METHODS AND MODELS OF THE EFFECTIVE DISTRIBUTION OF ENERGY BETWEEN CONSUMERS AND PRODUCERS

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Abstract: *Smart Grid – is a term used to describe advanced system of energy supply, which includes various aspects from power generation to consumption, high-quality management and utility services. It also involves new digital technologies to ensure reliability, safety, and efficiency, resulting in lower costs for the provision of utility services to consumers.*

Since Smart Grid is intellectual and self-renewing, we can automatically solve many problems with the help of new informational technologies.

The article offers the model of development of the Smart Grid based on the network architecture of the protocol G.9960. We offer the criteria of optimization and advanced data mining methods can bring new results in the field of cost-saving energy consumption and energy distribution.

Keywords: *Smart Grid, protocol G.9960, recursive structure, uncertainty, functional composition, sets of rules, decision-making, knowledge database, distribution of electricity, emergency situations, consumption, data mining analysis, real time pricing.*

ACM Classification Keywords*: H.5 Information Systems - Information systems applications, Decision support systems, Data analytics.*

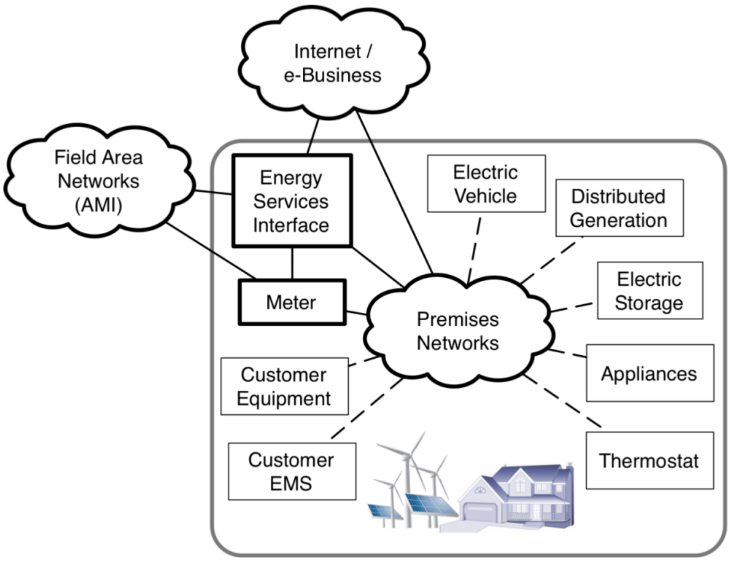
Introduction

“Smart Grids”(intelligent grids) − are electrical grids, that satisfy the future demands of energy-efficient and economical functioning of energy system through the coordinated management and with the help of the modern bilateral communication between the elements of the electrical grids, electrical stations, accumulating devices and consumers. One of the main elements of the energy management in the Smart Grid is the real-time pricing. Recently the electricity sector had been vertically integrated worldwide; the prices were fixed as a function of generation, transmission, and distribution costs. Due to little uncertainty in prices, producers could, therefore, make decisions by applying standard deterministic valuation tools such as discounted cash flow analysis. At the present time, electricity sectors in many countries have been deregulated with the aim of introducing competition in generation and retail activities. The change from a regulated monopoly to private ownership of generation and market liberalization may result in lower prices and more efficient use of resources. However, prices, which are now to be determined by the interaction of supply and demand, have become highly volatile with unexpected spikes. These sudden spikes may be explained as a response to temperature, supply, or transmission shocks.

Although there are many papers on modeling energy prices, there is limited information about modeling electricity and natural gas spot prices distinctly, i.e., taking into account their correlation together with either unexpected spikes or stochastic volatility.

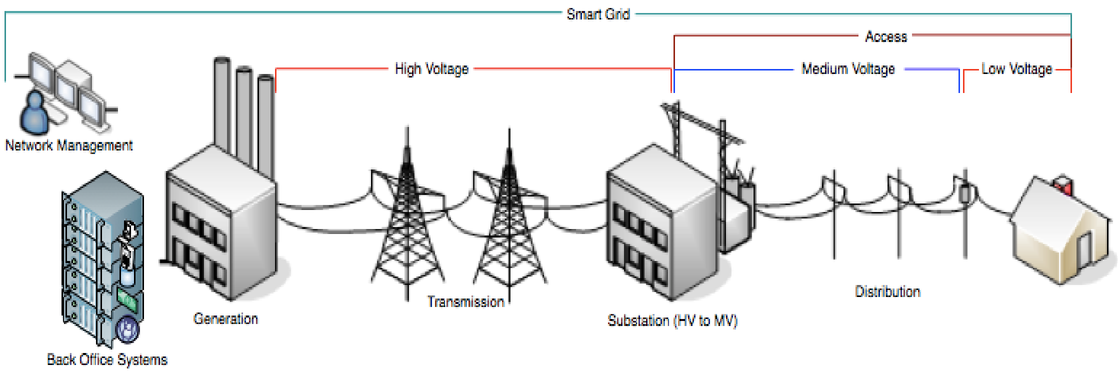
We offer the implementation of the smart grid on the base of protocol G.9960 that allows using any connection in home as part of the smart grid. By means of this protocol, we can monitor and control each device. Access to data about all devices helps to evaluate the effectiveness of energy use.

Network architecture of the protocol G.9960 provides all required functions for the technology of the smart grid and involves the nodes that work as the part of the smart grid in-home (Smart Grid Home Area Network (HAN)), and the nodes that are the part of the smart grid outside building (Smart Grid Utility Access Network (UAN)).



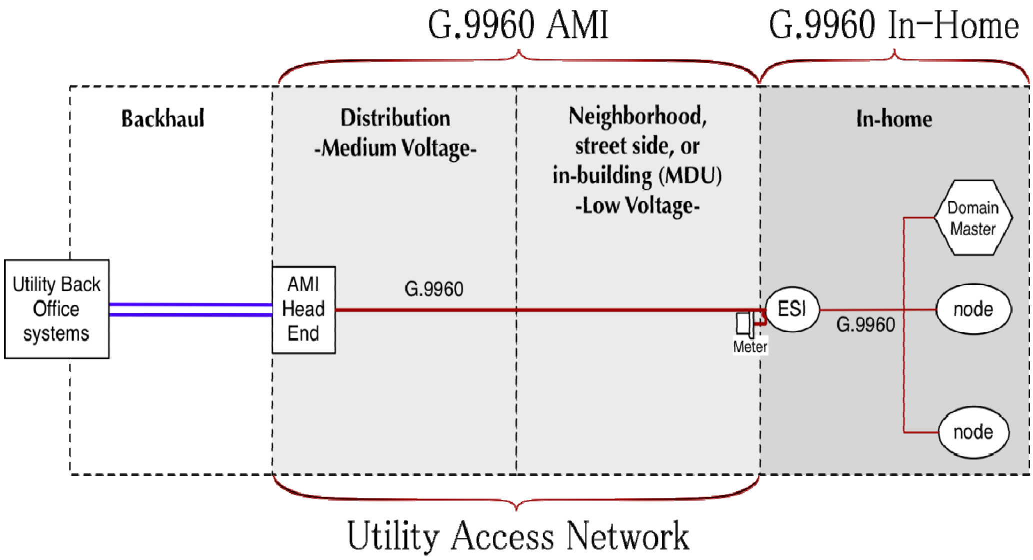
Smart Grid outside building includes: Advanced Metering Infrastructure (AMI), the system of the Automated Meter Management (AMM) and the system of the Automated Meter Reading (AMR). In-home applications of the smart grid provide the connection between the devices, plugged to the network and their energy sources; also these applications provide the connections between the intellectual devices, such as heaters, air-conditioners, washing machines, etc.

Smart grid components in-home provide the detail control of the smart technics, provide the ability to remotely control electrical devices, display the information about the consumption and related costs in order to better inform consumers, and thus to motivate them to save energy and consume less. The architecture of the protocol G.9960 promotes the widespread implementation of the smart-grid services in-house.



Smart Grid services are provided over Powerline Access. Smart Grid outside residential building is referred to the whole power system and related infrastructure, from back offices (BO), information technology systems, billing and management of the electricity generation, transmission and distribution, and finally, to the lines of residential building connection. Over the power lines the services of the smart grid allow to transmit information to the residential buildings (medium and low voltage power lines are used). Smart Grid provides more effective work of the network and in-home systems, as it is the upper layer of the connection of the digital information for monitoring, quality performance of the work, information connection and control of every component.

Below is a diagram of the network access utility.



The implementation of the Smart Grid on the base of the protocol G.9960 can significantly improve the the quality of the problem solving and provide the economy of resources for account of effective distribution and use of the access to data about all devices and management subsystems, but we need to develop the analytical superstructure settings for network management.

The essence of work

Goals and objectives of our work:

The problem of developing of a Smart Grid is actual nowadays due to lack of the energy recourses and pollution of the environment. The task of the Smart Grid is to redistribute power between producers and consumers and thus minimize its consumption with the help of real-time pricing. The implementation of distributed energy system allows combining the use of heat and electricity, batteries, renewable energy, using cogeneration and trigeneration plants. Our task is to develop a multicriteria function that would minimize the cost of energy and would reduce the negative impact of power plants on the environment. Furthermore we propose analyses of statistic data using data mining tools.

Sphere of application:

1. Complex use of the distributed energy resources with the help of Smart Grid. Combination of heat and electricity, along with real-time pricing allows bringing energy market to a new level and improving the quality of services provided to all customers, from small residential projects to large industrial enterprises.
2. Local generation. Local generation allows creating effective and reliable system of production of high quality electrical and heat energy directly at the consumer, taking into account specific consumer's requests.
3. Environmental and economic benefits. The use of smart grids helps to lower the discounted price of energy, reduce emissions.
4. Risk prevention. The proposed method helps to avoid risks during the peak loads due to higher prices.

5. Attractiveness of smart grid for consumers. The consumers become active participants in the energy production.
6. Analysis of the statistics. We propose a new data mining approach of the statistical analysis for energy systems that helps to make fast analysis of large databases and improves the effectiveness of decision making. Also data mining approach helps to find patterns that aren't obvious to the user.

Scientific novelty:

The researches show that electricity consumption grows faster than total energy consumption. When people work they need electricity for their jobs in industry or commerce; and they spend their earnings on goods and services that need electricity. As the consumer appetite for these services grows, producers and government are looking for reliable and cost-effective ways to distribute electricity energy throughout customers' homes. The protocol G.9960 is a technology designed specifically for this purpose. Our study demonstrates the implementation of Smart Grid on the basis of the architecture of the protocol G.9960.

We propose the criteria of decision making for Smart Grid that helps to adjust the optimal real-time price of electricity and natural gas including the cost of the use of energy sources, amortization and seasonal fluctuations.

For the effective analysis of the data we propose to use data mining tools. These tools can be implemented in the management system of the Smart Gird as an analytical superstructure. Producers can use the proposed method to find patterns or relationships, allowing making better marketing decisions, make predictions and reduce the cost of resources and time of decision-making. In addition to this, it can also help them to find potential problems that could cause risk and emergency situations. The ability to interact with customers is crucially important.

Practical value:

To be successful, an energy management campaign must combine an effective strategy with the right practical measures. We propose some of the practical short and long-term measures that producers and consumers can take to reduce the amount of energy they use on mutually beneficial terms, including a range of low and no-cost changes that can be made straightaway. It also gives advice on identifying opportunities for savings, building an action plan and effectively monitoring results.

The field of electricity production is confronted with various risks. For example, in April 2013 several main streets of Odessa were left without electricity due to the burned-out high-voltage cables. In March 2013 fire at one of the most powerful TPP in Donbas destroyed 4 turbines, the roof collapsed, and 12 thousand of people were left without heating.

Applied expert systems in the sphere of energy today:

Today, there are many methods of prediction and analysis of electricity consumption, for example, regression, correlation, spectral analysis, Box-Jenkins, exponential smoothing, adaptive predictors, etc.

Artificial neural networks and fuzzy systems are the most effective methods at the moment. The effectiveness of these systems is caused by their universal approximating capability and ability to learn directly in the process of forecasting and decision-making. In addition, these systems cover a very wide range of tasks. Furthermore one of the perspective areas of processing for large data sets is data mining analysis [Бодянский, Руденко, 2011].

The proposed method of analyses:

Proposed reliability criteria of real-time pricing for Smart Grid: we propose a criterion that optimizes the energy consumption, and thereby minimizes the discounted price of energy resources.

One of the main objectives of smart grids is minimizing of the weighted average annual costs of energy resources and emissions of CO_2 [Maribu, 1995]. If we use the stochastic price of natural gas and electricity, the optimality criteria can be represented as a function of the variables depending on the decision makers, price of natural gas and electricity and variables reflecting the characteristics of the behavior of the system at a certain time. During the researches we've developed a multicriteria function $Z_t(\vartheta_t)$, that minimizes the weighted average of the expected costs of consumption and emissions of CO_2 [Siddiqui, Marnay, 2007].

$$Z_t(\vartheta_t) = \min \frac{\alpha}{WithoutSG} Cena(\Omega_t, \vartheta_t) + \frac{(1-\alpha)}{EWithoutSG} VubrCO_2 + e^{-r\Delta t} E_{\vartheta_t}[Z_{t+1}(\vartheta_{t+1})],$$

where ϑ_t – is a sample of stochastic variables $OptElCena_t, OptGas_t$ at time t;

α – is a significance coefficient ($0 \le \alpha \le 1$), that displays the significance between weighted average annual costs and emissions of CO_2;

$Cena(\Omega_t, \vartheta_t)$ – t- weighted operational price;

$VubrCO_2$ – function of emissions CO_2;

$WithoutSG$ – annual price of energy resources without installing Smart Grid systems;

$EWithoutSG$ – annual price of CO_2 emissions without installing Smart Grid systems;

E_{ϑ_t} – is the sample of variables depending on the decision makers.

We propose modeling of electricity prices and natural gas prices, G_t and E_t, that is based on the Ornstein-Uhlenbeck processes, where parameters of the process are random variables with an unknown non-stationary distribution [Maribu, 1995].

$$dG_t = k_G(\theta_E - G_t)dt + \sigma_G dS_t,$$

$$dE_t = k_E(\theta_E - E_t)dt + p\sigma_E dS_t + \sqrt{1-p^2}\sigma_y dW_t$$

Here, for process k, θ_t is a long-term average, k_G is the attribute of the price repayment, σ_G the annual volatility, and $\{p = p_{GE}\frac{1}{2}\frac{(k_G+k_E)}{\sqrt{k_G k_E}}\}$, where p_{GE} is instantaneous correlation between $\{G_t, t > 0\}$ and $\{E_t, t > 0\}$. Moreover, $\{S_t, t > 0\}$ and $\{W_t, t > 0\}$ *are* independent functions of the Brownian motion. That's why, logarithm of the price of electricity and natural gas looks as follows:

$$\ln OptGas_t = G_t + f_t^G;$$

$$\ln OptElCena_t = E_t + f_t^E;$$

f_t^G is a seasonal function that displays weekly and annual trends for the process $k = G, E$, $t = 1, \dots\dots, T$, $s = 7$, $s' = 365$, where:

$$s/2 = \begin{cases} s/2 \\ (s-1)/2 \end{cases} or$$

$$f_t^G = \sum_{i=1}^{[s/2]} (\gamma_{1i}^k \cos\lambda_i t + \gamma_{1i}^{*k} \sin\lambda_i t) + \sum_{i=1}^{[s'/2]} (\gamma_{2i}^k \cos\lambda'_i t + \gamma_{2i}^{*k} \sin\lambda'_i t)$$

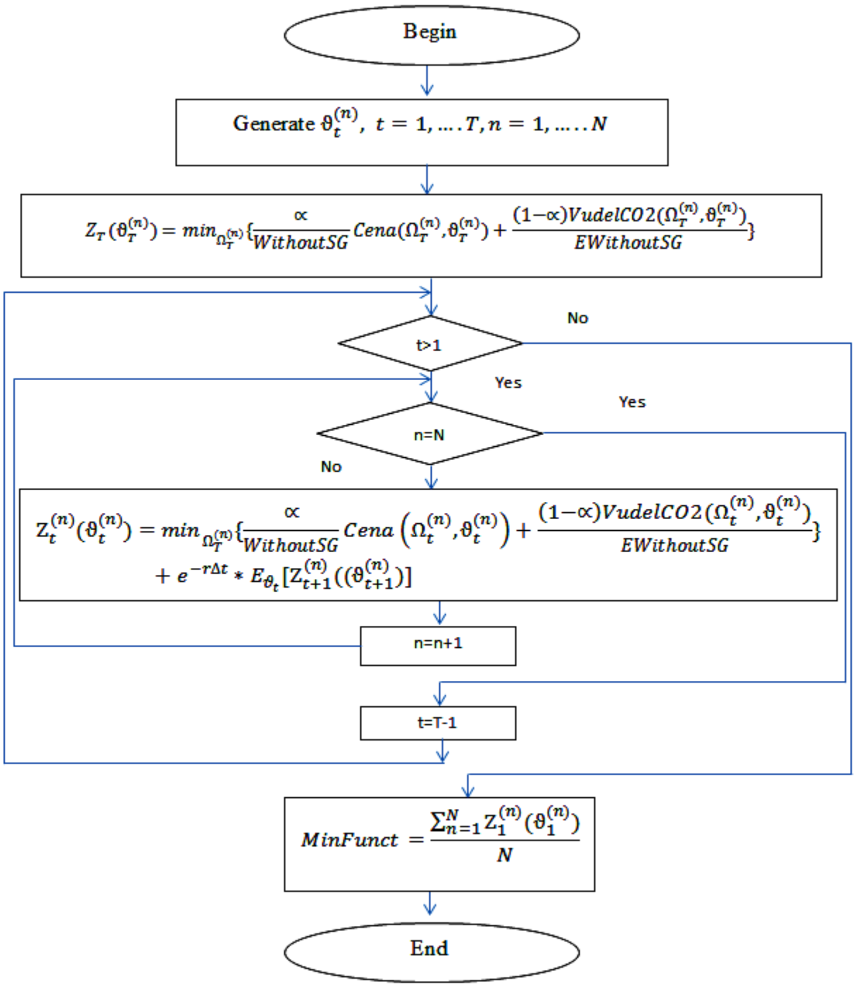
To estimate the parameters of the Ornstein-Uhlenbeck processes and seasonal functions we use coefficient $Cena(\Omega_t, \vartheta_t)$ that includes heat loads from distributed sources of energy generation, the performance level of the generators of distributed energy throughout the day t, variable rates for the operation and maintenance of generators and other factors that influence on the energy price [Maribu, 1995].

It is proposed modeling the Ornstein-Uhlenbeck in expressions with the help of two independent normally distributed random variables: the variable rates for the operation and maintenance of generators [Maribu, KM and S-E Fleten 2008].

$$G_{t+1} = G_t + k_G(\theta_t - G_t)\Delta t + \sigma_G \vartheta_G dS_t$$

$$E_{t+1} = E_t + k_E(\theta_E - E_t)dt + \vartheta_E p \sigma_E \sqrt{\Delta t} + \sqrt{1-p^2}\sigma_y \vartheta_G \sqrt{\Delta t}$$

We propose to use the optimization criterion sets to find the optimal price for natural gas and electricity for each day t within a year. To do this, with the help of expert assessments and statistical analysis of consumption in the previous years, we generate a sample N for the last day of year (T = 365), consisting of the prices of electricity and natural gas. Then, we calculate the expected value of the objective function at time step T for each sample. Then, we perform the calculation recursively along each sample, each time decreasing the t for 1, and then calculate the function of minimization for each step. When we reach the first step of each sample, we calculate the average of all the objective functions and add the depreciation costs of distributed energy sources to it. The following picture shows the algorithm for real-time price modeling:



Data mining analysis: Data mining – is the processing of information, identification of patterns and trends for decisions making. The traditional methods of analysis (statistical methods and OLAP) are mainly focused on pre-formulated hypotheses testing (verification-driven data mining), intelligence analysis, that forms the basis for online analytical processing (OnLine Analytical Processing, OLAP), while one of the main conditions of the Data Mining –is the search for non-obvious patterns [Han, Kamber, 2000]. The tools of Data Mining can find such tendencies and also build their own hypotheses about the interrelations. Since the formulation of hypotheses about the interrelations is the most difficult problem, the advantage of Data Mining tools over other methods of statistical analysis is obvious [Arseniev, Kiselev, 1995].

The data types of the PolyAnalist inner language form two classes: universal types of data, defined for all fields of application, and types of data defined by user, specific for a particular subject areas. The first class includes only two types of data, Boolean, denoted as **L**, and numerical (real number) **- N**. Type **N** includes the infinite number of values. All other types of data, including **L** and user-defined types, include a finite set of values [Arseniev, Kiselev, 1995].

The records of the analyzed database are defined as the set of mappings from some of the sets of access keys to the sets of values.

In this formalism the properties of each data type are determined by two characteristics. The first characteristic describes the properties of ordering, precisely, determines whether the type of data has the relation «more than» or operator «next». The second characteristic is called enumerability. It defines, whether the instruction «for each value of the X data type perform the next actions… » makes sense for X data type [Kiselev, 1994].

The functional primitives of the PolyAnalyst inner language appear to be the simplest programs of this language.

The program P is considered as the object, having a set of inputs (perhaps empty) **in**(P) and one output. Every input $\alpha \in$ **in**(P) is marked by its data type DT(α) and also by some other attributes, that will be described further. The type of data, returned by program is marked as DT(P). Every input α of the program can have some value $p(\alpha)$ according to its data type. A set of all possible mappings of inputs **in**(P) in their set of values will be denoted as *EVIN*(P). For every $p \in$ *EVIN*(P)*)* value P(*p*), returned by program, can be calculated as a result of the operations' sequences, defined by P(*p*) inner structure. These operations depend on the set of functional primitives (included to the program) and on the used structures of management. If the program includes so called primitives of the data access, then we should have given database entry, for which this program is calculated. In this case value returned by the program obviously depends on the number of record *i* in the database : P(*p, i*) [Arseniev, Kiselev, 1995].

Functional primitives (created by PolyAnalyst system), that can be included in the program, are also divided into two classes: universal and user-defined. The first class includes different operations, applicable to the universal data types **L** and **N**. They are Boolean operations AND, OR, NOT, that are represented by primitives with two (AND, OR) or one (NOT) input of the type **L** and the output of type **L**. Ternary primitive *inr* is used as a generalization of numeric relational operators with prototype *inr*:**L**(*x*:**N**, *y*:**N**, *z*:**N**). The meaning of this primitive is the meaning of inequality $y \le x < y + z$. Except these primitives universal primitives include so-called TF-commutator *if*: **N**(*b*:**L**, *x*:**N**, *y*:**N**). If *b* = 1, than the value of this primitive is equal to *x*, otherwise it is equal to *y*. The purpose of this primitive is similar to the if-purpose construction of the programming language C. User-defined primitives are divided into primitives automatically generated by the system for application-defined data types, data access primitives and special primitives. For example, for every data type ***T,*** the primitive, expressing the relation of equality, with prototype **L**(***T***, ***T***) and TF- commutator with prototype ***T***(**L**, ***T***, ***T***), are created automatically. The primitives, implementing relation «more than» and operation «next» are created, if the appropriate data types are described as ordered. The prototypes and primitives' bodies of the access to data records, defined by the structure of the analyzed database For example, if the records are organized as two-dimensional matrix, containing the values of the type *D*, than PolyAnalyst creates primitive with the prototype *D(PosX, PosY),* where *PosX* и *PosY* are datatypes, representing the horizontal and vertical positions in the matrix. Thus, PolyAnalyst system doesn't have inner restrictions on the structure of the researched database (it has the required primitives for the data access). The data can be organized as a set of scalar values, vectors, matrices, lists, or other structures. Finally, subgroup of special primitives includes the primitives, conforming the operations, specific to particular subject areas. For example, only narrow class of users requires the calculation of sinus. Therefore, the prototype and body of the primitive, implementing the calculation of sinus, must be explicitly defined, when necessary [Arseniev, Kiselev, 1995].

As it was previously mentioned, the functional entities are considered as the simplest programs. In order to create more complex programs from a simple one we use production technique (or, in this case, the management of structures). The internal language of PolyAnalyst has two main production techniques: functional composition and iteration/recursion.

Functional composition: the program, created by the functional composition, is defined as a foursome P_{FC} = $<P_{up}, \Pi_{down}, A \subset \mathbf{in}(P_{up}), m{:}A \xrightarrow{m} \Pi_{down}>$, where Π_{down} – is a variety of non-empty programs and $DT(m(\alpha)) = DT(\alpha)$. New program P_{FC} has the next syntax specifications: $DT(P_{FC}) = DT(P_{up})$, $\mathbf{in}(P_{FC}) = \bigcup_{P \in \Pi_{down}} \mathbf{in}(P) \cup \mathbf{in}(P_{up}) \backslash A$. In order to define the value P_{FC} for adjusted input values, the system calculates the values, returned from a set of programs Π_{down}. Then every input α of the program P_{up}, that belongs to the set A, receives the output value of the program $m(\alpha)$ and P_{up} program is calculated. Then received value becomes the output value of the whole structure P_{FC}.

Iteration / recursion: unlike to the simple and intuitive method of functional formulation, the method that creates the iterative and recursive structure is very complex. The most general form of this construction is expressed by the twelve following components: $P_{iter} = <P_{pred}, P_{ord}, P_{cond}, \Pi_{act}, \Omega, A_{pred} \subset \mathbf{in}(P_{pred}), A_{ord} \subset \mathbf{in}(P_{ord})$, $A_{iter} \subset \mathbf{in}(P_{cond}) \cup \bigcup_{P \in \Pi_{act}} \mathbf{in}(P)$, $m_{pred}{:}A_{pred} \xrightarrow{m_{pred}} \Omega$, $m_{ord}{:}A_{ord} \xrightarrow{m_{ord}} \Omega$, $m_{iter}{:}A_{iter} \xrightarrow{m_{iter}} \Omega \cup \Pi_{act}$, $\boldsymbol{out} \in \Omega \cup \Pi_{act}>$, where P_{xxx} – are programs, Π_{act} – is a set of programs and Ω - is a set of cycle variables. From the syntactic point of view, the variables of cycle – are objects that have only one attribute – the type of data (that must be enumerated). Iterative recursive construction is syntactically correct, if the following additional conditions are performed: $DT(P_{pred}) = DT(P_{cond}) = \mathbf{L}$, $DT(P_{ord}) = \mathbf{N}$, $DT(m_{xxx}(\alpha)) = DT(\alpha)$ for all m_{xxx}. The special pseudo program, without no input parameters, designated as $\Im$, can serve as a replacement of some components of the researched structure. The value, returned by this pseudo program, is always equal to 1. For example, if $\Omega = \varnothing$, than P_{pred} and P_{ord} must be $\Im$. The prototype P_{iter} is defined as $DT(P_{iter}) = DT(\boldsymbol{out})$, $\mathbf{in}(P_{iter}) = \bigcup_{P \in \Pi_{act}} \mathbf{in}(P) \cup (\mathbf{in}(P_{pred}) \backslash A_{pred}) \cup (\mathbf{in}(P_{ord}) \backslash A_{ord}) \cup (\mathbf{in}(P_{cond}) \backslash A_{iter})$. The semantics of this construction is defined by the following algorithm of calculation.

1. If $\Omega \neq \varnothing$, then list **LOOPVAR** of all combinations of possible values of the cycle variables is created, for which value P_{pred} is equal to 1. The transmission of values of variables to the inputs of the program cycle P_{pred} is defined by the mapping m_{pred}.

2. If $\Omega \neq \varnothing$ - then list **LOOPVAR** is sorted in ascending order, of the returned P_{ord}, for combinations of values of the cycle variables from **LOOPVAR**. The list **LOOPVAR** can be regarded as the matrix LV[i,ω], where i – the number of combinations of values of the cycle variables, is the appropriate variable of the cycle.

3. $i \leftarrow 1$.

4. The values of all the programs of the set Π_{act} are calculated. The values of the input parameters of these programs are defined by the following rule. If $m_{iter}(\alpha) \in \Omega$,, then the value of input α is accepted as LV[1,$m_{iter}(\alpha)$], otherwise it is equal to the appropriate input of the whole construction P_{iter}.

5. Value P_{cond} is calculated.

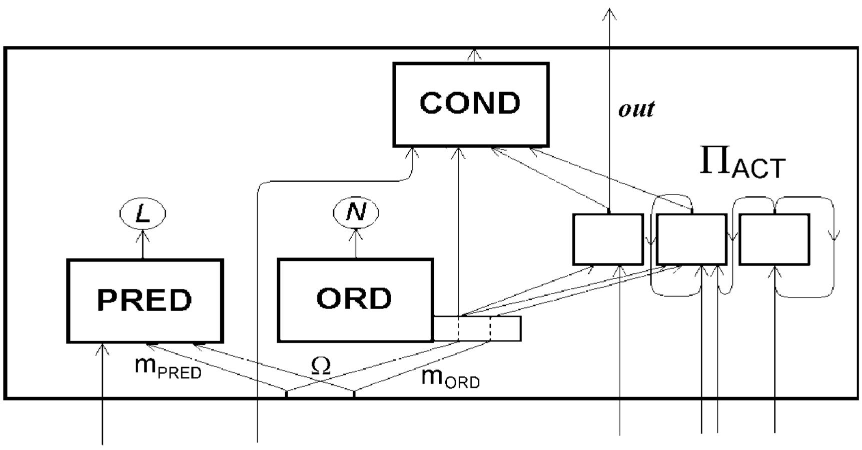
6. If $\Omega \neq \varnothing$ and i = <number of rows LV> or value P_{cond} is equal to 0, the calculation stops. Value ***out*** is accepted as the value of the construction P_{iter}.

7. $i \leftarrow i + 1$.

8. The values of all the programs of the set Π_{act} are calculated. The values of their inputs become the values of the cycle variables, or outputs of programs, belonging to the set Π_{act}, or inputs P_{iter}, that is determined by mapping m_{iter}. For example, if $m_{iter}(\alpha) = \omega \in \Omega$, then LV[$i$,$\omega$] is accepted as the value α.

9. Return to step 5.

Following picture shows the realization of Iteration / recursion [Kiselev, 1995].

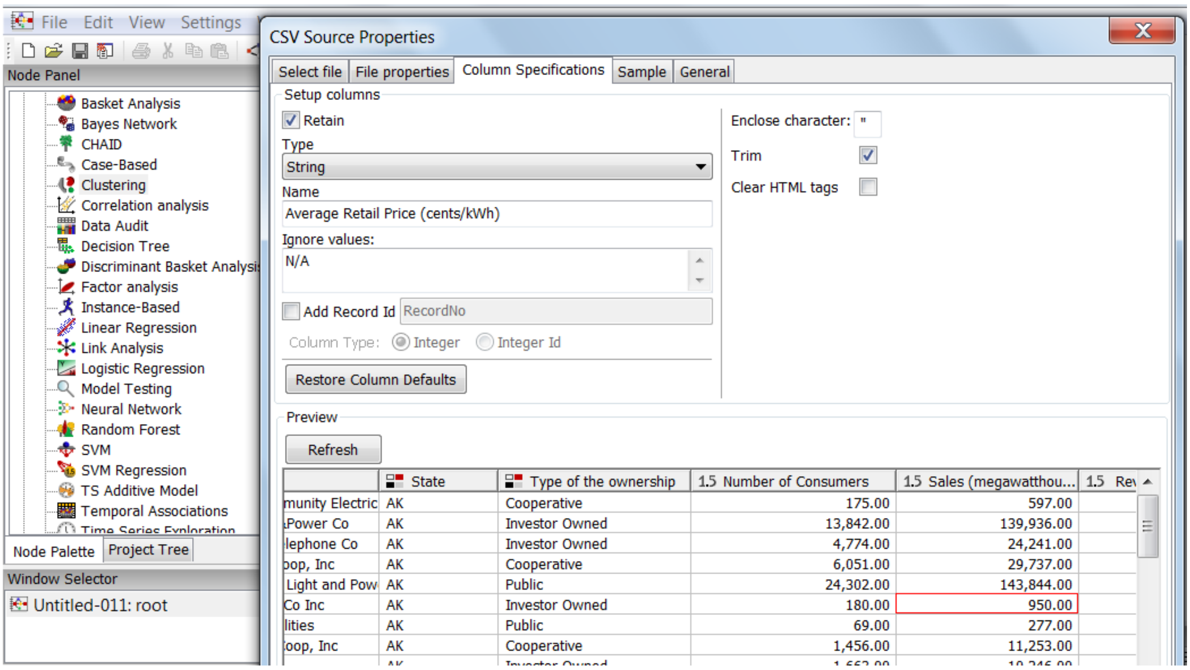


Also PolyAnalist includes functions, preventing the construction of trivial and equivalent programs and high-quality assessment of the built programs.

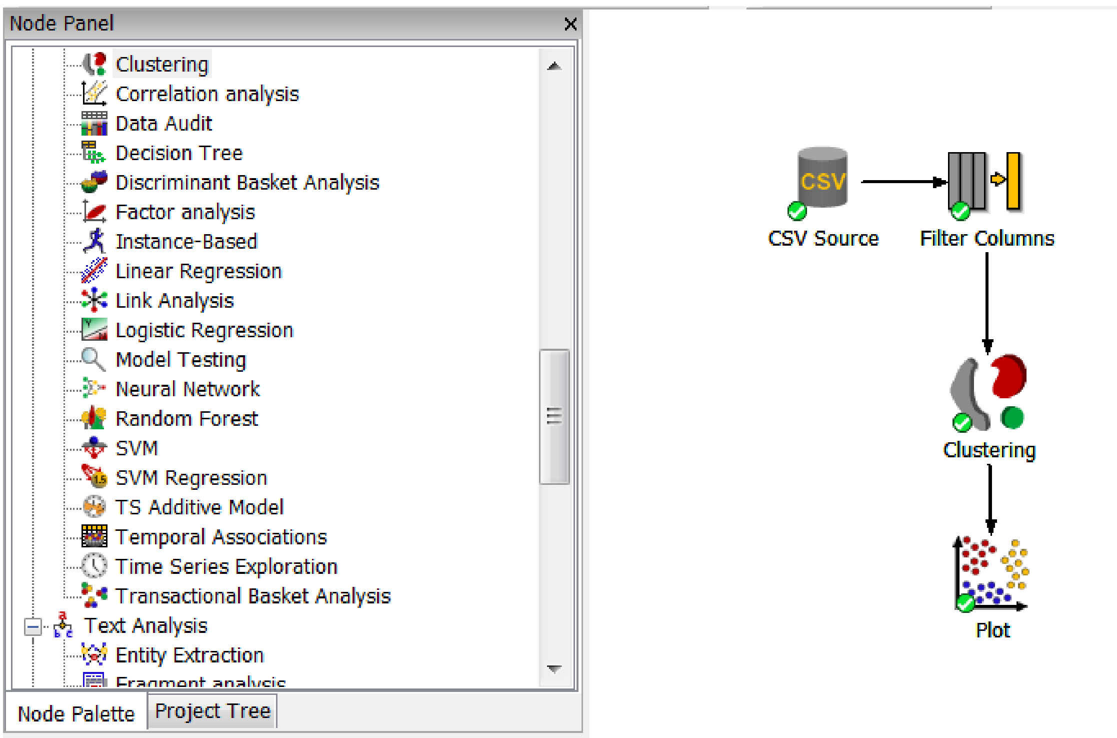
The university of the described approach is connected with the absence of any inherent system limitations as to the structure of the analyzed data, and for the procedure of evaluation of programs constructed according to arbitrary criteria, implemented out by the module of evaluation of PolyAnalyst. GT-search and the reduction mechanisms for generating trivial and equivalent programs solve or at least reduce the problem of combinatorial increase of the generated programs quantity. The use of assumptions about the structure of the data SAV allows making a significant simplification, that increases the performance of the system [Гелованн, Бритков, 2001].

The realization of the cluster analysis of energy consumption performed with the help of Polyanalist system:

For a sample we've downloaded statistical data about different electricity producers as a CVS file from Microsoft Excel database. PolyAnalyst determines columns and intelligently suggests what data type to assign to each field. But we accepted other datatypes for some columns.



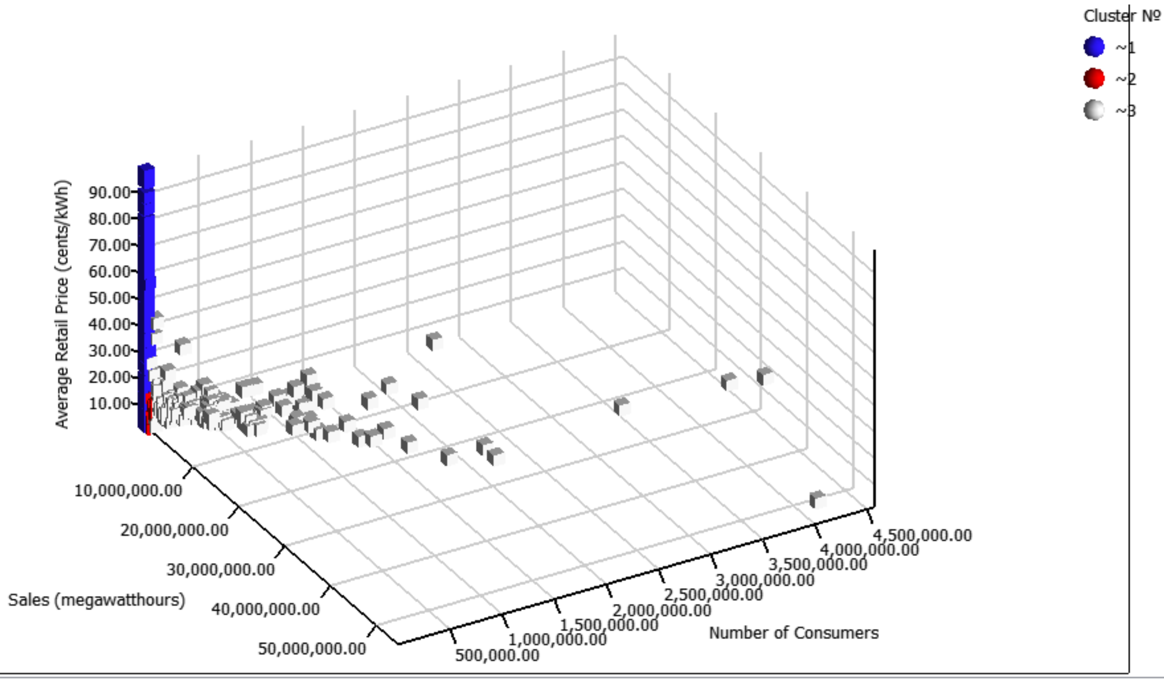
The following picture shows the node tree for analysis. Each node (box) on the tree represents a set of records formed by splitting the default data for analysis. We've split our default CSV file for clustering.



We use segmentation and clustering, to split producers into categories based on the sales reports (megawathours), number of customers and average retail price (cents/KWh). Following picture shows the visual realization of clusters.

Thus, during our research, we evaluated practical usefulness of data mining tools applied to the analysis of electricity reports. These tools have such advantages as: capturing previously unanticipated knowledge form row data, efficient use of analyst time, automation of repetitive processes, quick and intelligent analysis.

As a result, extracted patterns of terms can be further utilized for knowledge discovery processes together with the structure in the database and used for reliability criteria of real-time pricing for Smart Grid.



Conclusion

Energy consumption certainly depends not only on the work of power station, but also on the correct architecture, management services and of peripheral devices. The idea of implementation of the Smart Grid on the base of protocol G.9960 using the criteria of optimization and advanced data mining methods can bring new results in the field of cost-saving energy consumption and energy distribution.

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