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Bottom-up Approach to Spatial Load Forecasting: Preliminary Assumptions

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Abstract-- **The paper deals with a novel approach to a spatial load forecasting (SLF). All the known SLF methods are based on the top-down approach when the spatial load distribution depends on the global long-term forecasts (as for instance demographic indices). As the alternative to this problem, the author presents the bottom-up approach to SLF task, which uses the modified fuzzy cellular automaton (FCA). In this approach, all the global factors are overlooked on purpose. Only the local projections affecting the spatial load distribution are investigated. The paper presents briefly the mathematical formulation of the suggested FCA method with the simple example of SLF task. Finally the conclusions and planned future works are widely discussed.**

***Index Terms*-- Cellular automata, Fuzzy logic, Load forecasting, Distribution System Planning**

I. Introduction

THE plans of distribution power system development should be prepared on the basis of reliable long-term electric load forecasts. The efficiency, economy and reliability of modern distribution system depends not only on the type and size of power system components, but also on their optimal location with respect to area needs. Apart from the amount of power needed in the future, the long-term forecasts require the information about the location of this power demand. Such predictions are known as the spatial load forecasts (SLF) [2], [3], [4], [5], [6].

The grounds for analysing SLF have two aspects: legislative and economic. In Poland, the planning process of power delivery is regulated by the Energy Law [1]. This act obligates both the electric utilities and the local authorities to prepare the plans of power delivery systems development on their service areas and administrated areas, respectively. The accuracy of taking decisions in the distribution system planning can bring big economic advantages. First of all, reducing capital expenditures and operating costs for the energy utilities. The next important benefit is meeting consumers power demand and the maintenance of proper indices of power quality, which indirectly affect the economic development of the local authority's administration area. It can be stated that the SLF should be very significant field of interest for the electric utilities as well as the local authorities.

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II. Problem Statement

The analysed territory is divided into small areas (cells), either elements of uniform grid (squares or hexagons) or irregularly shaped cells (associated with equipment service areas). Then a load growth is forecasted in each elementary field. The prediction problem can be expressed as

$$C \xrightarrow{f_1} \mathrm{IN}^r \xrightarrow{f_2} \mathrm{IR} \qquad (1)$$

where f_1 function transformates the cell $c \in C$ to the r-dimensional vector $\mathbf{x} \in \mathrm{IN}^r$ of a number of electric energy consumers. Each element of vector $\mathbf{x}$ is assigned to the analysed consumer class. f_2 function maps the vector $\mathbf{x}$ to the power consumption value $P \in \mathrm{IR}$.

All the known SLF methods [2], [3], [4], [5], [6] are based on the top-down approach when the spatial load distribution depends on the global long-term forecasts (as for instance demographic indices). Such approach is presented in Fig. 1

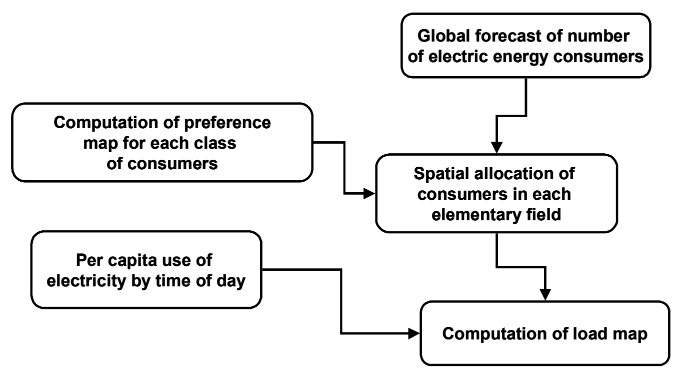

Fig. 1. Top-down approach to SLF problem

As the alternative to the aforementioned problem, the author presents the bottom-up approach to SLF task. In this method, all the global factors (demographic and economic) are overlooked on purpose. This approach has arisen from the fact that it is difficult to forecast on the long-term the aforementioned factors. with a relatively high accuracy. It is believed that the local projections put together condition mainly the behaviour of the investigated global system.

In this paper, the author describes only the method of the f_1 mapping (1), because the suggested bottom-up approach is closely connected with this module of SLF problem. The f_2 function is not raised here, but one can find this problem in the state-of-art literature, as for instance [2].

In general, for each cell the r-dimensional state (number of consumers for the analysed classes) will be predicted in the investigated time step. For that purpose, the use of fuzzy logic (FL) system in the cellular automaton (CA) structure is proposed. In the literature [7], [8], this hybrid technique is called the fuzzy cellular automata (FCA).

III. Formulation of Mathematical Model

The following FCA structure has been found

$$FCA = (C, O, L, P, NR_d, \zeta, A, B, D, \phi) \tag{2}$$

where C is the set of the regular analysed cells, whose geometry is defined (all the cells are equal closed geometric figures) on a geographic surface, O is the set of cells classes (given by the land development plan), L is the set of energy consumers classes (given by the electric utility) and P is the set of proximity factors types which give information about the distance (not necessarily the Euclidean one) between the cell location and the specific spatial objects (heavy industrial plants, motorways, etc.) affecting the land-use development, NR_d is the neighbourhood relation with the degree d, ζ is the classification function which assigns the individual cell to one of the land-use categories using the land development plan, A is the family of fuzzy sets which describe the states of the analysed individual cell, B is the family of fuzzy sets which describe the states of the investigated cell neighbourhood, D is the family of fuzzy sets which describe the states of proximity factors, and ϕ is the family of transition functions indexed by the cell class $o_i \in O$.

Apart from the aforementioned components of FCA structure, the egzogenic data are required such as: nonfuzzy values of proximity factors given for each individual cell in all analysed time steps as well as nonfuzzy values of the initial states for all investigated cells. The egzogenic data are also the time and the location of big energy consumers such as heavy industry, municipal infrastructure objects, etc. For these consumers it is unfeasible to use the bottom-up approach due to the above-local economic character.

In order to simplify the computation of the fuzzy output (the cell state in $t + 1$ time step), the authors suggest the use of Gupta's decomposition, according to [9].

The theoretical aspects of the proposed FCA structure are presented in detail in [10].

IV. Numerical Example

To show closer the use of the aforementioned FCA based method, the simple example of the discussed part of SLF task is presented. The spatial distribution of electric power demand is predicted in a given time range.

The time horizon length of the forecast is 5 years at the annual time interval, i.e. $T = \{t_0, t_1, \ldots, t_5\}$. The investigated area is the square sector of polish agglomeration. Let $C = \{c_1, c_2, \ldots, c_{100}\}$ be the set of the analysed cells with their geometry and a spatial position. Each of the cells is a square with the length of a side equal 200 meters.

O is the set of cells classes (given by the land-use development plan, as for instance single-family buildings, blocks of flats, industrial areas, etc.), $O = \{o_1, o_2, o_3\}$ is the set of cell classes describing the existing and planned type of a building. These classes are determined in the land-use development plan, prepared by the local authorities for the investigated territory. In the presented task the call classes O have been found as follows: o_1 is a flats building, o_2 is a single-family building and o_3 is a commercial-service building.

Let $L = \{l_1, l_2\}$ be the set of investigated energy consumers classes. It is important to note that this classification is not directly related to an electric energy amount and a demand profile. In this case these classes take into account the spatial-economic behaviour. The electric energy consumers classified as l_1 belong to a household sector. It consist of the residential population. l_2 class includes those business, administrative and other establishments which deal directly with the local residential population [11].

Let $P = \{p_1, p_2\}$ be the set of proximity factors defined as follows: $p_1$is a distance to the motorway, p_2 is a distance to the city centre.

In this example there are two motorway segments in the analysed area. The first one is an existing segment ($t_0 \in T$) and the second one is planned to use in the time step $t_3 \in T$. The constant spatial position of the city centre point is also determined.

For the considered example, the cells grid with the classification result of the cells (noted as ζ) and the selected specific spatial objects are shown in Fig. 2

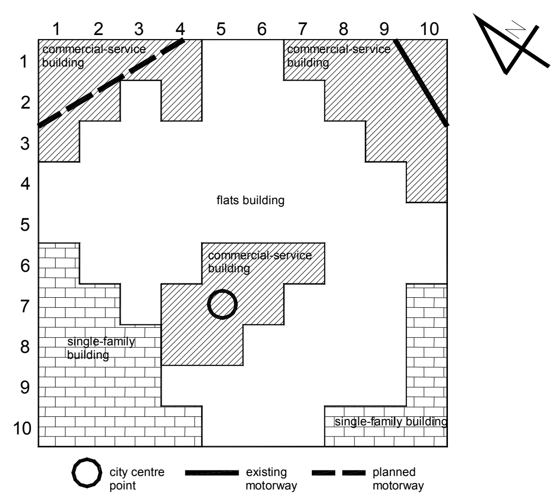

Fig. 2. An investigated area with classified cells and specific spatial objects

For the use of FCA, it is necessary to define a neighbourhood relation. Let $NR_d \subset C^2$ be a two-argument relation with symmetry and irreflexivity properties, where d is the index of the neighbourhood degree d = 1, 2,…, g. Assuming d = 1, the relation is expressed

$$NR_1 = \left\{ \begin{array}{l} c_i, c_k : c_i \text{ and } c_k \text{ have} \\ \text{at least one common} \\ \text{point} \end{array} \right\} \tag{3}$$

The first-order neighbourhood relation (3) is common in the conventional CA's [9]. In order to extend the CA use, where the interaction between relatively near but not adjacent cells is expected, it is necessary to introduce the neighbourhood relation with the degree d > 1, defined in the recursive way

$$NR_d = \begin{Bmatrix} (c_i, c_k) : \exists c_j \in C \wedge c_i NR_1 c_j \\ \wedge c_j NR_{d-1} c_k \\ \wedge \forall_{a \in \{1,2,..,d1\}} c_k \notin NR_a(c_i) \end{Bmatrix} \quad (4)$$

According to different consumers preferences [4], it is proposed to use the neighbourhood relations NR_1 for l_1 consumers class and NR_2 for l_2 category.

The discussed SLF problem involves some egzogenic data. Let **U** and **X** be the matrix and the vector respectively

$$\mathbf{U} = \begin{bmatrix} \mathbf{u}(c_1, t_0) & \ldots & \mathbf{u}(c_i, t_0) & \ldots & \mathbf{u}(c_{100}, t_0) \\ \ldots & & & & \\ \mathbf{u}(c_1, t_j) & \ldots & \mathbf{u}(c_i, t_j) & \ldots & \mathbf{u}(c_{100}, t_j) \\ \ldots & & & & \\ \mathbf{u}(c_1, t_5) & & \mathbf{u}(c_i, t_5) & & \mathbf{u}(c_{100}, t_5) \end{bmatrix} \quad (5)$$

$$\mathbf{X} = [\mathbf{x}(c_1, t_0) \ \ \ldots \ \ \mathbf{x}(c_i, t_0) \ \ \ldots \ \ \mathbf{x}(c_{100}, t_0)] \quad (6)$$

where $\mathbf{u}(c_i, t_j) = [u_{p1}(c_i, t_j) \ u_{p2}(c_i, t_j)]^T$ is the vector of the proximity factors (pseudo-neighbourhood) which assumes the crisp (nonfuzzy) values in the space $U_{p1} \times U_{p2} \subset \mathrm{IR}^2$ and is determined in the given time step $t_j \in T$ for each analysed cell $c_i \in C$. The element $\mathbf{x}(c_i, t_0) = [x_{l1}(c_i, t_0) \ x_{l2}(c_i, t_0)]^T$ is the vector of the initial cell state (at the first time step of the forecasting task $t_0 \in T$). The cell state (crisp values) is determined in the space $X_{l1} \times X_{l2} \subset \mathrm{IN}^2$.

In some cases, it is necessary to taken into consideration an additional consumers class, called a basic sector. This group includes industrial, business and administrative establishments whose clients are predominantly non-local [11]. In this SLF task, the presence of aforementioned consumers class has not been foreseen.

Let A mean a family of fuzzy sets indexed by the consumers class and which describe the potential states of the cell

$$A = \{A_{l1}, A_{l2}\} = $$
$$= \begin{Bmatrix} x_{l1}, \mu^1_{Al1}(x_{l1}), \mu^2_{Al1}(x_{l1}), \ldots, \mu^7_{Al1}(x_{l1}), \\ x_{l2}, \mu^1_{Al2}(x_{l2}), \mu^7_{Al2}(x_{l2}), \ldots, \mu^7_{Al2}(x_{l2}) \end{Bmatrix} \quad (7)$$

where $\mu^{1..7}_{Al1}$, $\mu^{1..7}_{Al2}$: X_{Al1}, $X_{Al2,} \rightarrow [0,1]$ are membership functions of the fuzzy subsets $A^{1..7}_{l1}$ and $A^{1..7}_{l2}$.

It is also important to determine the states of the cell neighbourhood. For that purpose, the family of fuzzy sets is formulated by analogy to equations (7)

$$B = \{B_{l1}, B_{l2}\} = \quad (8)$$
$$= \begin{Bmatrix} x_{l1}, \mu^1_{Bl1}(x_{l1}), \mu^2_{Bl1}(x_{l1}), \mu^3_{Bl1}(x_{l1}), \mu^4_{Bl1}(x_{l1}), \\ x_{l2}, \mu^1_{Bl2}(x_{l2}), \mu^2_{Bl2}(x_{l2}), \mu^3_{Bl2}(x_{l2}), \mu^4_{Bl2}(x_{l2}) \end{Bmatrix}$$

where $\mu^{1..4}_{Bl1}$, $\mu^{1..4}_{Bl2}$: X_{Bl1}, $X_{Bl2,} \rightarrow [0,1]$ are membership functions of the fuzzy subsets $B^{1..4}_{l1}$ and $B^{1..4}_{l2}$.

The same formulation is proposed for the pseudo-neighbourhood fuzzy states

$$D = \{D_{p1}, D_{p2}\} = \quad (9)$$
$$= \begin{Bmatrix} u_{p1}, \mu^1_{Dp1}(u_{p1}), \mu^2_{Dp1}(u_{p1}), \ldots, \mu^4_{Dp1}(u_{p1}), \\ u_{p2}, \mu^1_{Dp2}(u_{p2}), \mu^2_{Dp2}(u_{p2}), \ldots, \mu^4_{Dp2}(u_{p2}) \end{Bmatrix}$$

where $\mu^{1..4}_{Dp1}$, $\mu^{1..4}_{Dp2}$: U_{Dp1}, $U_{Dp2,} \rightarrow [0,1]$ are membership functions of the fuzzy subsets $D^{1..4}_{p1}$ and $D^{1..4}_{p2}$.

According to (7-9), the families of the fuzzy sets A, B and D are defined using triangular and trapezoidal membership functions. All of them are shown in Fig. 3.

Let $\mathbf{x}$^$(c_i, t_j) = [x$^$_{l1}(c_i, t_j) \ x$^$_{l2}(c_i, t_j)]$, $\mathbf{y}$^$(c_i, t_j) = [y$^$_{l1}(c_i, t_j) \ y$^$_{l2}(c_i, t_j)]$ and $\mathbf{u}$^$(c_i, t_j) = [u$^$_{p1}(c_i, t_j) \ u$^$_{p2}(c_i, t_j)]$ be the given fuzzy inputs determined respectively in the spaces $X_{l1} \times X_{l2}$, $X_{l1} \times X_{l2}$ and $U_{p1} \times U_{p2}$. (the notation "^" means the fuzzy variable). The vector of fuzzy sets $\mathbf{y}$^(c_i, t_j) describing the neighbourhood state of the cell $c_i \in C$ is calculated as the arithmetical sum of the states (treated as the fuzzy numbers) of the neighbouring cells.

The aforementioned fuzzy sets are used in the transition functions, described by the structure $\Phi = (\phi_{o1}, \phi_{o2}, \phi_{o3})$. For each class $o_i \in O$, the set of fuzzy rules IF-THEN is specified. The transition functions ϕ_{o1}, ϕ_{o2}, and ϕ_{o3} and include adequately 116, 53 and 142 rules. As an example, the selected fuzzy rule pertinent to ϕ_{o1} function is presented below

...

ALSO

IF $\hat{x}_{l1}(t_i)$ IS A^1_{l1} AND $\hat{x}_{l2}(t_i)$ IS A^1_{l2} AND

$\hat{y}_{l1}(t_i)$ IS B^1_{l1} AND $\hat{y}_{l2}(t_i)$ IS B^1_{l2} AND

$\hat{u}_{p1}(t_i)$ IS D^2_{p1} AND $\hat{u}_{p2}(t_i)$ IS D^3_{p2} (10)

THEN

$\hat{x}_{l1}(t_{i+1})$ IS A^2_{l1} AND $\hat{x}_{l2}(t_{i+1})$ IS A^1_{l2}

ALSO

...

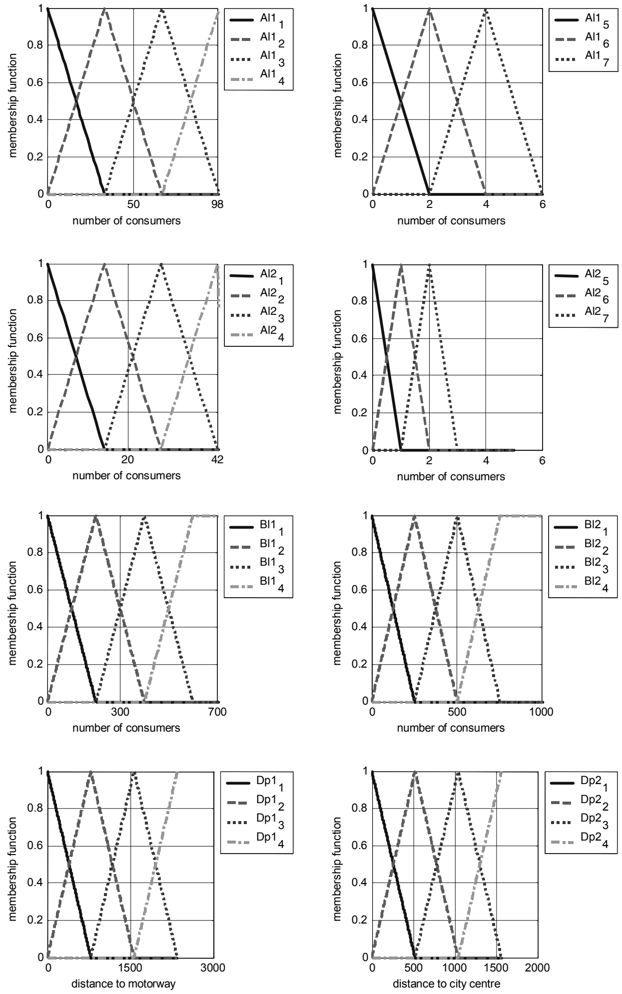

Fig. 3. A family of fuzzy sets describing the possible states of an individual cell (*A*), its neighbourhood (*B*) and proximity factors (*D*)

The appropriate algorithm has been developed for the aforementioned mathematical model in order to calculate the spatial distribution of electric energy consumers. For the algorithm implementation, the author has used Matlab software aided by the Fuzzy Logic Toolbox. The simplified diagram of the proposed algorithm is shown in Fig. 4.

On the basis of the proposed FCA method, the spatial distribution of the energy consumers (after the defuzzifiaction process) has been obtained. The results are shown in Fig. 5. One can observed the significant variations of the spatial distribution of consumers for two considered classes. As expected the meaningful spatial development of the consumers occurs in the cells destined to the appropriate spatial function (classes $\{o_1, o_2, o_3\} = O$). The number of consumers classified as the household sector (l_1) increases mostly close to the city centre. On the other hand, the proximity of the segments of the motorway restrains the growth of this time of building. It also can be noticed that the spatial development of residential building is more intensive where the adjacent cells are spatially highly developed. The occurrence of the motorway segments have an effect on a development of the commercial-service building belonging to the retail sector (l_2). One can observed the increased number of this type of energy consumers influenced the residential building in the neighbourhood. Like in case of household sector.

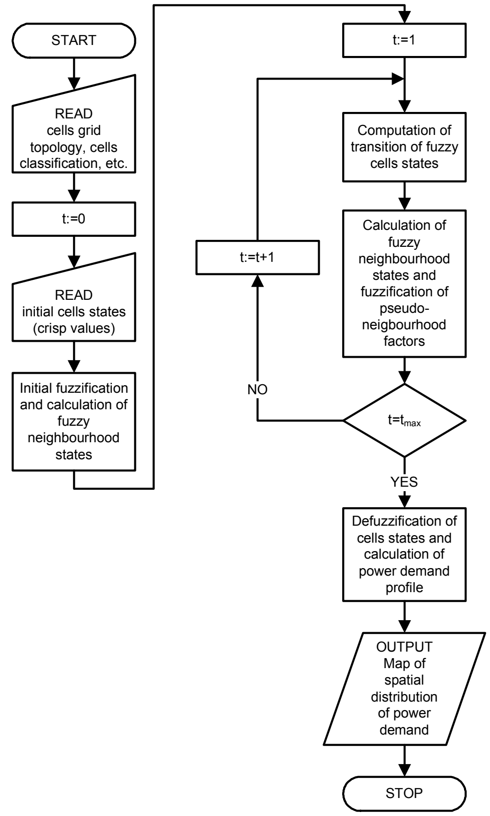

Fig. 4. A simplified algorithm for the FCA based method

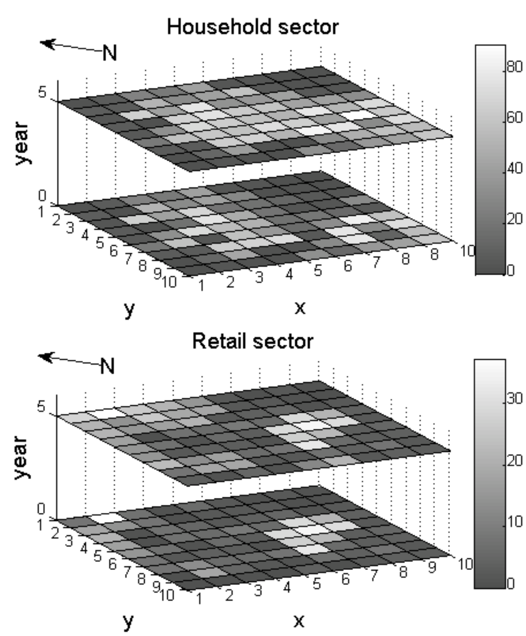

Fig. 5. A spatial distribution of energy consumers for the initial and the final time step of the forecast

V. Conclusions

For the prediction of the spatial distribution of electric load (strictly speaking the prediction of spatial distribution of electric energy consumers), the authors suggest the use of the FCA based method. For that purpose, the mathematical model has been developed. Apart from the information about the states of neighbouring cells, the proximity factors affecting the spatial distribution of electric energy consumers are involved to the model. Because of the lack of exact knowledge about the system dynamics, the FL is used to describe the cells transitions between the particular states. The developed FCA model takes into account the land-use development plan when determining all the investigated cells to the classes of the land-use.

The application of FCA method has been presented in the exemplary hypothetical forecast. The spatial distribution of energy consumers including their classification has been predicted. On the basis of the obtained results, it can be stated that bottom-up FCA based approach can give sensible output data. But it is important to continuously conduct systematic research and development in this field.

The proposed method can be called a synthesis approach or a bottom-up method. It is assumed that only local projections condition the spatial distribution of electric energy consumers in the future. Therefore the global trending factors are purposely overlooked. In the authors' opinion, this technique enables in easy way the simulation of the real behaviour of spatial systems (in this case - the spatial distribution of electric energy consumers). So it can be a good alternative for top-down approach based methods.

VI. Future Works

In future works, the authors intend to verify the usefulness of the proposed FCA in the real SLF problem and estimate the forecast accuracy. First of all, it is necessary to find the proper shape and size of cells as well as identify the FCA parameters. The proper number of rules and the membership functions can be automatically recognized with the use of data mining techniques [9,10]. These can also be used in order to select the meaningful proximity factors and determine the neighbourhood degree for the different consumer classes.

The next phase of the SLF research is to develop the f_2 mapping in the formula (2). It is necessary to estimate of a load profile for each investigated rate class at the base year of the forecast as well as find the actual and precise end-use models.

Apart from the amount of power needed, the spatial distribution of power quality demand (especially the reliability of power supply) should be forecasted. This issue is intended to become the object of future research by the author.

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VIII. Biographies

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