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ESTIMATION OF METABOLIC FLOWS OF URBAN ENVIRONMENT BASED ON FUZZY EXPERT KNOWLEDGE

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Abstract. The quality and comfort of the urban environment serve as one of the most important factors for ensuring the competitiveness of municipalities, regions and countries. The quality of the urban environment is determined by the quality of its three components: anthropogenic, natural and social environment. The main problem of assessing the state of the urban environment is the fragmentation of methodological approaches and adequate tools for assessing the qualitative state of the urban environment. This objectively makes it difficult for municipal authorities to use this assessment as an element in the system of urban planning decision making. We have developed an intelligent information system to provide an assessment of potential, real and lost opportunities of the urban environment using fuzzy expert knowledge. This system operates in the conditions of using non-numeric, inaccurate and incomplete information to ensure the management of sustainable city development. The system for assessing the potential, real and lost opportunities of the urban environment is based on the use of fuzzy logic equations. It allows to evaluate the effectiveness of metabolic transformations of each subsystem of the urban environment.

Keywords: knowledge base, if–then rules, fuzzy logic, expert system, the metabolism of the urban environment.

Introduction

In the last decade, the problem of the use of modern information technology in the study of sustainable urban development issues is of particular importance. This is connected both with the strengthening of the role of information and communication channels in the world as a whole, and the actualization of the introduction of information technologies in the regulatory and legal field of state and municipal government. At one time, Aristotle asserted that in human society, management is one of the main components of the development process.

For the first time, the definition of "sustainable development" was substantiated in 1987 by the United Nations World Commission on the Environment and Development. In general, sustainable development refers to social progress, which would satisfy the needs of the current generation without limiting the possibilities of the future generation. Since 1999, at international conferences under the auspices of the UN, the transition to a new paradigm of sustainable development has been discussed. This paradigm provides for a steady increase in free energy. In modern models of sustainable development, power is used as a measure of system development. The power of the system is its ability to perform work per unit of time. This was discussed by Bolshakov (2008), by Bettencour et al. (2007).

The problem of sustainable development is of particular relevance for large and small cities of Ukraine. Here, the management of vital systems must conform to this paradigm of sustainable development.

The power of the system can express space and time. This was discussed by Acebillo (2008), Bolshakov and Kuznetsov (2010) and by Ursul (2005). The power estimate may show qualitative and quantitative certainty. This value is a measure of the ability of the system to operate in time.

There are three groups of possibilities of the system with a measure of power. This was discussed by Bolshakov and Ryabkova (2009). The first is a potential opportunity. It is determined by the measure of full power at the entrance to the system. The second is a real opportunity. It

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is determined by the measure of the useful (active) power on the output of the system. The third group of system features is a lost opportunity. It is determined by the amount of losses (passive) power output on the system.

The law of conservation of power states that total, full power is stored (remains constant) in an open system during any transformation (Bolshakov & Ryabkova, 2009; Kapitsa, 2001):

$$N = P + L = const, \quad (1)$$

where N is full power (potential system capacity); P is an active (useful) power (real system capabilities); L is the power loss (lost system capabilities).

The language of analysis identifies three groups of system capabilities with a measure of system capacity. This system is the urban environment, which is subject to optimal management at the regional and municipal levels. The law of conservation of power for open systems is an ideal of noospheric control of sustainable development. This was discussed by Ursul (2005), by Yager and Filev (1994) and by Tsvetkov (2016). According to the law of conservation of power, the sustainable development of an open system takes place with non-decreasing growth of active (useful) power. Sustainable urban development can be achieved through noospheric management. In this case, the management must be consistent with the law of conservation of power (1).

The use of information technologies in ensuring the noospheric management of sustainable development of the urban environment will allow to solve the following tasks:

- monitoring of potential, real and lost opportunities of subsystems of the urban environment;
- forecast of the consequences of the proposed decisions on territorial development;
- calculation of normative parameters and indicators of the strategy of noospheric sustainable development at the state, regional and municipal levels;
- assessment of the existing, necessary state, forecast of possible problem situations and provision of an action plan for their elimination.

Heterogeneous, non-additive, non-comparable indicators are usually used to measure the sustainable development of the urban environment. You cannot perform arithmetic operations with these indicators. Even if these indicators are normalized and reduced to conditionally dimensionless form.

Summarizing the above, it should be noted that to ensure optimal noospheric control, it is necessary to assess the potential, real and lost opportunities of the urban environment. This estimate should be based on the processing of non-numeric (ordinal), inaccurate and incomplete information. Non-numeric, inaccurate, and incomplete information allows us to apply a set of weighting sets to obtain an integral assessment of the potential, actual and lost opportunities of the urban environment.

The purpose of this work is to develop an intelligent information system to assess the potential, real and lost opportunities of the urban environment. This system should use fuzzy expert knowledge in terms of using non-numeric, inaccurate and incomplete information about the urban environment.

1. Concept of the urban environment, based on network metabolism

The urban environment is a networked metabolic organism. The subsystems of the urban environment are interconnected by networks. These networks feed the urban environment with energy and resources from outside. The urban environment is a multilateral space. It is not limited to territory, the movement of people, information and goods. The urban environment carries out a permanent transformation of matter, energy, information, waste, etc. This transformation changes the forms of social organization and life forms of the population (Butera & Caputo, 2008).

From a functional point of view, the transport subsystem, the urban economy subsystem and the socio-economic subsystem can be considered the most significant subsystems of the urban environment. This was discussed by Tsvetkov (2016). The transport subsystem characterizes the spatial mobility of the population. Subsystem urban management sets the level of comfort of the urban environment. Socio-economic subsystem determines the level of healthy life of the population.

Supporting the life of the urban environment is the circulation of substances. That is, the very existence of the urban environment depends on the constant influx of external energy flow $N(t)$. This energy is necessary for the vital activity of living organisms, as well as for the production of materials, substances, products, resources and services.

Each subsystem receives a certain amount of different types of energy, matter and information $N(t)$. In this case, the subsystem produces two types of products. One type is negative production, it is determined by the loss stream $L(t)$. The second type of product is used by each subsystem to ensure its own life, this is the flow of useful work $P(t)$. This was discussed by Caputo et al. (2018) and by Bolshakov and Kuznetsov (2010).

In Figure 1 shows the information model of the interaction of the transport subsystem of the urban environment with the environment. Indicators of the total flows of matter, energy, information, as well as indicators of the flow of losses and indicators of the negentropic flow of the transport subsystem of the urban environment have a heterogeneous and multi-scale character. For example, the real possibility of a transport subsystem is determined by such indicators of flows of matter, energy and information: the density of the street-road network with dimensionality km/km^2; number of motor vehicles of city with dimensionality pcs; energy consumption by private motor vehicles with dimensionality $MWh/(veh. \cdot y)$; energy consumption by transport by dimension $MWh/(inh. \cdot y)$. Thus, we have measured flows of different nature.

In the modern identification theory (Rotshtein, 1996, 1999), a deterministic or statistical approach is used to derive mathematical models. However, in any case, establishing a connection between the input and output empirical data turns out to be a complex process in intellectual tasks that are solved by decision makers. In order to be able to formalize natural language statements in the conditions of vagueness, fuzziness of empirical data, we used a mathematical apparatus, which is called the theory of fuzzy sets.

Consider construction and customization of a fuzzy knowledge base. This base is a set of linguistic statements such as IF (inputs) TO (output). This allows us to assess the potential, real and lost opportunities of the urban environment.

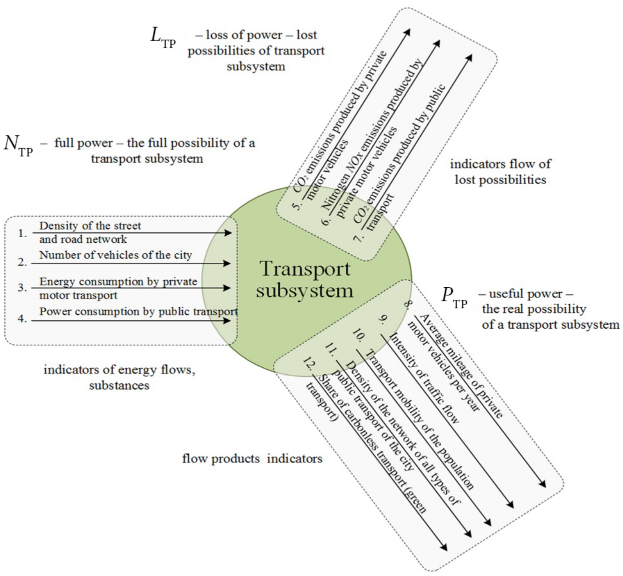

Figure 1. The general information model of the interaction of the transport subsystem of the urban environment with the environment

2. Building a fuzzy knowledge base for assessing the potential, real and lost opportunities of the urban environment

The key concept of any intellectual information system is the knowledge base. In this expert system, we used the production model of knowledge representation based on the processing of heterogeneous, non-additive and non-comparable primary indicators. This was discussed by Rotshtein (1999), by Gerasimov et al. (2004) In systems with knowledge bases, knowledge representation is a fundamental concept. In this case, the decision on the choice of the method of knowledge representation has a great influence on any part of them. Usually there are four groups of ways to represent knowledge (Newman, 1989; Gerasimov et al., 2004): logical, network, hierarchical and procedural representations. Knowledge processing systems that use production models are called "productive systems".

Any production rule that is contained in the knowledge base consists of two parts: the antecedent and the sequential. Antecedent is the premise of the rule (conditional part). Antecedent consists of elementary sentences that are connected by logical connections "AND", "OR". The consequent (conclusion) includes one or several sentences. These sentences express either a certain fact or an indication of the action that is to be executed. Production rules are usually written in the form of antecedent-sequential. Formally, a fuzzy rule can be represented as a tuple:

$$FR = \left\langle NFR,\ \left\{FSVAR_i\right\} \rightarrow FSD,\ CF \right\rangle,$$

where NFR is name of fuzzy rule; $FSVAR_i$ is fuzzy expression input variable; FSD is fuzzy expression output variable; CD is coefficient of activity of the production rule.

Formally, a fuzzy statement of one input variable can be represented as a tuple:

$$FSVAR = \left\langle LV^{inp},\ LT^{inp},\ M^{inp} \right\rangle,$$

where LV^{inp} is linguistic input variable; LT^{inp} is linguistic term of the input variable; M^{inp} is linguistic term modifier of the input variable, which correspond to the words "very", "more or less", "not very" and others.

Formally, a fuzzy statement of the output variable can be represented as a tuple:

$$FSD = \left\langle LV^{out},\ LT^{out},\ M^{out} \right\rangle,$$

where LV^{out} is linguistic output variable; LT^{out} is linguistic term of the output variable; M^{out} is modifier of the linguistic term of the output variable.

In the general case, the linguistic variable can be formally represented as a tuple:

$$LV^{inp} \cup LV^{out} = LV = \left\langle NLV, TSLV, ULV, GLV, MLV, TLV \right\rangle,$$

where NLV is the name of the linguistic variable; $TSLV$ is term set of linguistic variable; ULV is area of definitions of each element's function of $TSLV$; GLV is syntactic rules in the form of formal grammar, which generates the name of the linguistic terms; MLV is semantic rules, which are defined by the membership functions of linguistic terms. They are generated by syntax rules of GLV; TLV is type of linguistic variable (depends on fuzzy output algorithm).

Formally, the linguistic term of the variable can be given in the form of a tuple:

$$LT = \left\langle NLT, MF \right\rangle,$$

where NLT is the name of the linguistic term; MF is membership function of a linguistic term variable.

Usually, piecewise-linear functions are used as membership functions for fuzzing fuzzy variables, evaluating potential, real, and lost opportunities of subsystems of the urban environment. An example of such functions (Gerasimov et al., 2004) is triangular and trapezoidal, which are defined by expressions:

$$\mu(x;a,b,c)=\begin{cases}0, & \text{if} \quad x\le a;\\ \dfrac{x-a}{b-x}, & \text{if} \quad a<x\le b;\\ \dfrac{c-x}{c-b}, & \text{if} \quad b<x\le c;\\ 0, & \text{if} \quad c<x,\end{cases}$$

where *a, b, c* are some numeric parameters that are related by $a < b < c$.

The triangular membership function is used when it is known that a fuzzy variable is limited to a certain range of values. In addition, there is an assumption about the average value of the variable. Then *a* is minimum variable value, *b* – average value, *c* – maximum value.

Trapezoidal function of membership is given by an expression (Gerasimov et al., 2004):

$$\mu(x;a,b,c,d)=\begin{cases}a, & x\le a;\\ \dfrac{x-a}{b-a}, & a<x<b;\\ 1, & b<x\le c;\\ \dfrac{d-x}{d-c}, & c<x\le d;\\ 0, & d<x,\end{cases}$$

where a,b,c,d are some numeric parameters that are related by $a<b<c<d$.

The trapezoidal membership function is used when the range of variation of a fuzzy parameter is known, as well as the range of possible changes in the average value. These parameters are used to set such properties of sets that characterize the uncertainty of the type: "approximately equal", "average value", "located in the interval", "similar to the object", "similar to the object".

Let us dwell more on the formation of a knowledge matrix. This was discussed by Rotshtein (1996) and by Gerasimov et al. (2004). We use this matrix to evaluate the potential, real, and lost opportunities of each of the subsystems of the urban environment. The matrix of knowledge is the table, which we will form according to the following rules (Table 1).

1. The size of this table is equal $(n+1)\times N$, where $(n+1)$ is number of columns, and $N=k_1+k_2+\dots+k_n$ is number of lines.

2. The first n columns correspond to the input variables of x_i, $i=\overline{1,n}$, and the column of $(n+1)$ corresponds to the value of y_j of the output variable of y, $j=\overline{1,m}$.

3. Each matrix line represents a combination of the values of the output variable of y. The first *k* term corresponds to the value of the output variable of $y=y_1$. The following *l* lines correspond to the value of the output variable of $y=y_j$. The last *p* lines correspond to the value of the output variable $y=y_m$.

4. Consider an element of the matrix of A_i^{mp}. It is located at the intersection of the *i*-th column and the *mp*-th row. This element corresponds to the linguistic estimation of the parameter of x_i in the string of the fuzzy knowledge base with the number *mp*. In this case, the linguistic

Table 1. Basic elements of the matrix of knowledge

Input value combination number	Input variables				Output variable
	x_1	x_2	$\dots x_i \dots$	x_n	
11	A_1^{11}	A_2^{11}	$\dots A_i^{11} \dots$	A_n^{11}	y_1
12	A_1^{12}	A_2^{12}	$\dots A_i^{12} \dots$	A_n^{12}	
…	…	…	…	…	
1*k*	A_1^{1k}	A_2^{1k}	$\dots A_i^{1k} \dots$	A_n^{1k}	
…					
*j*1	A_1^{j1}	A_2^{j1}	$\dots A_i^{j1} \dots$	A_n^{j1}	y_j
*j*2	A_1^{j2}	A_2^{j2}	$\dots A_i^{j2} \dots$	A_n^{j2}	
…	…	…	…	…	
jl	A_1^{jl}	A_2^{jl}	$\dots A_i^{jl} \dots$	A_n^{jl}	
…					
*m*1	A_1^{m1}	A_2^{m1}	$\dots A_i^{m1} \dots$	A_n^{m1}	y_m
*m*2	A_1^{m2}	A_2^{m2}	$\dots A_i^{m2} \dots$	A_n^{m2}	
…	…	…	…	…	
mp	A_1^{mp}	A_2^{m2}	$\dots A_i^{mp} \dots$	A_n^{mp}	

estimate of A_i^{mp} is obtained from the term set, which corresponds to the variable x_i. That is $A_i^{mp}\in A_i$, $i=\overline{1,n}$, $j=\overline{1,m}$, $p=\overline{1,l}$.

This structure of the knowledge matrix allows us to define a system of production rules that link the values of the input indicators of the state of the urban environment $X=\{x_1,x_2,\dots,x_n\}$ with the assessment of the metabolic efficiency of the urban environment. Each state of the urban environment $X=\{x_1,x_2,\dots,x_n\}$ corresponds to the indicator of the efficiency of the metabolism of the urban environment $I(X)=I\{x_1,x_2,\dots,x_n\}$:

$$\{x_1,x_2,\dots,x_n\}\to I(X). \tag{2}$$

Let us consider a method for estimating potential, real, and lost opportunities in the urban environment $I(X)$ for a given vector of input linguistic variables $X=\{x_1,x_2,\dots,x_n\}$.

The obtained values of the input variables must be approximated. This was discussed by Rotshtein (1996) and by Gerasimov et al. (2004). From the numerical analysis it is known that any elementary function can be approximated by a linear function of the form:

$$I(x_1,x_2,\dots,x_n)=I_0+\textstyle\sum_{j=1}^{n}\lambda_j\times x_j,$$

here λ_j is coefficient of linear approximation, which characterizes the change in the value of the indicator, depending on the value of the *j*-th variable:

$$\Delta I_j=I(x_1,\dots,x_j+\Delta x_j,\dots,x_n)-I(x_1,\dots,x_j,\dots,x_n)=\lambda_j\times\Delta x_j. \tag{3}$$

In accordance with expression (1), the simultaneous change of two variables x_j and x_k, which does not affect the change in the indicator value, is characterized by the following condition:

$$\Delta I = \lambda_j \times \Delta x_j + \lambda_k \times \Delta x_k = 0\,;\ \Delta x_j = -\frac{\lambda_k}{\lambda_j} \cdot \Delta x_k. \quad (4)$$

For example, the variable of x_j is the number of private vehicles in a city, the variable of x_k is the amount of CO_2 emissions that are produced by private vehicles. In this case, condition (4) is interpreted as a compromise between the growth in the number of private vehicles and the volume of CO_2 emissions. We want to find an acceptable balance between increasing the number of private vehicles and increasing CO_2 emissions. This acceptable balance determines our expert system by the value of the relation λ_k / λ_j.

In reality, the balance, which is determined by equation (3), depends on the current situation. For example, there is a limit on the emission of pollutants, regardless of the number of vehicles in the city. On the other hand, if the value of the variable of $I(X)$ is within the legal norms, then the x_i value of the indicator should not change significantly. In this case, in accordance with expression (4), the coefficient λ_j should close to zero.

Thus, knowledge of the expert system can be useful in supporting various balances between the indicators of material-energy flows λ_k/λ_j of the urban environment. Balances can be adjusted using constraints on linear approximation coefficients of λ_i. These coefficients take into account existing environmental, social, urban planning, economic and other standards. That is, the if-then rules that determine the content of the knowledge base should have linear models as the output variable (Rotshtein, 1996):

$$IF\ x_1\ IS\ A_{11}\ AND\ x_2\ IS\ A_{12}\ AND\ ...$$

$$...\ AND\ x_n\ IS\ A_{1n}\ THEN\ I = I_{01} + \sum\nolimits_{j=1}^{n} \lambda_{1,j} \cdot x_j$$

$$\ldots \qquad \ldots \qquad \ldots$$

$$IF\ x_1\ IS\ A_{n1}\ AND\ x_2\ IS\ A_{n2}\ AND\ ...$$

$$...\ AND\ x_n\ IS\ A_{nn}\ THEN\ I = I_{0n} + \sum\nolimits_{j=1}^{n} \lambda_{n,j} \cdot x_j$$

Antecedents of production rules define different actions for each of the linear models. They are determined by a sequence of production rules.

Consider the construction of a matrix of knowledge for assessing the real possibilities of a transport subsystem of the urban environment. As an example, we define linguistic variables for evaluating the real capabilities of the transport subsystem as follows:

- linguistic variable of *"density of street-road network"*, (km/km^2): $TSLV$ is {high density; average density; not high density }; ULV is $x_1 \in [\underline{x}_1, \overline{x}_1]$; TLV is output variable $y \in [\underline{y}, \overline{y}]$;
- linguistic variable of *"amount of motor vehicles"*, (pcs): $TSLV$ is {large number; average quantity; few}; ULV is $x_2 \in [\underline{x}_2, \overline{x}_2]$; TLV is output variable $y \in [\underline{y}, \overline{y}]$;
- linguistic variable of *"the volume of energy consumption by private motor transport"*, MWh/(veh. · y) $TSLV$ is { large number; average quantity; few }; ULV is $x_3 \in [\underline{x}_3, \overline{x}_3]$; TLV is evaluation of the output variable of $y \in [\underline{y}, \overline{y}]$.

Figure 2 shows the membership functions of the linguistic variable "energy consumed by private vehicles".

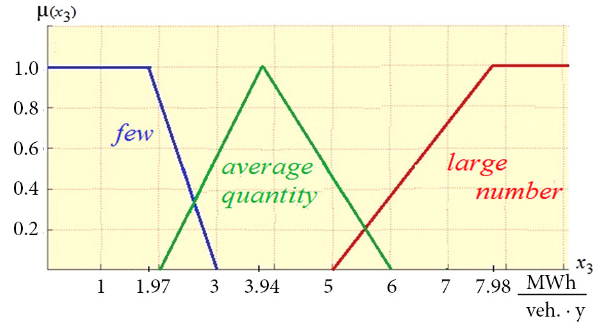

Figure 2. The membership function of the linguistic variable "the volume of energy consumed by private vehicles"

The matrix of knowledge of input indicators x_1, x_2, x_3, which are defined on the corresponding term-sets $A^j_{x_1}$, $A^j_{x_2}$, $A^j_{x_3}$, where *j={1,2,3}*, is given in the Table 2.

This knowledge matrix allows us to define ***the system of logical utterances*** like "$IF - THEN, OTHERWISE$", which connect values of input indicators to assessing the actual capabilities of the transport subsystem in the following way:

$$\begin{aligned}
& IF\ (x_1 = A^{11}_{x_1})\,AND(x_2 = A^{11}_{x_2})\,AND(x_3 = A^{11}_{x_3})\,OR \\
& \quad (x_1 = A^{12}_{x_1})\,AND(x_2 = A^{12}_{x_2})\,AND(x_3 = A^{12}_{x_3})\,OR \\
& \quad (x_1 = A^{13}_{x_1})\,AND(x_2 = A^{13}_{x_2})\,AND(x_3 = A^{13}_{x_3})\,OR \\
& THEN\ y_1 = I_{01} + \lambda_{11}x_1 + \lambda_{11}x_2 + \lambda_{11}x_3 + \lambda_{12}x_1 + \\
& \qquad \lambda_{12}x_2 + \lambda_{12}x_3 + \lambda_{13}x_1 + \lambda_{13}x_2 + \lambda_{13}x_3; \\
& OTHERWISE \\
& IF\ (x_1 = A^{21}_{x_1})\,AND(x_2 = A^{21}_{x_2})\,AND(x_3 = A^{21}_{x_3})\,OR \\
& \quad (x_1 = A^{22}_{x_1})\,AND(x_2 = A^{22}_{x_2})\,AND(x_3 = A^{22}_{x_3})\,OR \\
& \quad (x_1 = A^{23}_{x_1})\,AND(x_2 = A^{23}_{x_2})\,AND(x_3 = A^{23}_{x_3})\,OR \\
& THEN\ y_2 = I_{02} + \lambda_{21}x_1 + \lambda_{21}x_2 + \lambda_{21}x_3 + \lambda_{22}x_1 + \\
& \qquad \lambda_{22}x_2 + \lambda_{22}x_3 + \lambda_{23}x_1 + \lambda_{23}x_2 + \lambda_{23}x_3; \\
& OTHERWISE \\
& IF\ (x_1 = A^{31}_{x_1})\,AND(x_2 = A^{31}_{x_2})\,AND(x_3 = A^{31}_{x_3})\,OR \\
& \quad (x_1 = A^{32}_{x_1})\,AND(x_2 = A^{32}_{x_2})\,AND(x_3 = A^{32}_{x_3})\,OR \\
& \quad (x_1 = A^{33}_{x_1})\,AND(x_2 = A^{33}_{x_2})\,AND(x_3 = A^{33}_{x_3})\,OR \\
& THEN\ y_3 = I_{03} + \lambda_{31}x_1 + \lambda_{32}x_2 + \lambda_{33}x_3 + \lambda_{32}x_1 + \\
& \qquad \lambda_{32}x_2 + \lambda_{32}x_3 + \lambda_{33}x_1 + \lambda_{33}x_2 + \lambda_{33}x_3.
\end{aligned} \quad (5)$$

Table 2. Matrix of knowledge to term-sets $A_{x_1}^j$, $A_{x_2}^j$, $A_{x_3}^j$

Input value combination number	Input variables			Output variable
	x_1	x_2	x_3	
11	$A_{x_1}^{11}$	$A_{x_2}^{11}$	$A_{x_3}^{11}$	$y_1 = I_{01} + \lambda_{11}x_1 + \lambda_{11}x_2 + \lambda_{11}x_3 + \lambda_{12}x_1 + \lambda_{12}x_2 + \lambda_{12}x_3 + \lambda_{13}x_1 + \lambda_{13}x_2 + \lambda_{13}x_3$
12	$A_{x_1}^{12}$	$A_{x_2}^{12}$	$A_{x_3}^{12}$	
13	$A_{x_1}^{13}$	$A_{x_2}^{13}$	$A_{x_3}^{13}$	
21	$A_{x_1}^{21}$	$A_{x_2}^{21}$	$A_{x_3}^{21}$	$y_2 = I_{02} + \lambda_{21}x_1 + \lambda_{21}x_2 + \lambda_{21}x_3 + \lambda_{22}x_1 + \lambda_{22}x_2 + \lambda_{22}x_3 + \lambda_{23}x_1 + \lambda_{23}x_2 + \lambda_{23}x_3$
22	$A_{x_1}^{22}$	$A_{x_2}^{22}$	$A_{x_3}^{22}$	
23	$A_{x_1}^{23}$	$A_{x_2}^{23}$	$A_{x_3}^{23}$	
31	$A_{x_1}^{31}$	$A_{x_2}^{31}$	$A_{x_3}^{31}$	$y_3 = I_{03} + \lambda_{31}x_1 + \lambda_{31}x_2 + \lambda_{31}x_3 + \lambda_{32}x_1 + \lambda_{32}x_2 + \lambda_{32}x_3 + \lambda_{33}x_1 + \lambda_{33}x_2 + \lambda_{33}x_3$
32	$A_{x_1}^{32}$	$A_{x_2}^{32}$	$A_{x_3}^{32}$	
33	$A_{x_1}^{33}$	$A_{x_2}^{33}$	$A_{x_3}^{33}$	

We will name such system of logical utterances *a fuzzy knowledge base* (*Knowledge Matrix)* for estimating real possibilities of the transport subsystem of urban environment. This was discussed by Rotshtein (1999).

Using operations $\bigcup (AND)$ and $\bigcap (OR)$ the system of logical utterances (1) can be rewritten in a more compact form:

$$\bigcup_{p=1}^{3}\left[\bigcap_{j=1}^{9}\left(X = A_x^{jp}\right)\right] \rightarrow I = y_i,\ i = \overline{1,3}, \tag{6}$$

where $X \in \{x_1, x_2, x_3\}$.

On the basis of above, it is necessary to design a method that allows to put the vector of input variables $X = (x_1, x_2, x_3)$, $x_1 \in [\underline{x}_1, \overline{x}_1]$, $x_2 \in [\underline{x}_2, \overline{x}_2]$, $x_3 \in [\underline{x}_3, \overline{x}_3]$ in conformity the assessment $I = y_i, i = \overline{1,3}$.

The method of estimating of real possibilities (full power – *P(t)*) of the urban environment transport subsystem is based on *fuzzy logic equations*, which are obtained on *the system of logical utterances of knowledge matrix* (1).

We will consider in more details obtaining of *fuzzy logic equations*. Linguistic estimations (Table 1) A_i^{mp} of variables x_1, x_2, x_3, that are included in the logical utterances of the value of estimation $I = y_i, i = \overline{1,3}$ are considered as fuzzy sets which are defined on the universal set $U_i = [\underline{x}_i, \overline{x}_i], i = \overline{1,3}$:

We will denote:

- $\mu^{A_{x_1}^{mp}}(x_1)$ – linguistic variable membership function x_1 "*street-road network density*", where $x_1 \in [\underline{x}_1, \overline{x}_1]$, in fuzzy term $A_{x_1}^{mp}$, $m = \overline{1,3}$, $p = \overline{1,3}$, (Table 2);
- $\mu^{A_{x_2}^{mp}}(x_2)$ – linguistic variable membership function x_2 "*number of vehicles*", where $x_2 \in [\underline{x}_2, \overline{x}_2]$, in fuzzy term $A_{x_2}^{mp}$, $m = \overline{1,3}$, $p = \overline{1,3}$ (Table 2);
- $\mu^{A_{x_3}^{mp}}(x_3)$ – linguistic variable membership function x_3 "*energy consumption volumes by private vehicles*", where $x_3 \in [\underline{x}_3, \overline{x}_3]$, in fuzzy term $A_{x_3}^{mp}$, $m = \overline{1,3}$, $p = \overline{1,3}$ (Table 2);
- estimation of real possibilities of the transport subsystem of the urban environment y_i, $i = \overline{1,3}$ depends on values of linguistic variables x_1, x_2, x_3:

$$y_i = I_{0i} + \sum_{j=1}^{n} \lambda_{i,j} \times x_j.$$

The connection between the considering functions is defined by *fuzzy knowledge base* (5) and can be presented as the following equations:

$$\begin{aligned}
y_1 &= I_{01} + \lambda_{11}x_1 + \lambda_{12}x_2 + \lambda_{13}x_3 = \\
&\mu^{A_{x_1}^{11}}(x_1) \wedge \mu^{A_{x_2}^{11}}(x_2) \wedge \mu^{A_{x_3}^{11}}(x_3) \vee \\
&\mu^{A_{x_1}^{12}}(x_1) \wedge \mu^{A_{x_2}^{12}}(x_2) \wedge \mu^{A_{x_3}^{12}}(x_3) \vee \\
&\mu^{A_{x_1}^{13}}(x_1) \wedge \mu^{A_{x_2}^{13}}(x_2) \wedge \mu^{A_{x_3}^{13}}(x_3); \\
y_2 &= I_{02} + \lambda_{21}x_1 + \lambda_{22}x_2 + \lambda_{23}x_3 = \\
&\mu^{A_{x_1}^{21}}(x_1) \wedge \mu^{A_{x_2}^{21}}(x_2) \wedge \mu^{A_{x_3}^{21}}(x_3) \vee \\
&\mu^{A_{x_1}^{22}}(x_1) \wedge \mu^{A_{x_2}^{22}}(x_2) \wedge \mu^{A_{x_3}^{22}}(x_3) \vee \\
&\mu^{A_{x_1}^{23}}(x_1) \wedge \mu^{A_{x_2}^{23}}(x_2) \wedge \mu^{A_{x_3}^{23}}(x_3); \\
y_3 &= I_{03} + \lambda_{31}x_1 + \lambda_{32}x_2 + \lambda_{33}x_3 = \\
&\mu^{A_{x_1}^{31}}(x_1) \wedge \mu^{A_{x_2}^{31}}(x_2) \wedge \mu^{A_{x_3}^{31}}(x_3) \vee \\
&\mu^{A_{x_1}^{32}}(x_1) \wedge \mu^{A_{x_2}^{32}}(x_2) \wedge \mu^{A_{x_3}^{32}}(x_3) \vee \\
&\mu^{A_{x_1}^{33}}(x_1) \wedge \mu^{A_{x_2}^{33}}(x_2) \wedge \mu^{A_{x_3}^{33}}(x_3),
\end{aligned} \tag{7}$$

where $\wedge -$ logical "AND", $\vee -$ logical "OR".

Such fuzzy logic equations are derived from the fuzzy knowledge base (7) by replacing the linguistic terms A_i^{mp} with the corresponding membership functions, and operations $\bigcup$ and $\bigcap$ – with logical operations $\vee$ and $\wedge$.

The logical equations system can be written shorter as follows:

$$y_i(x_1, x_2, x_3) = \bigcup_{p=1}^{3}\left[\bigcap_{j=1}^{3} \mu^{A_X^{jp}}(X)\right],$$

where $p = \overline{1,3}$, $j = \overline{1,3}$, $X \in \{x_1, x_2, x_3\}$.

In conclusion, we consider a generalized methodology for estimating potential, real and lost opportunities of urban environment subsystems, which is based on fuzzy logic equations.

The generalized methodology for estimating potential, real and lost opportunities of the urban environment subsystems, which corresponds to a vector of fixed values of input variables $X = \{x_1, x_2, ..., x_n\}$ will be implemented as follows:

1. Define linguistic variables list that influence on the estimation of potential, actual and lost opportunities of urban environment subsystems.
2. Define vector of input values of linguistic variables: $X = (x_1, x_2, ..., x_n)$.
3. Set membership functions of fuzzy terms for each linguistic variable to be used in the fuzzy knowledge base (1) and define values of these functions for given values of linguistic variables.
4. Using logical equations (3) define multidimensional membership functions of vector $X = (x_1, x_2, ..., x_n)$ for each value of output variable y_j. In this case, operations $\wedge -$ logical "AND" and $\vee -$ logical 'OR" with membership functions are replaced by operations *min, max*:

$$\mu(a) \wedge \mu(b) = \min[\mu(a), \mu(b)],$$
$$\mu(a) \vee \mu(b) = \max[\mu(a), \mu(b)]$$

5. Define the value of output variable $I(x_1, x_2, ..., x_n)$ for the maximal membership function:

$$I(x_1, x_2, ..., x_n) = \max_{j=1,m}\left(\mu^{y_j}(x_1, x_2, ..., x_n)\right). \quad (8)$$

Expression (8) allows to estimate potential, actual and lost opportunities for each urban environment subsystems using input heterogeneous, non-additive and variable dimension indicators.

If – then rules that define the content of knowledge base are some kind of switches from one linear "input-output" law to another linear law (Figure 3).

Thus, the proposed method is based on the definition of the value of the linguistic term with respect to the maximum of the membership function, and allows us to generalize this idea to the entire matrix of knowledge. The computational part of the proposed method is easily realized on the matrix of values of membership functions derived from the matrix of knowledge by performing operations *min, max*. This was discussed by Rotshtein (1996, 1999).

The considered method can be used as the basis for implementation of algorithm for obtaining an integrated estimation of the effectiveness of urban environment metabolism using non-numeric, inaccurate, and incomplete information.

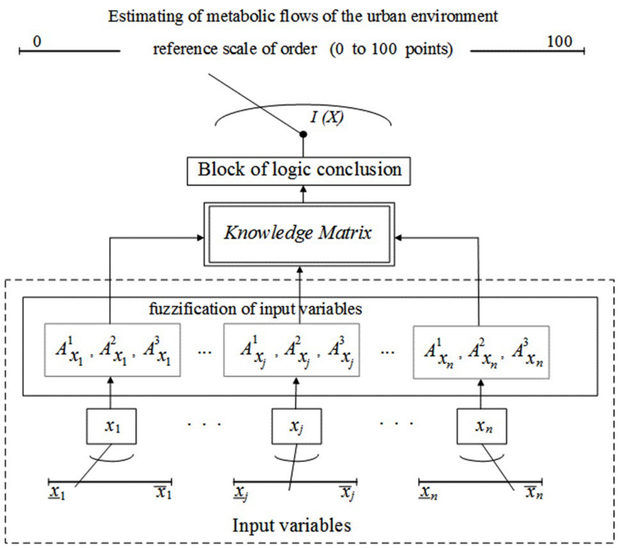

Figure 3. Scheme of communication between input primary indicators $(x_1, ..., x_j, ..., x_n)$ and output variable $I(X)$ based on the knowledge matrix

3. Software realization of expert knowledge representation for estimating of metabolic flows of urban environment

The unified modeling language (*UML*) is used at the design stage. The *UML* diagram of software classes of the knowledge database for estimating of metabolic flows of the urban environment is given in Figure 4.

There are 14 software classes in which the *KnowledgeMatrix* class is the main class. Each class consists of attributes and methods. The *KnowledgeMatrix* class provides knowledge acquisition from experts related to urban planning, building comfortable urban environment, reforming housing and communal services sector, improving environmental conditions, etc. In addition, this class provides the ability to save and download knowledge *in* or *from* the object-relational database.

The *FuzzyRule* class is used to store information about knowledge base rules. The *SugenoAlgorithm* class is used to store information about quantitative characteristics of fuzzy rules and input and output variables that are involved in fuzzy logic algorithm. *Condition* and *Conclusion* classes are used to store information about conditions of fuzzy rule execution and consequences of its execution. The *ActivatedFuzzyRule* class is used for storing information about activated fuzzy sets for each rule. The *FuzzyStatement* class is used to store fuzzy expressions, and the *Variable* class is used to store variables which are obtained as a result of fuzzy logic conclusion algorithm.

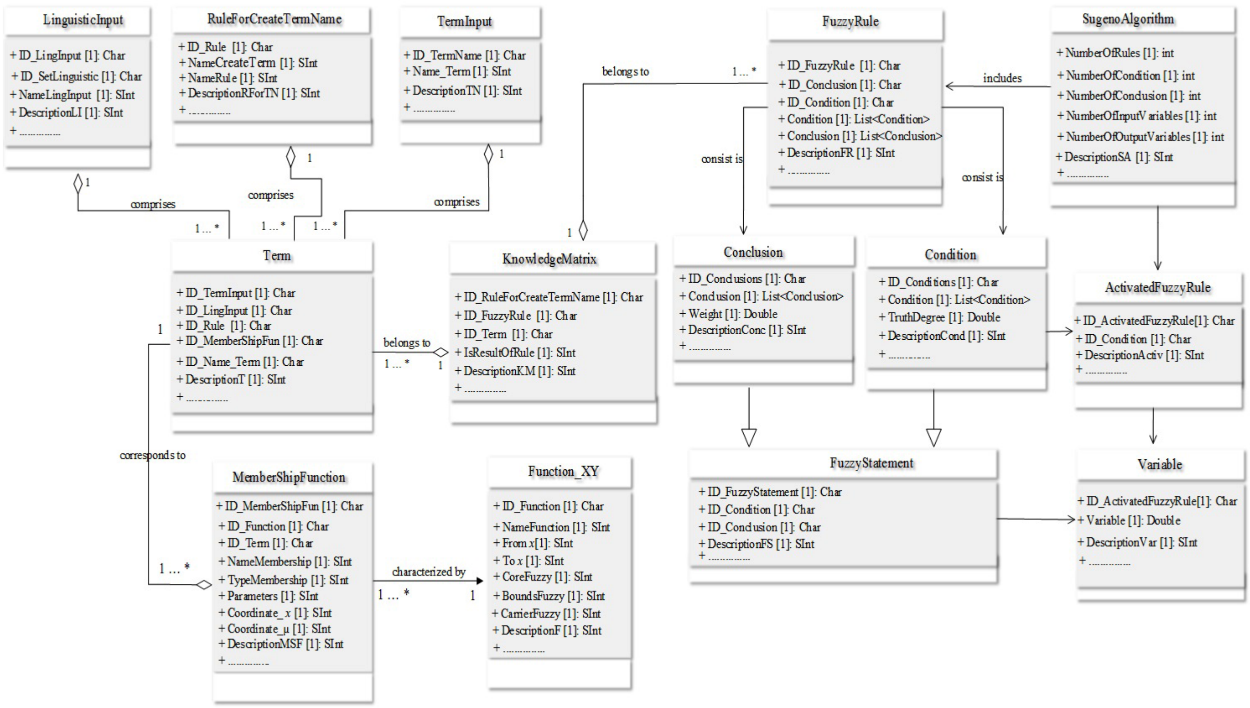

Figure 4. UML diagram of software classes of the knowledge database of metabolic flows estimating of the urban environment

The developed *UML* diagram can be used as information support for geoinformation monitoring of the urban environment metabolism. The developed knowledge base is based on fuzzy logic methods, which make it possible to simplify the quality estimating process of certain substances transformation (material, energy, information) into others. Ultimately this will simplify the process of estimating and forecasting the transformation of changes in the social and functional structure of the city and will ensure sustainable development of urban environment through noospheric control, consistent with the law of power saving.

Conclusions

In this paper the structure of intelligent information system to estimate full power (potential opportunities), useful power (real opportunities) and lost power (lost opportunities) of the urban environment using fuzzy expert knowledge in condition of non-numeric, inaccurate and incomplete information for the management of sustainable city development is developed. It is shown that the sustainable development of the urban environment can be achieved by the noospheric control consistent with the law of power saving.

The problem of noospheric control of sustainable development is especially relevant for large and small cities of Ukraine. The proposed method allows to estimate the effectiveness of metabolic transformations of each subsystem of the urban environment and integrate the obtained estimates to obtain an integrated estimation of the effectiveness of the urban environment metabolism. This method allows using the fuzzy logic equations derived from the knowledge matrix to solve difficulties associated with the problem of sharing heterogeneous, non-additive and non-comparable primary indicators of material-energy and information flows of the urban environment.

The diagram of software classes that participate in the presentation of fuzzy knowledge that can be used in the decision-making system for sustainable urban development is presented. The proposed scheme of fuzzy knowledge storage can be expanded and used to store many fuzzy knowledge bases, thereby ensuring their integration.

The method of *KnowledgeMatrix* constructing and the implementation of the fuzzy knowledge base can be used as the basis of the information support of geoinformation monitoring of metabolism in the expert system of management of the sustainable development of the urban environment.

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