controlling the execution of the network planning modules.
- **Network planning modules (programmed in ANSI C++)**, which design the distribution network given the data provided by the user interface.

The results of the model are given in two different file formats: (i) text ASCII files describing network costs, losses, length, installed capacities of HV/MV substations and MV/LV transformers... and (ii) Arc/View's Shape files containing detailed graphical information.

The Arc/View Shape files can be displayed using Arc/Explorer, which is an exceptional free GIS capable of performing queries, zooms...

6 Practical Uses

The main features of this model are: (i) it is capable of tackling large scale networks, (ii) there is no need to classify the service area beforehand in urban or rural areas, (iii) the geographic features service area, the reliability assessment, the demand are modelled in detailed, and (iv) the optimization of the whole service area is unbiased. These features make the PECO model suitable for both electric utilities and regulators.

From an **electric utility's** point of view, this model is a useful tool capable of performing several tasks, such as: (i) greenfield planning of a new service area, (ii) long-term and sensitivity analyses of an existing network, (iii) identifying areas of poor reliability of supply and putting forward improvement plans.

From **regulator's** point of view, this model is a suitable tool for: (i) assessing the technical efficiency of electric utilities, and (ii) setting targets for both reliability of supply and losses. These are the key features needed by any regulator for the tasks of determining an objective remuneration for electric utilities and tariff setting.

Section 9 briefly describes the real applications where the PECO model has been validated.

7 Execution examples

This section shows the key features of the model through some case studies. More specifically, this section describes: the modelling of demand and settlements, (ii) the input parameters and electric hardware, and (iii) the distribution planning models.

The modelling of demand and the determination of settlements comprise four phases:

1. *Identification of settlements.* The settlements and their outline are automatically identified from the customers' GPS coordinates, based on their number and dispersion.
2. *Determination of the street maps of each settlement* in order to constrain the network routes inside a settlement.
3. *Selecting aerial and underground areas* in each settlement. Aerial lines and/or underground cables may be installed within a settlement depending on the user's choice, but outside the settlements the model only considers aerial lines.
4. *Processing geographic information* (orography, forbidden rights-of-way...) that can affect the location costs of MV/LV transformers, HV/MV substations and the LV, MV and HV network routes outside settlements.

After this initial demand modelling, the PECO model comprises several planning modules, which can be run one after the other sequentially, or one at a time only. These planning modules are:

1. Locating MV/LV transformers.
2. Locating HV/MV substations.
3. LV network planning.
4. MV network planning.

The PECO model designs the network from scratch, that is, without considering the existing network, but also the user may be able to fix the location of MV/LV transformers, the location of HV/MV substations and/or the topology of the network beforehand.

7.1 The identification of settlements

The pictures shown bellow represent a service area comprised of 900000 customers. The model defines a settlement as a group of customers verifying a minimum number of them and a maximum distance between the farthest neighbours.

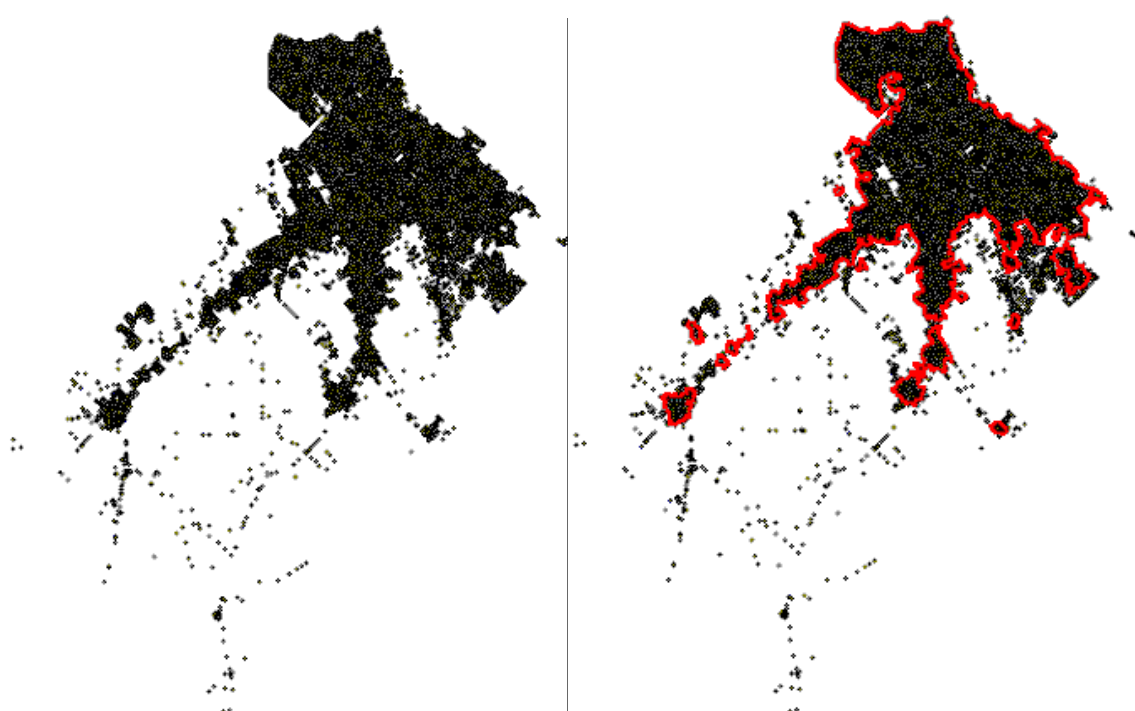


Figure 1 Identification of settlements

The picture shown on the right depicts the outlines of the settlements in red. These outlines represent the frontier between the network affected by orography, forbidden ways through... and the network constrained by the street maps.

7.2 The street maps

After all settlements have been identified, the model determines a street map for each one. These street maps are graphs, whose nodes are comprised of the GPS coordinates of customers and transmission substations, and whose edges constrain the possible network routes within a settlement.



Figure 2 A street map built by the model

The picture on the left shows the customers within a settlement. On the right, the obtained street map is depicted². Note on this picture how the "blocks" are detected, and how the network cannot cross over the streets from everywhere. Also note that without these two key features, the length of urban networks designed by the model could not be realistic.

7.3 Orography

The orography of the service area may be given in the [Arc/View](#) ASCII raster format. The network routes are optimized taking into account that the slope of the terrain affects the cost of installing a line. The next picture shows the settlements, the HV/MV substations and the MV network obtained by the model of the northern part of the province of Madrid.

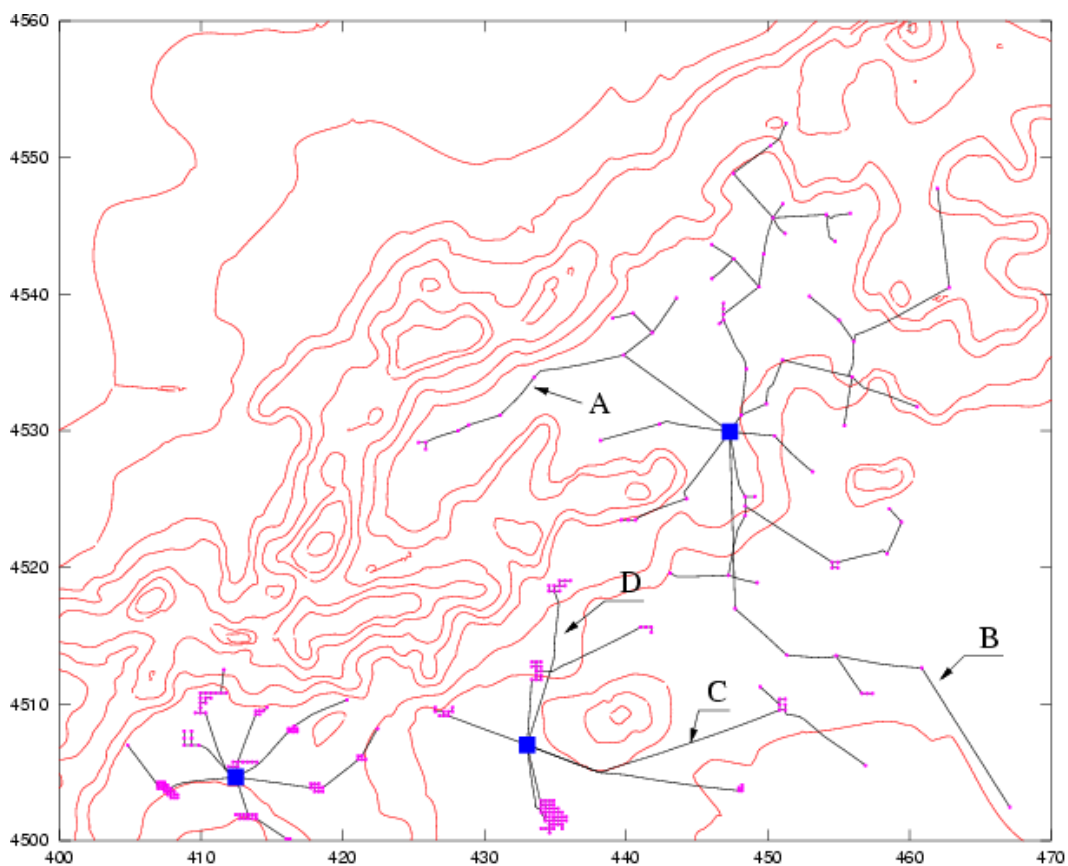


Figure 3 A MV network considering orography

The model considers the orography during the optimization of the network, see the picture above. Note how line "C" does not cross over a mountainous area which had been defined as a forbidden way through beforehand, and how line "D" does not cross over a settlement.

² The user may give the real street map to the model.

7.4 Parameters and equipment

The PECO model is a versatile tool that obtains realistic results thanks to the great number of input parameters and to the complete standardized electric hardware that can be given. Basically, the model needs three types of data:

1. **Equipment**³

- LV, MV and HV aerial lines and underground cables.
- Aerial and underground HV/MV substations.
- Aerial and underground MV/LV transformers.
- Protective devices for the MV network.
- Capacitors and voltage regulators for the MV network.

2. **Technical and economic parameters**

- Rate of return to assess the present worth of investment, losses and operation and maintenance.
- Rate of demand growth.
- Number of years of linear depreciation.
- The cost of energy losses.
- Load and loss factors for LV, MV and HV networks.
- Simultaneity factors in LV, MV and HV networks.

3. **Demand modelling.**

- Definition of a settlement.
- Rate of aerial/underground LV, MV and HV networks.

The model has a graphical user interface in order to introduce this data easily.

7.5 Location of MV/LV transformers

The objective function of this module is to minimize investment, operation&maintenance and losses of the MV/LV transformers and the corresponding LV networks, subject to capacity and voltage constraints.

³ For example, the file that describes the different conductors (aerial lines and underground cables) that the model may use contains the following parameters: resistance, reactance, failure rate, repairing time, and investment and maintenance costs. The user may also give different parameters for aerial lines that are going to be installed under 500m of altitude, between 500 and 1000m, and over 1000m of altitude.

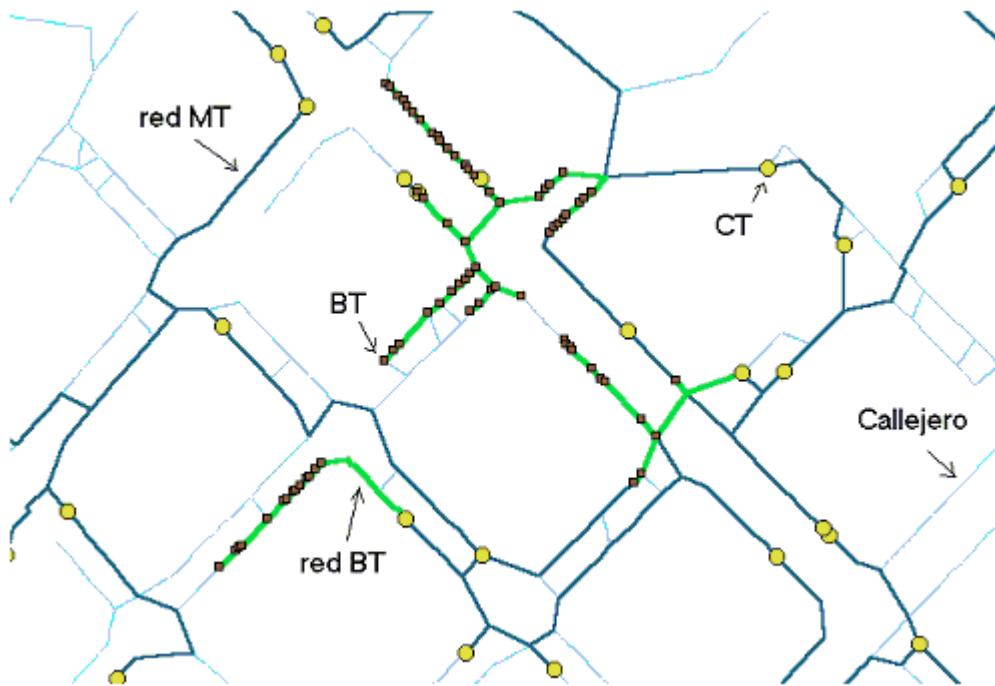


Figure 4 LV & MV network, and MV/LV transformers within a settlement

The figure depicts a very small example of a LV network within a settlement. This figure depicts: (i) the street map, (ii) the MV network, (iii) several LV customers, (iv) the MV/LV transformers that supply those customers, and (v) the LV network that connects both. Note that LV and MV cables may share the same ditch.

7.6 Location of HV/MV substations

The next figure shows the settlements and the transmission substations of an area of 26.000 km² and 300.000 customers. Note the three zones (A, B and C) that have been depicted.

This section describes the module that locates HV/MV substations in an area given the MV/LV transformers, the MV customers, and the transmission substations. This module considers the following costs in the objective function:

1. Investment, operation and maintenance costs of HV/MV substations to be installed,
2. The costs of a simplified MV network (considering reliability) that links the HV/MV substations with the MV/LV transformers and MV customers,
3. The costs of a simplified HV network that links the transmission substations with the HV/MV substations.

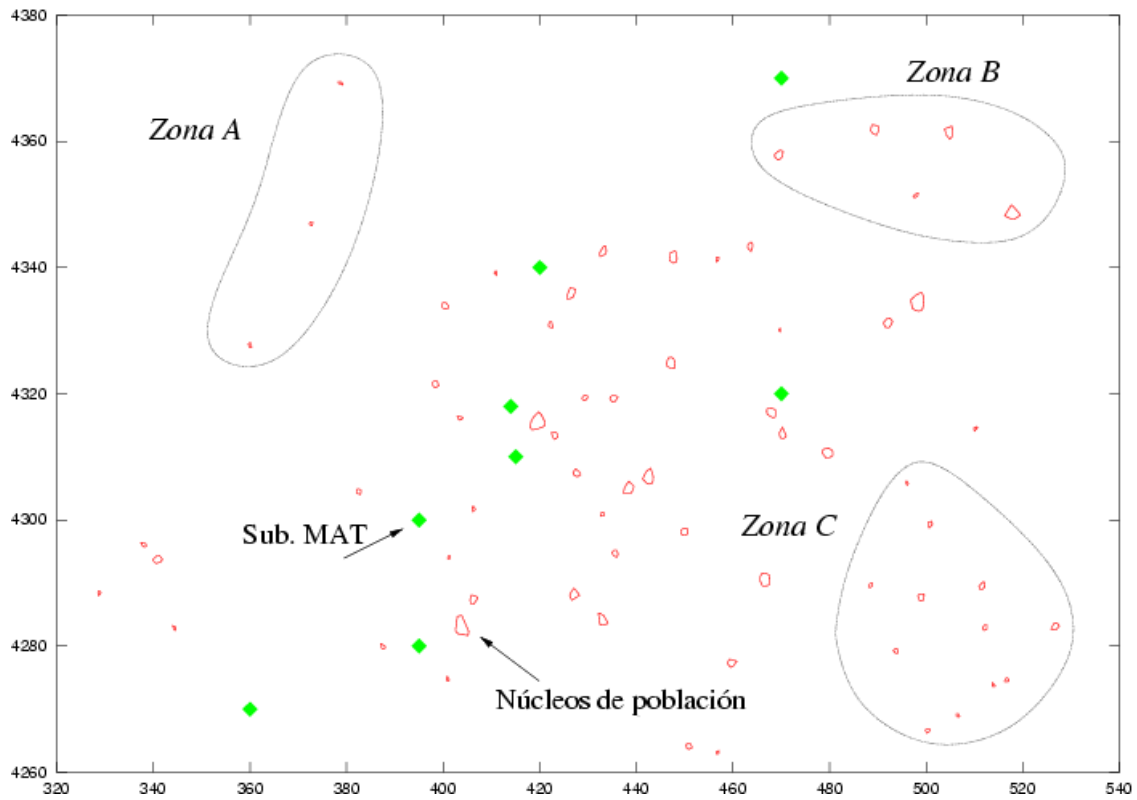


Figure 5 HV/MV substations location case study

The figure below shows the location of HV/MV substations and the simplified MV network supposing that the non-supplied energy costs of every MV/LV transformer and every MV customer is 0.6€/kWh.

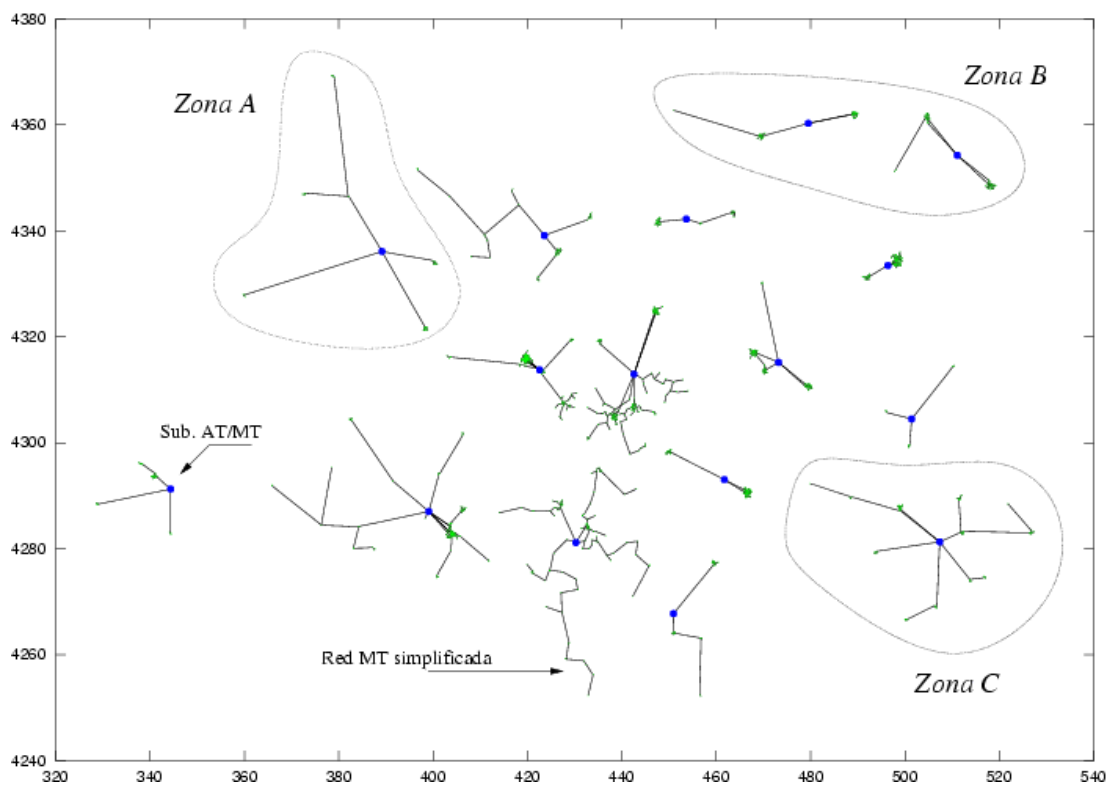


Figure 6 HV/MV substations location considering 0.6 €/kWh

The next picture shows the results of the same module but considering that the costs of non-supplied energy is 1.8€/kWh.

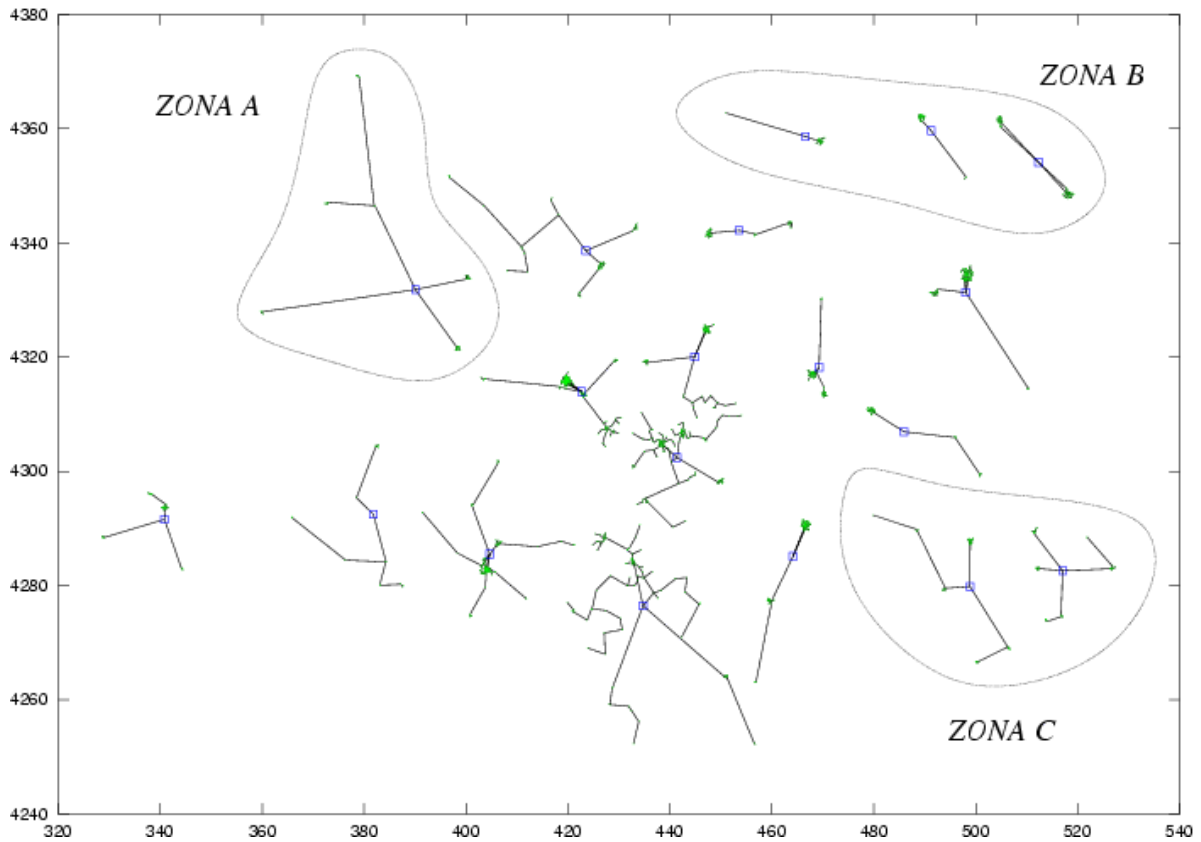


Figure 7 HV/MV substations location considering 1.8 €/kWh

The next table shows an abstract of the results of both case studies. Note the different number of HV/MV substations, and the reliability indexes of areas A, B and C.

| | ENS = 0.6 €/kWh | | | ENS = 1.8 €/kWh | | |
|---------------|-----------------|--------------|------------------|-----------------|--------------|------------------|
| | <i>TIEPI</i> | <i>NIEPI</i> | <i>no. HV/MV</i> | <i>TIEPI</i> | <i>NIEPI</i> | <i>no. HV/MV</i> |
| Zone A | 13.0 | 2.9 | 1 | 9.4 | 2.6 | 1 |
| Zone B | 5.6 | 1.6 | 2 | 2.1 | 0.8 | 3 |
| Zone C | 4.8 | 2.1 | 1 | 2.2 | 1.5 | 2 |

This example reflects the importance of reliability in the results. Both the difference in the number of interruptions and their duration are due to both the different number of HV/MV substations and the number of protective devices that the model installs in the MV network.

It is interesting to mention that zone "A" is very disperse and its demand is not large enough (less than 2 MVA) as to make an additional HV/MV substation worthy.

7.7 MV network planning

The MV network planning comprises three phases:

1. Planning a radial network that links the HV/MV substations with the MV/LV transformers and the MV customers, minimizing investment, maintenance and losses costs, subject to capacity constraints.
2. Given the radial network obtained in the previous phase, optimize the location of maintenance teams, sectionalizing switches, fault indicators, automatic circuit reclosers, feeder reinforcements and alternative supply feeders (tie circuits) in order to improve the reliability of supply.
3. Finally, locate capacitors and voltage regulators to minimize losses and verify voltage constraints.

The next two figures depict a MV network comprised of 20000 MV/LV transformers and 65 HV/MV substations. The former represents the southern part of a large settlement. Note that both the urban and the rural areas shown are optimized simultaneously. The blue triangles represent the HV/MV substations, the yellow boxes are MV/LV transformers, the MV network is shown in black and the tie-lines in red.

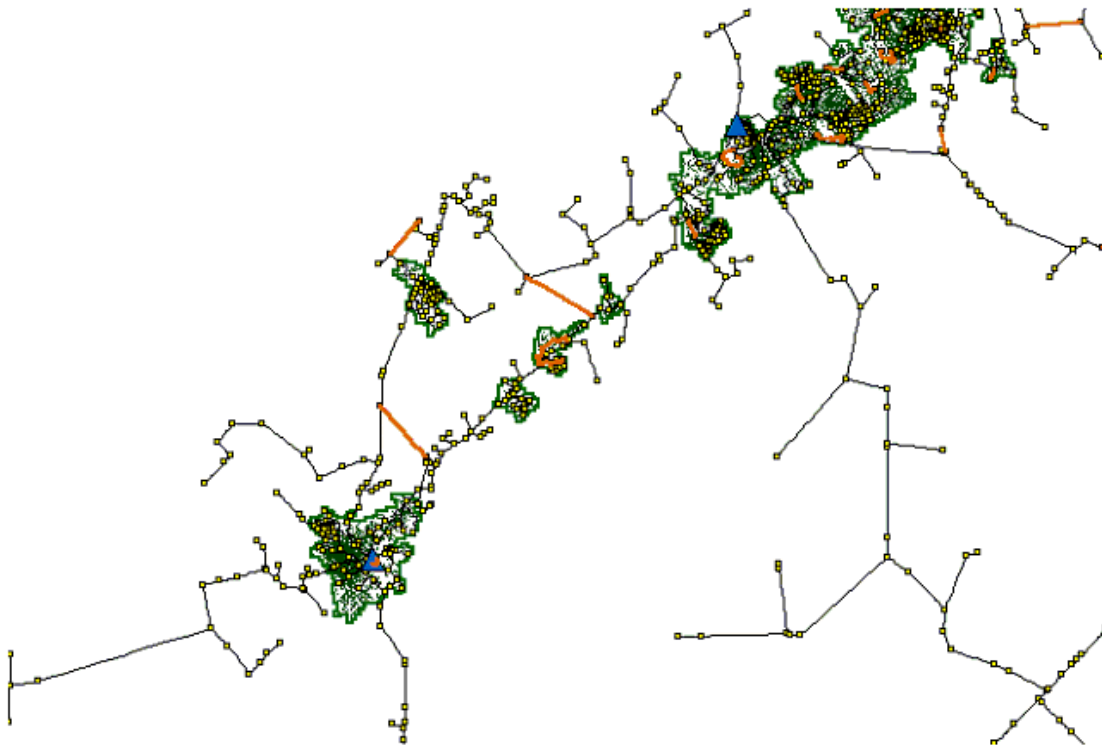


Figure 8 MV network with alternative feeder supplies

The next figure depicts the MV network and the street map designed by the model in an urban area. Note how the routes are constrained by the street map and how the wide avenues cannot be "crossed" from everywhere.

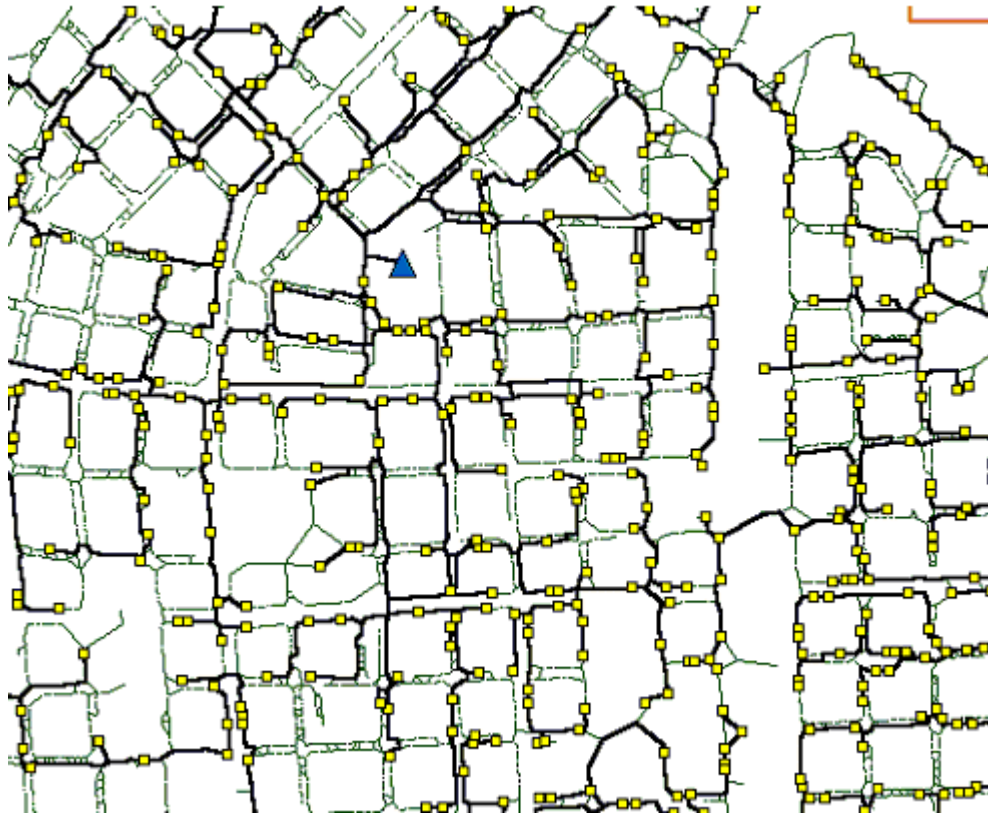


Figure 9 An urban MV network

Both the street map and the MV network optimization modules have been validated with real networks larger than 5.000 km (given the location of both HV/MV substations and MV/LV transformers). The resulting error was less than 7%.

7.8 Reliability of supply

Reliability of supply is a key issue due to its impact on network investment. The PECO model has been developed to tackle large service areas comprising both urban and rural areas. In order to optimize both areas even-handedly, the model is based on the following:

1. The total unavailability time due to an equipment failure is divided into:
 - A "*locating time*" to find the fault.
 - A "*sectionalizing time*" to isolate the fault and restore the supply partially or totally depending on each case.
 - A "*repairing time*": to repair the damaged equipment.
2. The model obtains the optimum equilibrium in: (i) maintenance crews, (ii) fault indicators, manual switches, automatic circuit reclosers, and (iii) feeder reinforcements and alternative supply feeders; in order to improve reliability of supply.
3. The parameters associated with the reliability assessment (failure rates, the displacement speed of maintenance crews, repairing times...) are modelled by "fuzzy" numbers to take into account the randomness and the uncertainty related to the whole process (equipment failure, location, repair and restoration of supply).

These three features of the model are basic to obtain robust⁴ and even-handedly solutions in both urban and rural areas.

The next figure shows investment to improve reliability (in thousands of €) vs the network's non-supplied energy for values of non-supplied energy costs ranging from 0.6 and 7.8 €/kWh. For each value of non-supplied energy costs, the model gives three possible values of non-supplied energy: minimum, expected and maximum, all of them are depicted as a vertical segment in the figure. These minimum, expected and maximum network's non-supplied energy values are related to the aforementioned "fuzzy parameters".

Note that the impact of investments to improve reliability (maintenance crews, reclosers, manual switching devices...) on the overall network investment (16 million € in this case study) can be very significant.

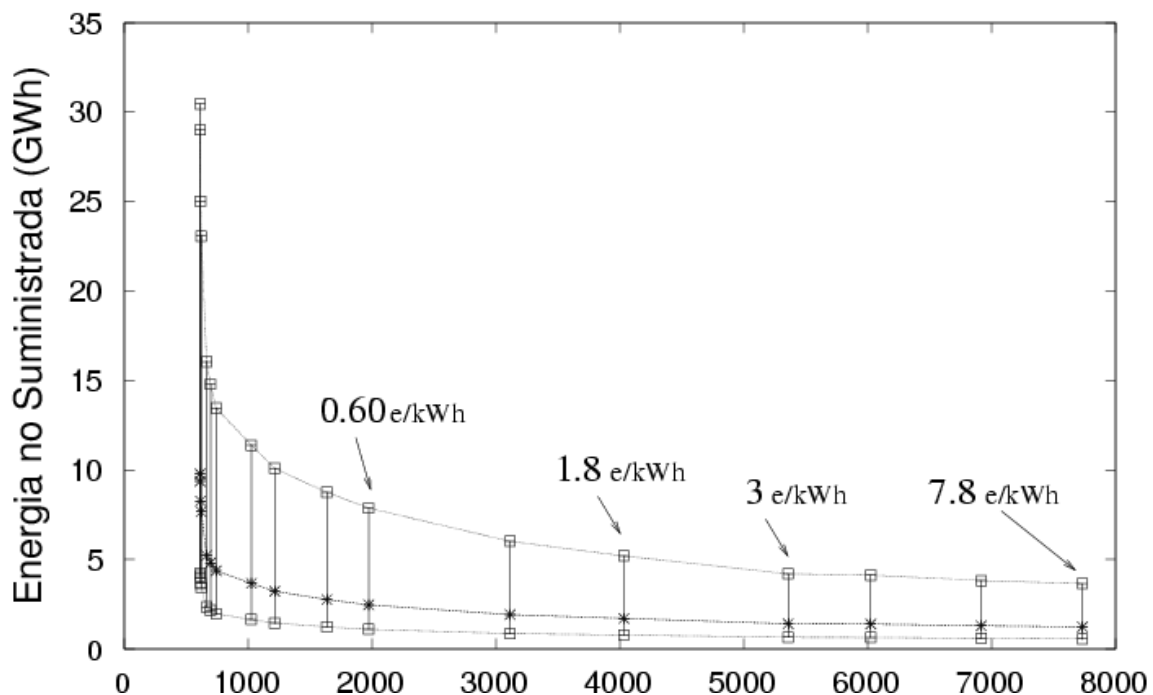


Figure 10 Non-supplied energy vs investment to improve network reliability

The three key features of the reliability model are: (i) the optimization depends on the costs of non-supplied energy given, (ii) the accurate modelling of reliability, and (iii) the use of fuzzy parameters. This module has been validated with real MV networks of 15000 MV/LV transformers comprising both urban and rural areas.

The PECO model is also capable of taking optimal investment strategies in order to comply with given global and individual reliability indexes.

⁴ The model optimizes investment taking into account three possible scenarios given by the parameters that influences on reliability. Therefore, the obtained solution is said to be robust as it is suitable within a large range of scenarios (low failure rates, high repairing times, high crew's speeds...).

8 The PECO model graphical tour

The graphical user interface has been developed using wxWidgets, which is an easy-to-use API for writing GUI applications on multiple platforms. This user interface has been tested under both linux and windows.

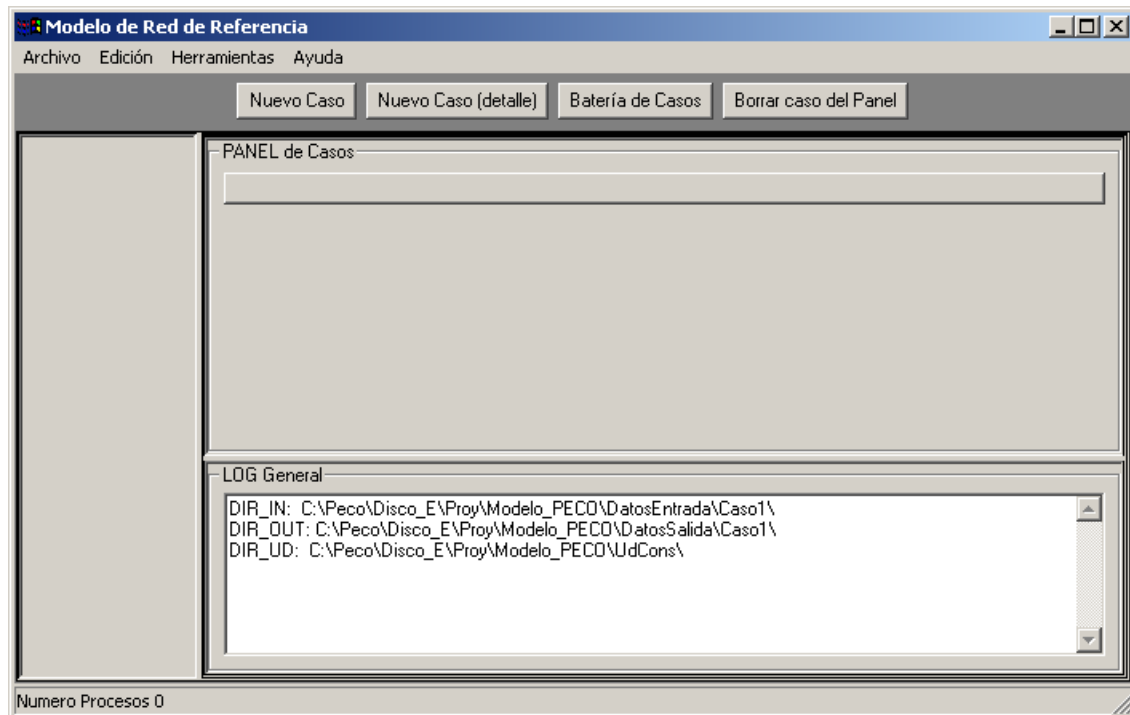


Figure 11 The Graphical User Interface main window

8.1 Executing a case study

The main window is comprised of a menu and a panel, which is divided into three sections:

- The left hand side of the panel is used to show a table describing the case studies that are currently being executed.
- The upper right part of the panel (“PANEL de Casos”), is used to show the key data of each case study and its state during its execution.
- Finally, the lower right part of the panel shows the application main log (“Log general”).

There are two types of case studies that can be performed with the model. First of all, to design the whole distribution network from scratch. Secondly, to design only a part of the distribution network.

In order to design the whole distribution network, the “Nuevo Caso” button has to be pressed. Next figure depicts the main window with two panels representing two case studies (“PANEL de casos”). Note the data needed to be introduced in the model in this case.

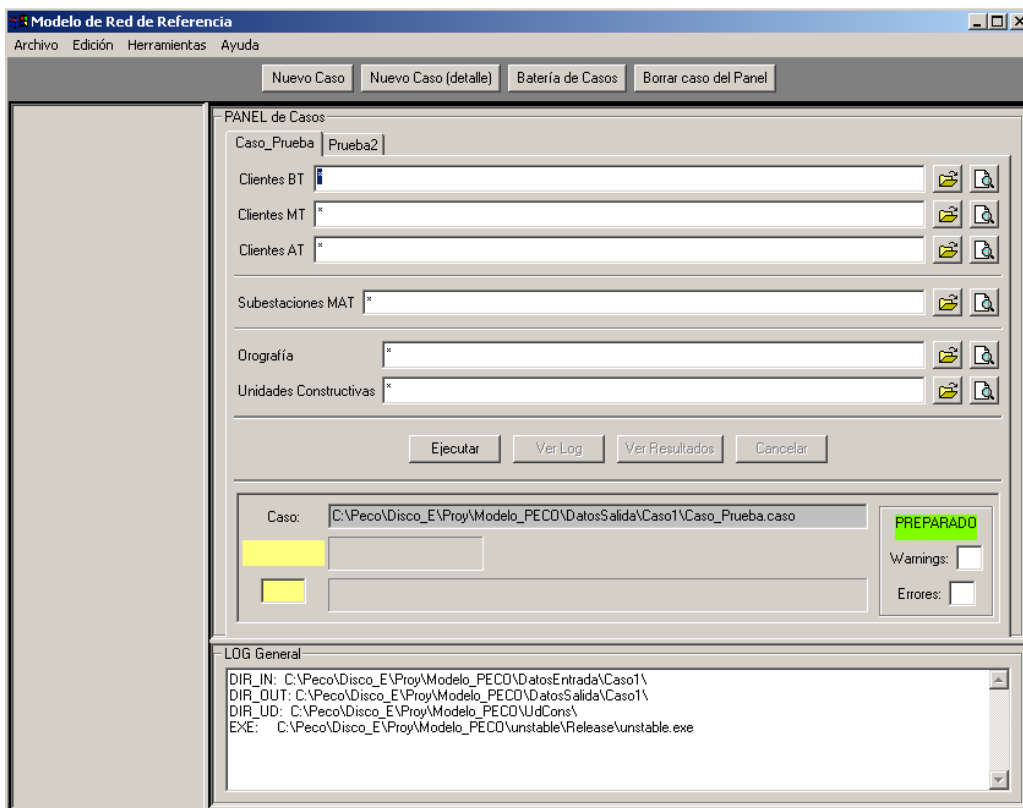


Figure 12 The main window with two case study panels (to plan the whole distribution network)

In this case, the model designs the whole network considering customers and transmission substations location. Note that the data files needed by the model is:

- LV, MV, HV customers.
- Transmission substations.
- Orography.
- Standardized equipment database and parameters.

If only part of the distribution network is needed to be planned, press the button named “Nuevo Caso (detalle)”, and a wizard-like dialog will guide the user through the whole process of choosing the part of the distribution system to be designed (HV/MV substations location, MV/LV transformer location, MV network planning...) and the data needed.

The next figure shows the first ‘page’ of the wizard. The goal of this ‘page’ is to let the user choose to perform: data processing, data checking and the part of the distribution system to be designed. The possibilities are:

- Location of MV/LV distribution transformers
- Location of HV/MV distribution substations
- MV network planning (with or without voltage regulators, capacitors, protective devices...)
- LV network planning and MV/LV distribution transformers considering real locations for HV/MV distribution substations.
- Designing the whole distribution system.

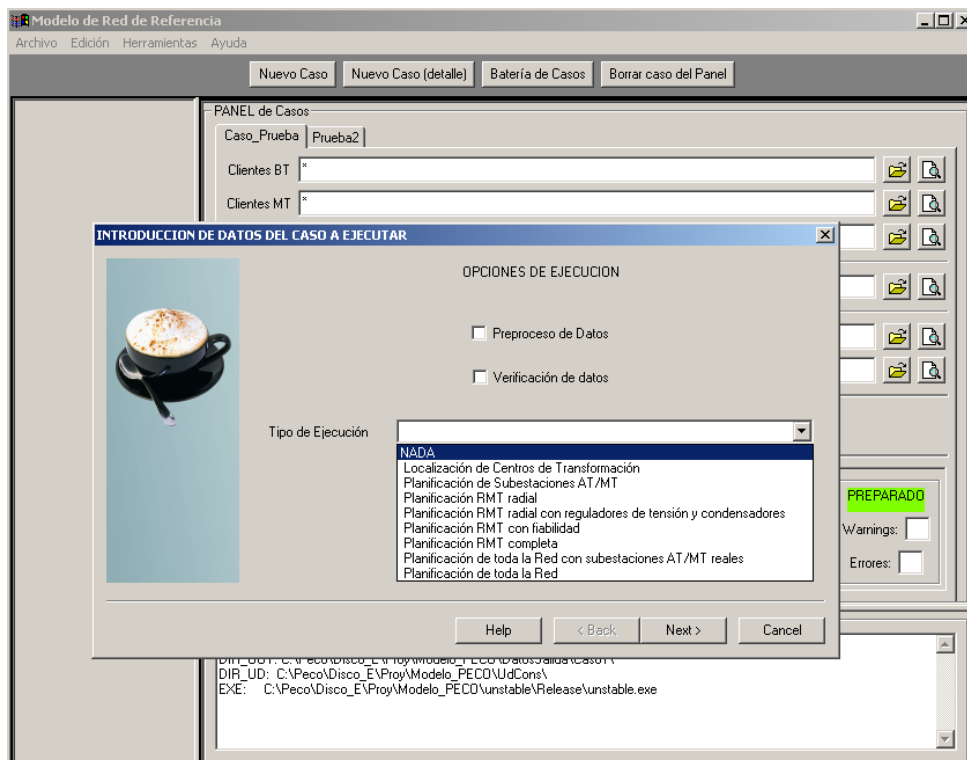


Figure 13 The wizard dialog for choosing a particular network planning module

After choosing what part of the distribution system is going to be designed, the wizard-like dialog asks the user to introduce the data files needed.

8.2 Standardized equipment and parameters database

One of the options of the user interface is to browse/edit a standardized equipment and parameters database.

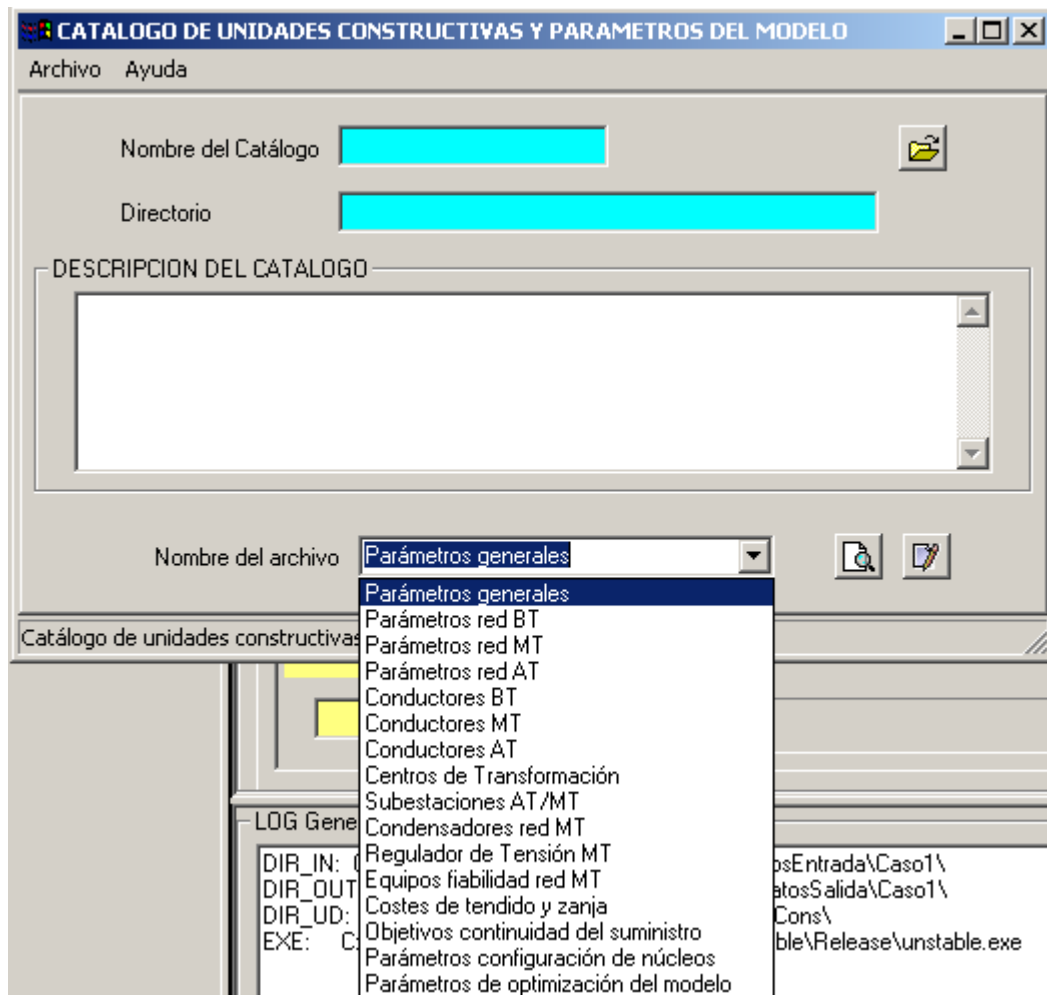


Figure 14 The standardized equipment and parameters browser/editor

Next, the following windows belonging to the database are shown:

- Protective devices to be installed in the MV network.
- Standardized LV lines and cables.
- Standardized MV/LV transformers
- Standardized HV/MV substations.

Parametros de fiabilidad

| EQUIPO DE FIABILIDAD | Inversión | Preventivo | Correctivo | Tasa fallos | Vida útil |
|---------------------------|-----------|------------|------------|-------------|-----------|
| Brigadas de mantenimiento | 210240.00 | 210.24 | 10.00 | 0.01 | 10 |
| Reconectores | 15789.40 | 1578.00 | 10.00 | 0.01 | 10 |
| Seccionadores manuales | 526.30 | 52.00 | 10.00 | 0.01 | 10 |
| Teleseñalizadores | 421.00 | 42.00 | 10.00 | 0.01 | 10 |

| VELOCIDAD BRIGADAS | mínimo | medio | máximo |
|--------------------|--------|-------|--------|
| Urbano | 10.00 | 25.00 | 40.00 |
| Interurbano | 40.00 | 50.00 | 80.00 |

Grabar Salir

Figure 15 Protective devices and maintenance crews

Catálogo de Conductores BT

Número de conductores:

Interurbanos: 2

Urbanos aéreos: 3

Urbanos subterráneos: 3

Tiempos de reparación:

| | Mínimo | Medio | Máximo |
|--------------------|--------|-------|--------|
| Interurbano | 4.0 | 6.0 | 8.0 |
| Urbano aéreo | 1.0 | 2.0 | 6.0 |
| Urbano subterráneo | 3.0 | 5.0 | 8.0 |

Grabar Salir

INTERURBANO ZONA B

| | Nombre | R(ohms) | X(ohms) | I_max(A) | Sobrecarga(pu) | Tf_min | Tf_med | Tf_max | Cinv | Cmanp | Cmanc |
|---|-----------|---------|---------|----------|----------------|--------|--------|--------|---------|--------|--------|
| 1 | Cu4X12 | 2.270 | 0.088 | 55 | 1.1 | 0.26 | 0.28 | 0.3 | 4221.0 | 822.18 | 1000.0 |
| 2 | Al3X25/25 | 1.590 | 0.317 | 138 | 1.1 | 0.26 | 0.28 | 0.3 | 10700.0 | 822.18 | 1000.0 |

INTERURBANO ZONA C

| | Nombre | R(ohms) | X(ohms) | I_max(A) | Sobrecarga(pu) | Tf_min | Tf_med | Tf_max | Cinv | Cmanp | Cmanc |
|---|-----------|---------|---------|----------|----------------|--------|--------|--------|---------|--------|--------|
| 1 | Cu4X12 | 2.270 | 0.088 | 55 | 1.1 | 0.26 | 0.28 | 0.3 | 4221.0 | 822.18 | 1000.0 |
| 2 | Al3X25/25 | 1.590 | 0.317 | 138 | 1.1 | 0.26 | 0.28 | 0.3 | 10700.0 | 822.18 | 1000.0 |

URBANO AEREO

| | Nombre | R(ohms) | X(ohms) | I_max(A) | Sobrecarga(pu) | Tf_min | Tf_med | Tf_max | Cinv | Cmanp | Cmanc |
|---|-----------|---------|---------|----------|----------------|--------|--------|--------|---------|--------|--------|
| 1 | Cu4X10 | 2.270 | 0.088 | 55 | 1.1 | 0.26 | 0.28 | 0.3 | 4221.0 | 822.18 | 1000.0 |
| 2 | Al3X25/25 | 1.590 | 0.317 | 138 | 1.1 | 0.26 | 0.28 | 0.3 | 10700.0 | 822.18 | 1000.0 |
| 3 | Al3X50X25 | 0.795 | 0.276 | 155 | 1.1 | 0.26 | 0.28 | 0.3 | 12020.0 | 822.18 | 1000.0 |

URBANO SUBTERRANEO

| | Nombre | R(ohms) | X(ohms) | I_max(A) | Sobrecarga(pu) | Tf_min | Tf_med | Tf_max | Cinv | Cmanp | Cmanc |
|---|-----------|---------|---------|----------|----------------|--------|--------|--------|-------|---------|--------|
| 1 | Al3X50/25 | 0.822 | 0.0620 | 168 | 1.1 | 0.13 | 0.14 | 0.15 | 10363 | 1809.05 | 1000.0 |
| 2 | Al3X70X35 | 0.568 | 0.0740 | 206 | 1.1 | 0.13 | 0.14 | 0.15 | 12786 | 1809.05 | 1000.0 |
| 3 | Al3X95/50 | 0.410 | 0.0720 | 246 | 1.1 | 0.13 | 0.14 | 0.15 | 16151 | 1809.05 | 1000.0 |

Figure 16 Standardized LV lines and cables

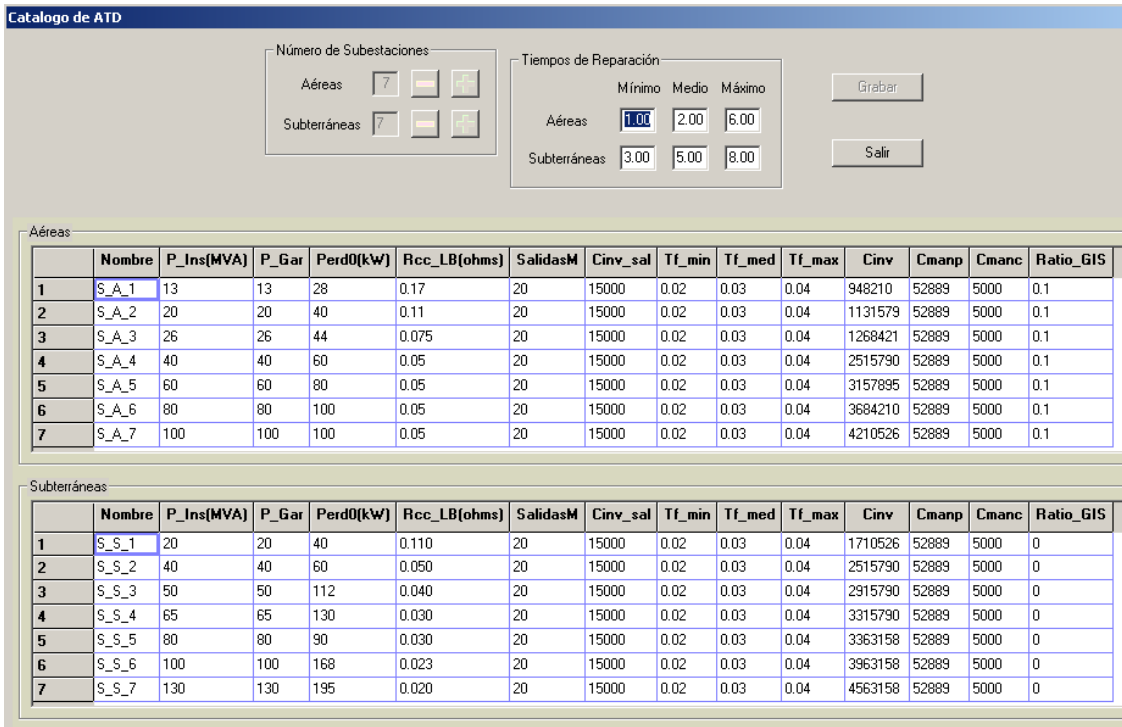


Figure 17 Standardized HV/MV substations

8.3 Results of the model

The results given by the model are saved in three sets of files:

- A log describing the execution in ASCII text file format.
- Several ASCII text files describing the results from the different modules that have been run: MV network, HV/MV substations...
- A HTML file with the main results of the case study.
- A set of shapefiles comprising: customers, networks, MV/LV transformers, HV/MV substations, protective devices and transmission substations.

Next, a brief description of the HTML file and the shapefiles are presented.

8.3.1 Results in HTML file format

The model saves, in HTML format, a set of tables comprising the main features of the case study that has been run and its results. The tables included in that file are:

- The number of customers and their contracted power in each voltage level.

- The number, demand and the installed capacity of MV/LV transformers and HV/MV substations.
- Aerial and underground network kilometres in each distribution voltage level.
- Investment, maintenance costs of: networks, distribution transformers, distribution substations, MV protective devices, voltage regulators and capacitors.
- Global continuity of supply indexes.

Next, a toy case study result HTML file is shown.

| | |
|--|--|
| Name of the case study | \demo |
| Standardized equipment & parameters file name | C:\Peco\PECO-Demo\UdCons\CatalogoInventado.dat |
| Execution date | Mon Feb 16 18:58:43 2004 |
| Version | C:\Peco\PECO-Demo\EXES\modelo_lim.exe |
| Execution time (minutes) | 85 |

Customers

| | Initial number | Final number | Contracted power (MVA) | Peak demand (MVA) | Energy year 0 (MVAh) | Average power factor |
|--------------|-----------------------|---------------------|-------------------------------|--------------------------|-----------------------------|-----------------------------|
| LV | 28622 | 28622 | 1331.76 | 532.70 | 1299817.84 | 0.93 |
| MV | 523 | 523 | 228.61 | 182.88 | 446244.72 | 0.93 |
| HV | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOTAL | 29145 | 29145 | 1560.37 | 715.59 | 1746062.56 | 0.93 |

Number of BT customers moved to MV customers: 0

Networks

| | Length (km) | | Investment | Preventive M (annual) | Reactive M (annual) |
|-------------------|--------------------|--------------------|-------------------|------------------------------|----------------------------|
| | Aerial | Underground | | | |
| LV network | 2007.03 | 414.82 | 32,990,418.45 | 146,35.33 | 111,650.53 |
| MV network | 726.92 | 148.73 | 26,650,192.12 | 636,246.60 | 1,085,062.50 |
| HV network | 243.12 | 5.30 | 190,69,369.43 | 316,860.35 | 1,496,375.57 |
| TOTAL | 2977.06 | 568.85 | 787,09,980.00 | 967,742.28 | 2,693,088.60 |

MV/LV Transformers & HV/MV substations

| | Number | Core losses (MW) | Copper losses (MW) | Demand (MVA) | Installed capacity (MVA) | Investment | Preventive M (annual) | Reactive M (annual) |
|--------------|--------|------------------|--------------------|--------------|--------------------------|---------------|-----------------------|---------------------|
| MV/LV | 1194 | 1.02 | 2.88 | 479.43 | 721.32 | 21,988,694.69 | 1,230,873.60 | 58,442.40 |
| HV/MV | 23 | 1.12 | 6.07 | 544.66 | 890.00 | 53,466,637.77 | 1,442,429.10 | 721.21 |

Distribution costs

| | Investment | | Preventive M (annual) | | Reactive M (annual) | | TOTAL | |
|---------------------|---------------|--------|-----------------------|--------|---------------------|--------|----------------|--------|
| | euros | % | euros | % | euros | % | Euros | % |
| LV net | 32,990,418.45 | 21.40 | 14,635.33 | 0.40 | 111,650.53 | 4.06 | 53,584,338.96 | 28.09 |
| MV/LV transf | 21,988,694.69 | 14.26 | 1,230,873.60 | 33.81 | 58442.40 | 2.12 | 23,278,010.69 | 12.20 |
| MV net | 26,650,192.12 | 17.29 | 636,246.60 | 17.47 | 1,085,062.50 | 39.42 | 39,930,901.07 | 21.24 |
| HV/MV subs | 53466637.77 | 34.68 | 1,442,429.10 | 39.62 | 721.21 | 0.00 | 19,069,369.43 | 10.14 |
| HV net | 19,069,369.43 | 12.37 | 316,860.35 | 8.70 | 1,496,375.57 | 54.37 | 72,536,007.20 | 38.57 |
| TOTAL | 78,709,980.00 | 100.00 | 3,641,044.98 | 100.00 | 2,752,252.21 | 100.00 | 190,772,408.25 | 100.00 |

Network losses

| | Network losses Year 0 | | | | Network losses Year N | | | |
|------------------------------|-----------------------|--------|------------|--------|-----------------------|--------|------------|--------|
| | Energy (MWh) | % | Power (MW) | % | Energy (MWh) | % | Power (MW) | % |
| LV net | 27,344.32 | 21.44 | 6.24 | 23.14 | 49,386.89 | 22.94 | 11.28 | 23.98 |
| MV/LV transformer | 21,504.25 | 16.86 | 3.89 | 14.43 | 31,660.00 | 14.71 | 6.21 | 13.21 |
| MV network | 31,181.91 | 24.45 | 7.12 | 26.38 | 56,317.99 | 26.16 | 12.86 | 27.35 |
| HV/MV substation | 36,394.24 | 28.54 | 7.19 | 26.65 | 57,837.26 | 26.87 | 12.09 | 25.71 |
| HV network | 11,106.79 | 8.71 | 2.54 | 9.40 | 20,060.10 | 9.32 | 4.58 | 9.74 |
| TOTAL | 127,531.52 | 100.00 | 26.98 | 100.00 | 215,262.24 | 100.00 | 47.01 | 100.00 |
| losses in % of demand | 7.30% | | 3.77% | | 9.17% | | 6.57% | |

Ditches and Poles

| | Length (km) | | | Investment | | |
|--------------|-------------|-------------|---------|---------------|---------------|---------------|
| | Aerial | Underground | Total | Aerial | Underground | Total |
| LV | 678.95 | 280.58 | 959.53 | 6,450,031.15 | 14,143,889.36 | 20,593,920.51 |
| MV | 101.39 | 146.91 | 248.30 | 4,635,716.87 | 10,383,925.05 | 15,019,641.93 |
| HV | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOTAL | 780.34 | 427.49 | 1207.83 | 11,085,748.03 | 24,527,814.41 | 35,613,562.44 |

MV network devices

| | Number | Investment | Predictive M (annual) | Reactive M (annual) |
|---------------------------------------|---------------------------|------------|--------------------------|------------------------|
| Circuit recloser | 0 | 0.00 | 0.00 | 0.00 |
| Fault indicator | 40 | 16,840.00 | 1,680.00 | 4.00 |
| Manual sectionalizer | 357 | 187,889.10 | 18,564.00 | 35.70 |
| Total protective devices | 397 | 20,4729.10 | 20,244.00 | 39.70 |
| Capacitors | 1 | 5,200.00 | 5,200.00 | 1.00 |
| Voltage regulators | 0 | 0.00 | 0.00 | 0.00 |
| Total voltage support devices | 1 | 5,200.00 | 5,200.00 | 1.00 |
| Maintenance crews | 1 | 21,0240.00 | 210.24 | 0.10 |
| Alternative supply feeders | Km aerial | 15.17 | 343,973.59 | 10,825.33 |
| | Km underground | 3.14 | | |
| | | | | 17,215.91 |

8.3.2 Results in ArcView' shape file format

[ArcExplorer](#) is a lightweight GIS data viewer developed by ESRI. This freely available software offers an easy way to perform basic GIS functions. ArcExplorer is used for a variety of display, query, and data retrieval applications and supports a wide variety of standard data sources. It can be used on its own with local data sets or as a client to Internet data and map servers.

ArcExplorer comes with a straightforward user interface that includes an intuitive menu bar and tool bars. With these, you can easily add themes from existing data sources, control theme characteristics, print your maps, zoom in/out, pan, and identify map features.

As a complete data explorer, ArcExplorer lets you display and query a wide variety of standard data sources. Using ArcExplorer as a stand-alone desktop application, you can view and query industry-standard ESRI shapefiles, ArcInfo coverages, and ArcSDE (Spatial Database Engine) layers. You can also pan and zoom through multiple map layers and identify, locate, and query geographic and attribute data.

Use ArcExplorer software's powerful symbolization tools to create thematic maps based on attributes contained in the database, and even perform basic statistical analysis on the geographic data.

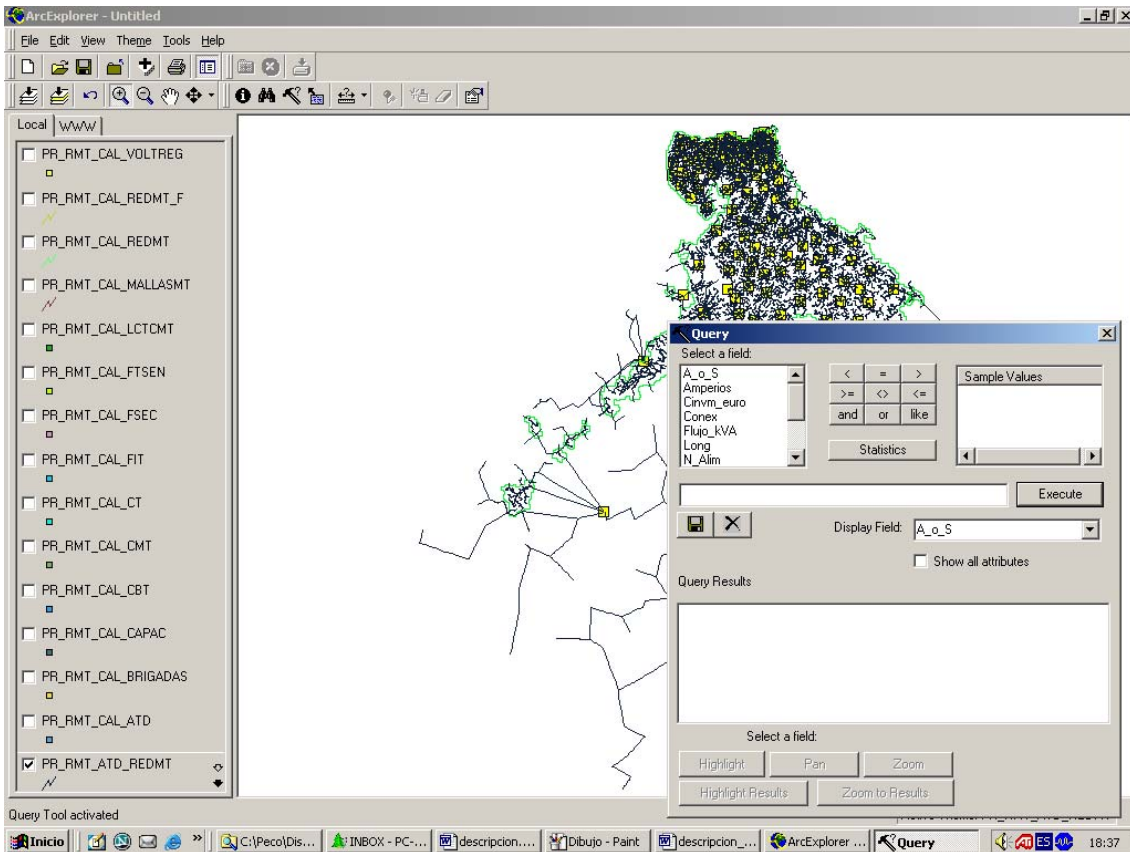


Figure 18 A MV network shown in ArcExplorer

The figure shows a MV network and the location of HV/MV substations of a service area comprising two million customers. In the lower right corner of the figure, the query window related to the MV network feeders is shown. Within this window, the user may select feeders meeting a specified criteria regarding one of or a combination of the following features:

- Aerial or underground feeder.
- Peak current.
- Feeder length.
- Feeder number.
- The HV/MV substation that supplies this feeder.

.....

Both the text and the HTML results file, as well as the set of SHAPE files given by the model allows an exhaustive and detailed analyses of the results given by the model.

Moreover, the results given by the model can be easily compared with actual networks thanks to the ArcExplorer, which is able to display reference networks and real networks at the same time.

8.4 Dealing with errors

The planning modules of the PECO model comprises approximately 50.000 lines of code, and depending on the size of the case study, the model may be running several hours or even a couple of days. Therefore, it is essential that the execution is free of errors.

In order to achieve that goal, the program uses exceptions and checks all the accesses to array elements, and the allocation and deallocation of variables, vectors, matrices, graphs...

Therefore, if an execution of a case study ends returning the correct code, one can virtually guarantee that every read/write memory access has been.

If an error occurs during the execution of a case study, the model saves an error file describing: (i) the type of error and in which procedure has taken place and, (ii) the stack of functions and their corresponding key variables that called the function that failed. Next, an example is shown.

ERROR: Relacion Coste/Resistencia del conductor Condor66 y/o Hawk132 erroneos

STACK DE ERRORES:

| | | |
|----------|----------------------------|--|
| Nivel: 0 | MDcable:CalculoFmaxOpt() | 'cTipo' = 2 |
| | | 'cLinea' = TiempoRepUrbanoSubterraneo: , 3 , 5 , 8 |
| | | 'iNT' = 3 |
| Nivel: 1 | CABLE:load | 'sFich' = C:\Peco\Disco_E\Proy\Modelo_PECO\UdCons\CatalogoUdCons.dat |
| | | 'cNivelTension' = A |
| | | 'NivelTension constructor' = A |
| Nivel: 2 | COMMAND:InterpreteComandos | |
| Nivel: 3 | main() | |

The maintenance tasks of the code are easier with both the execution log and this error file. Actually, most of the times, there is no need to have the input data regarding the case study that made the program to fail, in order to detect and fix the errors. This is a key issue, especially when input data (such as customer data or network topologies) is confidential.

9 Projects

The features of the PECO model make it suitable for both electric utilities and regulators, and it has been used in the following projects:

- Chilean Tariff Revision 2000 (Valor Agregado de la Distribución) for [Systep](#) and [Chilectra](#) (Enersis group), in Santiago de Chile. The model was used to compute investment, ohmic losses and reliability of supply of the MV network that electrifies the city of Santiago de Chile. The real network routes, HV/MV substations, MV/LV transformers and MV customers were given. The tasks performed by the model were: (i) network re-conductoring, and (ii) optimize investments in order to improve the reliability of the MV network and achieve the reliability targets imposed by the regulator. The results were presented to the regulator.
- Argentina Tariff Revision 2001 for the [Ente Nacional Regulador de la Electricidad](#) (Argentina's regulator). The goal was to assess the new replacement cost of the LV and MV network of Buenos Aires belonging to the utility [Edesur](#). The case study comprised more than a million customers, and the location of HV/MV substations and MV/LV transformers were given. A street map was built automatically and the LV and MV networks were designed.

The results in both cases matched the features of the actual networks.

Nowadays, the PECO model is being used in:

- Chilean Tariff Revision 2004 (Valor Agregado de la Distribución) for [Systep](#) and [Chilectra](#) (Enersis group), in Santiago de Chile.
- Chilean Tariff Revision 2004. [SYNEX](#) is using the PECO model to determine the aggregate distribution value of six distribution service areas in Chile, for the [Chilean Regulatory Commission](#).
- Spanish Tariff Revision 2004. The IIT is developing a Network Reference Model for the [Spanish Regulatory Commission](#), based on the PECO model.

10 References

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