







### 3.2. Fuzzy cognitive models for the estimating the effects of actions on the subsystems indicators

The input factors of these models are actions  $a_{k_j}^{(s_j)} \in A_{s_j}, k_j = 1, \dots, K_j$  for the corresponding subsystem  $s_j, j = 1, \dots, J$ . The output variables of these models are: the indicator  $p_1(s_j)$  characterizing the state of this subsystem; the indicator  $p_2(s_j)$  of the energy- and resource saving potential of the  $j$ -th subsystem.

Nonlinear and indirect dependencies between the factors of the models make it possible to justify the using of fuzzy cognitive models (maps) as such models [1], [2], [3], [4], [5].

The advantages of using fuzzy cognitive models are as follows:

- formalized assignment of system factors of STS, and direct, indirect and aggregated influence of these factors on each other as well;
- consideration of the nature and degree of the direct and indirect influence of various factors of the model on each other;
- flexible analytical tool for various types of STS with a constant model structure (a set of system factors and the interactions between them);
- modeling of various events to assess and identify the factors and interactions of mutual influence provoking instability of STS;
- modelling the dynamics of changes in subsystems and the system as a whole, with an assessment of the impact of various systemic factors, as well as various actions on these changes.

Fuzzy cognitive model is fuzzy-cause-and-effect-networks (FCE-Nets):

$$G = \langle C, W \rangle,$$

where  $C = \{C_1, \dots, C_N\}$  – many concepts,  $W = \{w_{ij} | i, j = 1, \dots, N\}$  – many influence relationships in the form of directed arcs with weights  $w_{ij} \in [-1, 1]$ . Indicator  $w_{ij} = -1$  means the maximum negative impact of the concept,  $w_{ij} = 1$  – maximum positive impact of the concept  $C_i$  on the concept  $C_j$ , and indicator  $w_{ij} = 0$  determines the absence of any direct influence  $C_i$  on  $C_j$ .

With a positive effect  $C_i \xrightarrow{w_{ij}} C_j$  and an increase in the value  $C_i$  the value  $C_j$  increases, and with a decrease, it decreases. With a negative value  $w_{ij}$  an increase in the value  $C_i$  causes a decrease in the value  $C_j$  and vice versa. In addition, it is possible the simultaneous direct influence of a pair of concepts on each other with a mismatch  $w_{ij}$  and  $w_{ji}$ .

To simulate a change in concept values, the following equation is used (separately for positive and negative values,  $w_{ij}$  followed by combining the results obtained):

$$C_j(t+1) = f \left( C_j(t) + \sum_{i=1}^n w_{ij} C_i(t) \right),$$

Where, as a function  $f$  - a non-linear sigmoid function is used, designed to prevent the concept values out of range  $[0, 1]$  or  $[-1, 1]$ .

Let's give an example of the proposed fuzzy cognitive model for the estimating the impact of actions on the indicators of the of electricity subsystem [6].

Figure 2 shows the structure of fuzzy cognitive model which can be used for estimating the impact of actions  $a_{k_j}^{(s_1)} \in A_{s_1}$  on the indicators  $p_1(s_1)$  and  $p_2(s_1)$ , which using for characterizing the state of the subsystem  $s_1$  and energy- and resource saving potential, respectively.

Modeling of the impact of actions  $a_{k_j}^{(s_1)} \in A_{s_1}$  on the indicators  $p_1(s_1)$  and  $p_2(s_1)$  of subsystem  $s_1$  is carried out in accordance with the following stages:

- *firstly*, setting the initial values of the concepts of fuzzy cognitive model;
- *secondly*, the starting the simulation in accordance with the expression to change the values of the concepts;
- *thirdly*, changing the values of the model concepts (including changing its output indicators  $p_1(s_1)$  and  $p_2(s_1)$ ) under the influence of the events from  $A_{s_1}$ ;
- *fourthly*, the completion of the simulation either at the set time, or when the model goes to a stable state, or when the criterial values of any concepts are reached.

Similarly, the designing and using of fuzzy cognitive models for estimating the impact of actions on the indicators of heat- and water supply subsystems are performed.

### 3.3. Fuzzy rule-based models for efficiency estimating of energy- and resource saving of subsystems: power supply, heat and water supply

We will use a fuzzy logic approach to design models for estimating of energy- and resource efficiency for different subsystems. This approach makes it possible to take into account the uncertainty in the estimating the impact of various factors on energy- and resource efficiency [7], [8], [9], [10], [11].

The procedures for the designing and using the proposed models will be considered using the example of the energy- and resource efficiency of the power supply subsystem  $s_1$ .

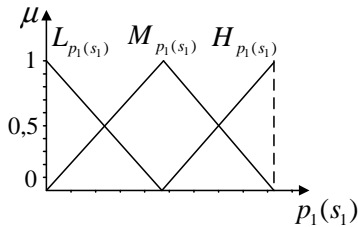
**Step 1.** The designing of model's structure. Input variables of the model:  $p_1(s_1)$  – the state of the subsystem  $s_1$ ;  $p_2(s_1)$  – potential of energy- and resource saving subsystem  $s_1$ ;  $p_3(s_1)$  –

the share of energy- and resource saving costs of subsystem  $s_1$ ;  
 $p_4(s_1)$  – tariffs for energy- and resource saving subsystem  $s_1$ .  
 The output variable is the indicator of energy- and resource efficiency  $e(s_1)$  of the power supply subsystem  $s_1$ .

**Step 2.** The designing of linguistic scales for input and output fuzzy variables. For this, typical  $L$ – $R$  functions (Gaussian, triangular) can be used [7]. We set the same terms for the describing all the variables  $\{L$  – small,  $M$  – medium,  $H$  – large}:

- for  $p_1(s_1) - \{L_{p_1(s_1)}, M_{p_1(s_1)}, H_{p_1(s_1)}\}$ ;
- for  $p_2(s_1) - \{L_{p_2(s_1)}, M_{p_2(s_1)}, H_{p_2(s_1)}\}$ ;
- for  $p_3(s_1) - \{L_{p_3(s_1)}, M_{p_3(s_1)}, H_{p_3(s_1)}\}$ ;
- for  $p_4(s_1) - \{L_{p_4(s_1)}, M_{p_4(s_1)}, H_{p_4(s_1)}\}$ ;
- for  $e(s_1) - \{L_{e(s_1)}, M_{e(s_1)}, H_{e(s_1)}\}$ .

Figure 3 shows an example of a linguistic scale for a fuzzy input variable  $p_1(s_1)$ .



**Figure 3.** An example of a linguistic scale for input fuzzy variable  $p_1(s_1)$

**Step 3.** Generation of the fuzzy rules:

$R_1$ : If  $p_1(s_1)$  is  $L_{p_1(s_1)}$  AND  $p_2(s_1)$  is  $L_{p_2(s_1)}$  AND  $p_3(s_1)$  is  $L_{p_3(s_1)}$  AND  $p_4(s_1)$  is  $L_{p_4(s_1)}$ , Then  $e(s_1)$  is  $L_{e(s_1)}$ ;

$R_2$ : If  $p_1(s_1)$  is  $M_{p_1(s_1)}$  AND  $p_2(s_1)$  is  $M_{p_2(s_1)}$  AND  $p_3(s_1)$  is  $M_{p_3(s_1)}$  AND  $p_4(s_1)$  is  $M_{p_4(s_1)}$ , Then  $e(s_1)$  is  $M_{e(s_1)}$ ;

$R_3$ : If  $p_1(s_1)$  is  $H_{p_1(s_1)}$  AND  $p_2(s_1)$  is  $H_{p_2(s_1)}$  AND  $p_3(s_1)$  is  $H_{p_3(s_1)}$  AND  $p_4(s_1)$  is  $H_{p_4(s_1)}$ , Then  $e(s_1)$  is  $H_{e(s_1)}$ .

The energy- and resource efficiency of the power supply subsystem is evaluated based on fuzzy logic inference [7].

This procedure consists of the following steps.

**Step 1.** Determination of the degrees of membership of the values of input variables for all fuzzy statements in the premises of all rules.

For example, for the  $R_1$ :

$$\mu_{M_{p_1(s_1)}}(p'_1(s_1)), \mu_{M_{p_2(s_1)}}(p'_2(s_1)), \mu_{M_{p_3(s_1)}}(p'_3(s_1)), \mu_{M_{p_4(s_1)}}(p'_4(s_1)).$$

**Step 2.** Aggregation of truth degrees of fuzzy statements of prerequisites for each rule.

For example, for the  $R_1$ :

$$\alpha_y = \min \left( \begin{array}{l} \mu_{M_{p_1(s_1)}}(p'_1(s_1)), \mu_{M_{p_2(s_1)}}(p'_2(s_1)), \\ \mu_{M_{p_3(s_1)}}(p'_3(s_1)), \mu_{M_{p_4(s_1)}}(p'_4(s_1)) \end{array} \right).$$

**Step 3.** Activation of conclusions for each rule.

For example, for the  $R_1$ :

$$\mu_{M_{e(s_1)}}(e(s_1)) = \min(\alpha_y, \mu_{M_{e(s_1)}}(e(s_1))).$$

**Step 4.** Accumulation of activated conclusions according to all the rules:

$$\mu_{e'(s_1)}(e(s_1)) = \max \left( \begin{array}{l} \mu_{L_{e(s_1)}}(e(s_1)), \dots \\ \mu_{M_{e(s_1)}}(e(s_1)), \dots \\ \mu_{H_{e(s_1)}}(e(s_1)) \end{array} \right).$$

**Step 4.** Getting clear output variable values:

$$e'(s_1) = \frac{\sum_{n=1}^N e(s_1)_{(n)} \cdot \mu_{e'(s_1)}(e(s_1)_{(n)})}{\mu_{e'(s_1)}(e(s_1)_{(n)})},$$

where  $K$  – the number of elements in the sampled base set output variable  $e(s_1)$ .

Similarly, the designing and using of fuzzy rules-based models for efficiency estimating of energy- and resource saving of heat- and water supply subsystems are performed.

### 3.4. Generalized fuzzy rules-based model for efficiency estimating of energy- and resource saving of system as a whole

The process of designing a generalized fuzzy rules-based model for assessing the effectiveness of energy- and resource saving of system is similar to designing a model for a separate subsystem.

The input fuzzy variables of this model are fuzzy indicators  $e(s_1), e(s_2), e(s_3)$  of energy- and resource efficiency of electrical, heat and water subsystems, respectively. The output fuzzy variable is a generalized fuzzy indicator  $E(S)$  of energy- and resource efficiency of the system  $S$ . The fragment of fuzzy rules base of this model is presented in Table 1.

**Table 1.** The fragment of fuzzy rules base of this generalized model

No	Input variables			Output variable, $E(S)$
	$e(s_1)$	$e(s_2)$	$e(s_3)$	
$R_1$	$L_{e(s_1)}$	$L_{e(s_2)}$	$L_{e(s_3)}$	$L_{E(S)}$
$R_2$	$L_{e(s_1)}$	$L_{e(s_2)}$	$M_{e(s_3)}$	$L_{E(S)}$
...	...	...	...	...
$R_g$	$M_{e(s_1)}$	$M_{e(s_2)}$	$M_{e(s_3)}$	$M_{E(S)}$
...	...	...	...	...
$R_{Q-1}$	$H_{e(s_1)}$	$H_{e(s_2)}$	$M_{e(s_3)}$	$H_{E(S)}$
$R_Q$	$H_{e(s_1)}$	$H_{e(s_2)}$	$H_{e(s_3)}$	$H_{E(S)}$

The algorithm of the generalized evaluation of the energy- and resource efficiency of the system is implemented

in a manner analogous to the algorithm for estimating the energy- and resource saving of a separate subsystem.

### 3.5. Simulating for the selection of a set of actions to improve the efficiency of energy- and resource saving of system

The procedure for the selection of a set of actions  $C(S)$  to improve the efficiency of energy- and resource saving of system consists in assigning various combinations of actions  $a_{k_j}^{(s_j)} \in A_{s_j}, k_j = 1, \dots, K_j$  for all resource-intensive subsystems  $\{s_1, s_2, s_3\}$  (under the restrictions on the amount of financial costs and the time of their implementation), and in determining such actions which provide the maximum value of the energy efficiency and resource saving of the system (indicator  $E(S)$ ).

The given compositional fuzzy model is implemented as software, and as a pilot project in 2018, it was used in modeling the development of the power system of Moscow. According to the results of the simulation:

- the factors that have the most significant impact on the problem of energy and resource conservation have been identified;
- measures are formed and justified to increase the efficiency of energy and resource saving of this system.

## 4. Conclusion

The formulation of the task of increasing the efficiency of energy and resource saving in STS. The choice of fuzzy cognitive modeling and fuzzy logical inference methods for evaluating the formation of a set of measures to improve the efficiency of energy and resource conservation in STSs is substantiated.

A compositional fuzzy model for efficiency estimating of energy- and resource saving of STSs is proposed. This composite fuzzy model consists of the following models: firstly, a set of fuzzy cognitive models for estimating the effects of actions on the subsystems' indicators; secondly, a set of fuzzy rules-based models for efficiency estimating of energy- and resource saving of subsystems; thirdly, a generalized fuzzy model for efficiency estimating of energy- and resource saving of system as a whole. The procedure of compositional fuzzy modeling of energy- and resource saving in STSs is described.

The given compositional fuzzy model is implemented as software, and as a pilot project in 2018, it was used in

modeling the development of the power system of Moscow. According to the results of the simulation: first, the factors that have the most significant impact on the problem of energy and resource conservation have been identified; secondly, measures are formed and justified to increase the efficiency of energy and resource saving of this system.

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