**EAI Endorsed Transactions on Energy Web and Information Technologies** Research Article **EAI.EU**

# Compositional fuzzy modeling of energy- and resource saving in socio-technical systems

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## Abstract

The paper poses the problem of increasing the efficiency of energy- and resource saving in socio-technical systems, which consist of resource-intensive subsystems (for example, subsystems of electricity, heat and water supply). A compositional fuzzy model for efficiency estimating of energy- and resource saving of socio-technical systems is proposed. This compositional 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 socio-technical systems is described.

**Keywords:** energy- and resource savings; socio-technical system; rules-based fuzzy model; fuzzy cognitive model.

Received on 30 May 2018, accepted on 14 October 2018, published on 25 October 2018



doi: 10.4108/eai.12-9-2018.155863

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## 1. Introduction

At present, the complexity of processes in socio-technical systems (STS) is increasing. Therefore, the importance of the problem of energy- and resource saving in these STS increases under the conditions of complex impact of system and external parameters, as well as their uncertainty. The multi-factorial and nonlinear interactions between the parameters of processes in STSs, the uncertainty how the characteristics are interrelated and the complexity of the formalization of the tasks to be solved determine the urgency of developing modern analytical methods in this area. The development and application of intellectual methods and technologies is a promising direction to solve these problems in the conditions of inaccuracy and incompleteness of the initial data.

According to this, modelling and management of energy- and resource saving in STSs should take into account the following features: firstly, a comprehensive approach of modelling, estimating and management of energy- and resource saving in STSs; secondly, the application of compositional models consisting of sets of models for implementation of separate stages of modelling, evaluation and management of energy- and resource saving processes; thirdly, the use of methods of fuzzy analysis and modelling of complex systems and processes, namely the methods of fuzzy cognitive modeling and fuzzy logical inference.

## 2. Problem formulation

Let's assume that the efficiency of energy- and resource saving of the STS $S$ is estimated by a generalized indicator $E(S)$.

The system $S$ consists of subsystems:

$$S = \{s_j\},\ j = 1, ..., J.$$

For the problem being solved:

$$S = \{s_1, s_2, s_3\},$$

where $s_1, s_2, s_3$ – energy- and resource-intensive subsystems of power supply, heat supply and water supply, respectively.

Efficiency of energy- and resource saving of STS is determined by the energy- and resource efficiency of its subsystems and expressed by the following dependence:

$$E(S) = F\left(e(s_1), ..., e(s_J)\right).$$

where $e(s_j),\ j = 1, ..., J$ – an indicators of energy- and resource efficiency of subsystems $s_j,\ j = 1, ..., J$.

Each subsystem $s_j \in S$ is characterized by a set of indicators:

$$P(s_j) = \left\{p_l(s_j)\right\}, l = 1, ..., L.$$

For the problem being solved:

$$\forall s_j:\ P(s_j) = \left\{p_1(s_j),\ p_2(s_j),\ p_3(s_j),\ p_4(s_j)\right\},$$

where $p_1(s_j)$ – an indicator which characterizes the state of jth subsystem; $p_2(s_j)$ – an indicator of energy- and resource saving potential of the *j*th subsystem; $p_3(s_j)$ – share in total cost allocated for energy- and resource saving of the *j*th subsystem; $p_4(s_j)$ – tariffs for energy- and resource savings of the *j*th subsystem.

For each subsystem $s_j,\ j = 1, ..., J$, its own group $A_{s_j}$ of actions has been formed, aimed at increasing its energy- and resource efficiency:

$$A_{s_j} = \left\{a_{k_j}^{(s_j)}\right\}, k_j = 1, ..., K_j.$$

The actions $a_{k_j}^{(s_j)} \in A_{s_j}, k_j = 1, ..., K_j$ are characterized by the following set of indicators:

$$Q\left(a_{k_j}^{(s_j)}\right) = \left\{q_m\left(a_{k_j}^{(s_j)}\right)\right\}, m = 1, ..., M.$$

For the problem being solved:

$$\forall e_{k_j}^{(s_j)}:\ Q\left(a_{k_j}^{(s_j)}\right) = \left\{q_1\left(a_{k_j}^{(s_j)}\right), q_2\left(a_{k_j}^{(s_j)}\right), q_3\left(a_{k_j}^{(s_j)}\right)\right\},$$

where $q_1\left(a_{k_j}^{(s_j)}\right)$ – an indicator which characterizes impact of the action $a_{k_j}^{(s_j)}$ on *j*th subsystem condition; $q_2\left(a_{k_j}^{(s_j)}\right)$ – indicator which characterizes the impact of the action $a_{k_j}^{(s_j)}$ on changing the energy- and resource saving potential of the *j*th subsystem; $q_3\left(a_{k_j}^{(s_j)}\right)$ – an indicator which determines the cost of implementing the action.

It is required to choose a set of actions $C(S)$ (from groups of events $\left\{A_{s_1}, A_{s_2}, A_{s_3}\right\}$) to maximize the efficiency of energy- and resource saving all system, with restrictions on the financial costs and the time $T\left(C(S)\right)$ of implementation of the set of actions:

$$E(S) \xrightarrow{C(S)} \max,$$

$$\sum_{k_j \in K_J} q_3\left(a_{k_j}^{(s_j)}\right) \le p_3(s_j),\quad j = 1, ..., J,$$

$$T\left(C(S)\right) \le T_{max}\left(C(S)\right).$$

## 3. Compositional fuzzy model for the efficiency estimation of energy- and resource saving in STS

### 3.1. Structure of the composite model

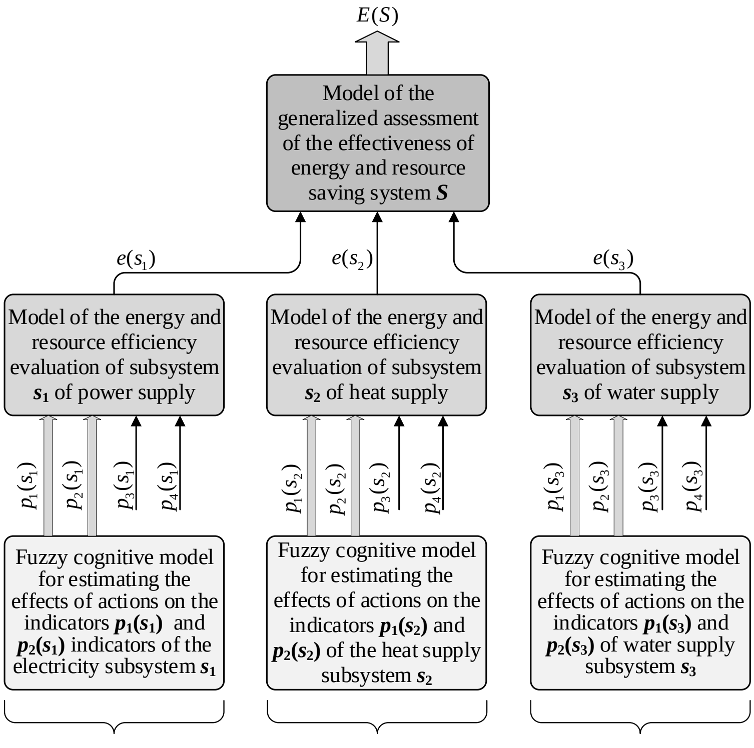
Figure 1 shows the structure of the compositional fuzzy model for the efficiency estimation of energy- and resource saving in STS, based on the proposed problem formulation.

The compositional fuzzy model consists of the sets of the following models:

- *fuzzy cognitive models* for estimating the effects of actions on the subsystems' indicators (power supply, heat and water supply);
- *fuzzy rule-based models* for efficiency estimating of energy- and resource saving of subsystems: power supply, heat and water supply;
- *generalized fuzzy rule-based model* for efficiency estimating of energy- and resource saving of system as a whole.

The fuzzy cognitive models are affected by events from groups of measures $A_{s_j} = \left\{a_{k_j}^{(s_j)}\right\}, k_j = 1, ..., K_j$, corresponding to subsystems $\forall s_j \in S$. As a result, the values of the output variables $p_1(s_j)$ and $p_2(s_j)$ of these models, which (together with indicators $p_3(s_j)$ and $p_4(s_j)$, do not depend on the impact of the events) are fed to the inputs of fuzzy rule-based models for efficiency estimating $e(s_j),\ j = 1, ..., J$ of energy- and resource saving of subsystems. Then, these estimates are aggregated into a generalized indicator $E(S)$ of energy and resource efficiency of the entire system $S$ using generalized fuzzy rule-based model.

Sections 3.2–3.5 of this article present more details on how to construct and how to use these models for assessing the effectiveness of energy and resource saving in STSs.




$A_{s_1} = \{a_{k_j}^{(s_1)}\}$ $A_{s_2} = \{a_{k_j}^{(s_2)}\}$ $A_{s_3} = \{a_{k_j}^{(s_3)}\}$

**Figure 1.** Structure of the compositional fuzzy model

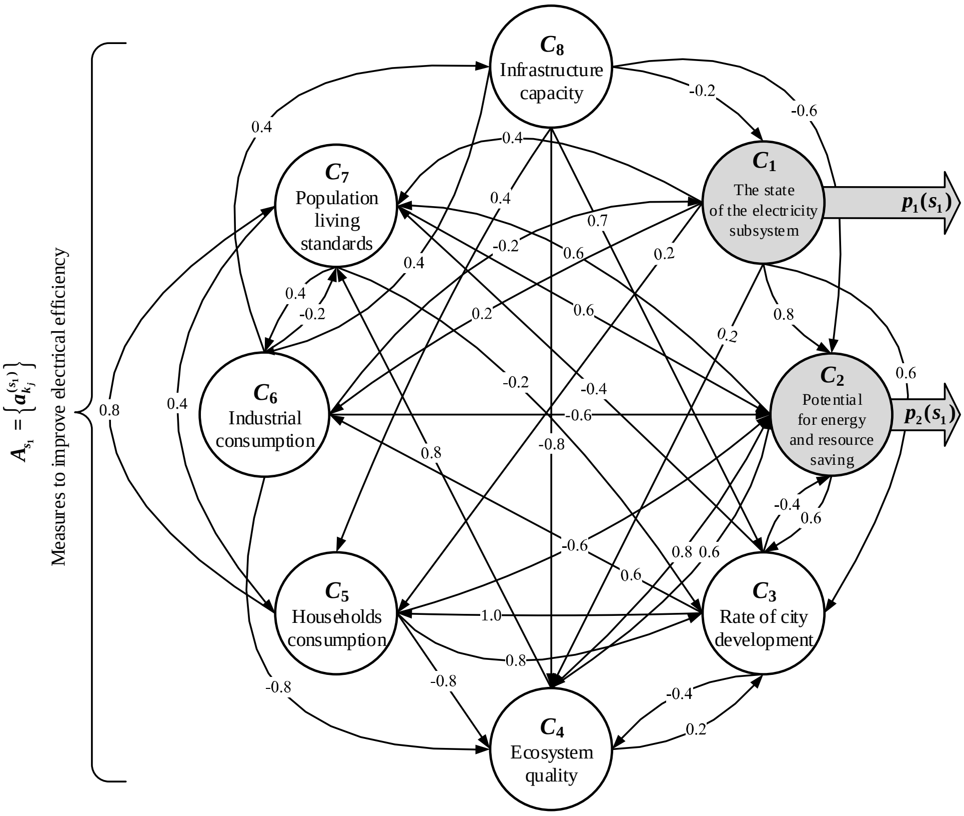



**Figure 2.** Fuzzy cognitive model for estimating the impact of actions $a_{k_j}^{(s_1)} \in A_{s_1}$ on indicators $p_1(s_1)$ and $p_2(s_1)$ of the subsystem $s_1$

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

The input factors of these models are actions $a_{k_j}^{(s_j)} \in A_{s_j}, k_j = 1, ..., K_j$ for the corresponding subsystem $s_j$, $j = 1, ..., J$. 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 $C = \{C_1, ..., C_N\}$ – many concepts, $W = \{w_{ij} \mid i, j = 1, ..., N\}$ – 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 $\boldsymbol{A}_{s_1}$;
- *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 $p_1(s_1)$.

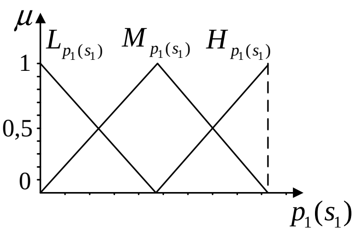



**Figure 3.** An example of a linguistic scale for input fuzzy variable $p_1(s_1)$

***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 $L_{e(s_1)}$;

…

$R_y$: **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 $M_{e(s_1)}$;

…

$R_Y$: **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 $R_y$:

$$\mu_{M_{p_1(s_1)}}(p_1'(s_1)),\mu_{M_{p_2(s_1)}}(p_2'(s_1)),\mu_{M_{p_3(s_1)}}(p_3'(s_1)),\mu_{M_{p_4(s_1)}}(p_4'(s_1)).$$

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

For example, for the $R_y$:

$$\alpha_y = \min\begin{pmatrix}\mu_{M_{p_1(s_1)}}(p_1'(s_1)),\mu_{M_{p_2(s_1)}}(p_2'(s_1)),\\ \mu_{M_{p_3(s_1)}}(p_3'(s_1)),\mu_{M_{p_4(s_1)}}(p_4'(s_1))\end{pmatrix}.$$

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

For example, for the $R_y$:

$$\mu_{M'_{e(s_1)}}(e(s_1)) = \min\left(\alpha_y,\ \mu_{M_{e(s_1)}}(e(s_1))\right).$$

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

$$\mu_{e'(s_1)}(e(s_1)) = \max\begin{pmatrix}\mu_{L'_{e(s_1)}}(e(s_1)),\ ...,\\ \mu_{M'_{e(s_1)}}(e(s_1)),\ ...,\\ \mu_{H'_{e(s_1)}}(e(s_1))\end{pmatrix}.$$

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

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

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 $a_{k_j}^{(s_j)} \in A_{s_j}, k_j = 1, ..., K_j$ 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.

## Acknowledgment

The work is conducted under the support of the Russian Science Foundation (project 16-19-10568).

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