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Application of algebraic operations on fuzzy numbers

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Abstract.
The main difficulty in working with fuzzy quantities is that, even in the case of the simplest relevance functions, as a result of elementary operations carried out on them, relevance functions of a complex form requiring a large number of parameters are formed. Therefore, the article analyzes the approximation of the current relevance functions and the results of operations performed on them by triangular, exponential, and trapezoidal functions of a certain class depending on a set number of parameters. In this case, there is an opportunity to build relatively simple basic operations that do not exceed the class of selected functions.

Keywords:
theory of fuzzy sets
algebraic operations
relevance function
calculation
experiment

1. Introduction. The analysis of the effect of the degree of fuzzy and appearance of the parameters on the sensitivity of the numerical alternative function in relation to several types of functions is presented in [1-3]. Attempts to create portable, universal, structured packages for performing interval analysis on the AUGMENT processor have increased the execution time of operations by 50-200 times, depending on the conditions, compared to traditional calculations on the same primitive objects [1-2]. An original extension of the standard programming language by introducing variables of the FUZZY type in order to work with fuzzy quantities is presented in [4]. The FAGOL language made it possible to perform calculations on fuzzy quantities by approximating them to the F-function using the triangular relevance function.

Also universal microprocessor; OXQ, special processors designed to carry out calculations on fuzzy sets; work is being carried out on the creation of linguistic terminal complexes consisting of DXQ-terms designed to store the initial term-values of linguistic variables [5].

But all these methods are based on the approximation of the resulting relevance functions by certain functions, which leads to loss of information and an increase in the area of fuzzy.

2. Main part. The operations of addition, multiplication, subtraction and division defined in the set of real numbers extend to the class $F(R)$ as follows. Every binary operation in R [1]

$$f\colon R * R \to R$$

consists of reflection. If two intervals $A=[a,b]$, $B=[c,d]$ are taken, then their sum

$$f\colon A * B \to R$$

determined by reflection, it is relative to $\forall x \in A, \forall y \in B$

$$f(x,y) = z = x+y$$

takes the form, where $(x,y) \in A \times B$. So, $A+B = [a+c,\ b+d]$.

The law of transition to algebraic operations on F-magnitudes is now clear.

A, $B \in F(R)$ and $\circ$ - $\{+, -, *, /\}$ be an arbitrary operation taken from the set. Taking into account the reflection relations, it is possible to write as follows:

$$\mu_{A\circ B}(z) = \sup_{U}\{\mu_A(x) \wedge \mu_B(y)\},$$
$$U = \{x, y) \in \sigma(A \times B) \big| x \circ y = z\}. \quad (1)$$

If the Cartesian product is determined by the second type, then

$$\mu_{A\circ B}(z) = \sup_{U}\{\mu_A(x) \cdot \mu_B(y)\} \quad (2)$$

we will have a relationship.

The general case for the four types of Cartesian multiplication takes the following form:

$$\mu_{A\circ B}(z) = \sup_{U} f_i\{\mu_A(x), \mu_B(y)\}, i = \overline{1,4} \quad (3)$$

where f_i *- is one of the four types of function introduced above.*

Thus, in order to create an $\mu_{A\circ B}$ *F*-function, it is necessary to solve the parametric problem of finding a conditional extremum, that is, to find the upper limit of the function to $z \in R$ $\mu_{A\circ B}$ in the set U given by the following limitation (binding equation):

$$g(x, y; z) = x \circ y - z = 0. \quad (4)$$

It should be noted that the solution of the given problem is always available, unlike the problem of finding the maximum of a function in a given set [2].

If we express one of the variables in (4) by another, for example, *y* by *x* in the form *y = u(x,z)*, then by putting the resulting expression with respect to *y* in (3) we get the problem can be reduced to the following unrestricted extremal problem with a single element *x*:

$$\mu_{A\circ B}(z) = \sup_{x} f_i\{\mu_A(x), \mu_\beta(u(x,z))\} \tag{5}$$

Another approach is to use Lagrange polynomials. In this case, problem (3) takes the following form due to (4).

$$\mu_{A\circ B}(z) = \sup_{x,y,z}\{f_i[\mu_A(x), \mu_B(y)] + \lambda g(x,y;z)\}, \lambda \in R \tag{6}$$

In the future, if no changes are made, algebraic operations will be determined according to the first type, that is, by relation (1).

Fuzzy number limits. If the following relation is fulfilled with respect to the number a

$$\forall \delta \mu_A = 0; \quad \mu(a-\delta) \neq 0, \mu(a+\delta) \neq 0,$$

then that relation is called the limit of the function. If we consider that there are two such limits: upper (b) and lower (a), the fuzzy number *A* can be written in the following form:

$$A = \int_{a}^{\bar{a}} (x-a)/x + \int_{\bar{a}}^{b} (b-x)/x \tag{11}$$

The principle of generalization presented in the previous chapters takes the following form. Let *A* and *B* be fuzzy numbers on a real straight line *R*. The * operation on *A* and *B* can be performed using the following relation

$$A * B = \int_R \min(\mu_A(x), \mu_B(y)) / (x * y) \tag{12}$$

Keeping the points mentioned in the previous chapter, instead of the hypothetical operation *, using arithmetic +, -, , : , four arithmetic operations on *A* and *B* can be formed:

$$A + B = \int_R \min(\mu_A(x), \mu_B(y)) / (x + y), \tag{13}$$

$$A - B = \int_R \min(\mu_A(x), \mu_B(y)) / (x - y), \tag{14}$$

$$A \times B = \int_R \min(\mu_A(x), \mu_B(y)) / (x \times y), \tag{15}$$

$$A : B = \int_R \min(\mu_A(x), \mu_B(y)) / (x : y). \tag{16}$$

Using (11), the following can be obtained:

$$A * B = \left(\int_a^{\bar{a}} \mu_A(x)/x + \int_{\bar{a}}^{b} \mu_A(x)/x \right) * \left(\int_{a'}^{\bar{b}} \mu_B(x)/x + \int_{\bar{b}}^{b'} \mu_B(x)/x \right) =$$

$$= \int_{a''}^{\bar{a}*\bar{b}} \mu_{A*B}(x)/x + \int_{\bar{a}*\bar{b}}^{b''} \mu_{A*B}(x)/x. \tag{17}$$

where a'', b'' *are derived from a, b, and* a', b' *are formed according to a known axis, and* $\mu_{A*B}(x)$ *is determined according to the normalization of* μ *with respect to the axis.*

Let's calculate *A+B*:

$$A+B=\left(\int_{a}^{\bar{a}}\mu_A(x)/x+\int_{\bar{a}}^{b}\mu_A(x)/x\right)+\left(\int_{a'}^{\bar{b}}\mu_B(x)/x+\int_{\bar{b}}^{b'}\mu_B(x)/x\right)=$$

$$=\int_{a''}^{\bar{c}}\mu_C(x)/x+\int_{\bar{c}}^{b''}\mu_C(x)/x=C, \qquad (18)$$

where

$$\bar{c}=\bar{a}+\bar{b}\,,\quad a''=a+a'\,,\quad b''=b+b' \qquad (19)$$

μ_C is determined by $\mu_C=k_1x+k_2$ appearance. Based on the normalization, with respect to $a''\leq x\leq\bar{c}$, (18) can be written as follows:

$$A+B=\int_{a''}^{\bar{c}}\frac{x-a''}{\bar{c}-a''}\Big/x+\int_{\bar{c}}^{b''}\frac{b''-x}{b''-\bar{c}}\Big/x=C \qquad (20)$$

For the rest of the arithmetic operations, the following can be obtained in a similar way [5]:

$$A-B=\int_{a''}^{\bar{c}}\frac{x-a''}{\bar{c}-a''}\Big/x+\int_{\bar{c}}^{b''}\frac{b''-x}{b''-\bar{c}}\Big/x=C\,, \qquad (21)$$

Where

$$a''=a-b'\,,\quad b''=b-a'\,,\quad \bar{c}=\bar{a}-\bar{b}\,. \qquad (22)$$

Accepting the relevance function in the form $\mu_c=k_1\sqrt{x}+k_2$, we get the following:

$$A*B=\int_{a''}^{\bar{c}}\frac{\sqrt{x}-\sqrt{a''}}{\sqrt{\bar{c}}-\sqrt{a''}}\Big/x+\int_{\bar{c}}^{b''}\frac{\sqrt{b''}-\sqrt{x}}{\sqrt{b''}-\sqrt{\bar{c}}}\Big/x=C \qquad (23)$$

Where

$$a'' = a * a' \text{,} \quad b'' = b * b' \text{,} \quad \bar{c} = \bar{a} * \bar{b} \tag{24}$$

Taking the membership function μ_C in the form $\mu_C = \frac{k_1}{x} + k_2$, we get the following:

$$A : B = \int_{a''}^{\bar{c}} \frac{(x - a'')\bar{c}}{(\bar{c} - a'')x} \Big/ x + \int_{\bar{c}}^{b''} \frac{(b'' - x)\bar{c}}{(b'' - \bar{c})x} \Big/ x = C \tag{25}$$

Where

$$a'' = a' : a \text{,} \quad b'' = b' : b \text{,} \quad \bar{c} = \bar{b} : \bar{a} \tag{26}$$

Below we consider another method of performing operations on fuzzy numbers based on the use of degree polynomials, the calculations in which are simplified compared to operations based on the principle of generalization [2-5]. In addition, the following definitions should be used [5]: A binary operation * in *R* is called increasing if $(x_1 > y_1, x_2 > y_2) \Rightarrow x_1 * x_2 > y_1 * y_2$. * operation is called decreasing if $(x_1 > y_1, x_2 > y_2) \Rightarrow x_1 * x_2 < y_1 * y_2$.

If fuzzy numbers *A* and *B* with membership function μ_A and μ_B are given, then the result of the generalized * operation on them is the fuzzy number $C = A * B$ given by the following membership function:

$$\mu_C(z) = \sup_{Z = X * Y} \min(\mu_A(x), \mu_B(y)) \tag{27}$$

More precisely, the four arithmetic operations can be described as follows:

Addition.

$$\mu_{A+B}(z)=\sup_{Z=X+Y}\min(\mu_A(x),\mu_B(y))=\sup_X\min(\mu_A(x),\mu_B(z-x)) \tag{28}$$

Subtraction.

$$\mu_{A-B}(z)=\sup_{Z=X-Y}\min(\mu_A(x),\mu_B(y))=\sup_X\min(\mu_A(x),\mu_B(x-z)) \tag{29}$$

Multiplication.

$$\mu_{A\times B}(z)=\sup_{Z=X\times Y}\min(\mu_A(x),\mu_B(y))=\sup_X\min(\mu_A(x),\mu_B(z:x)),\ x\neq 0 \tag{30}$$

Division.

$$\mu_{A:B}(z)=\sup_{Z=X:Y}\min(\mu_A(x),\mu_B(y))=\sup_X\min(\mu_A(x),\mu_B(x:z))= \\ =\sup_Y\min(\mu_A(yz),\mu_B(y)). \tag{31}$$

If the fuzzy numbers *A* and *B* are described as:

$$A=\{\omega_1/x_{11};\,\omega_2/x_{21};\,\omega_1/x_{12}\};\quad B=\{\omega_1/y_{11};\,\omega_2/y_{21};\,\omega_1/y_{12}\},$$

then the result of the * generalized operation on them will be the following fuzzy number:

$$C=A*B=\{\omega_1/(x_{11}*y_{11});\,\omega_2/(x_{21}*y_{21});\,\omega_1/(x_{12}*y_{12}\} \tag{32}$$

This * is appropriate when the operation is ascending or descending. Subtraction and division operations are not like this, but they can be described as follows [7]:

$$A-B=A+(-B);\quad A:B=A\times(B^{-1}). \tag{33}$$

Examples. Two fuzzy numbers are given

$$\tilde{2} = \{0/1;\ 0,5/1,5;\ 1/2;\ 0,5/2,5;\ 0/3\},$$

$$\tilde{3} = \{0/2;\ 0,5/2,5;\ 1/3;\ 0,5/3,5;\ 0/4\}.$$

Below are four general operations on them $(+,-,\times,:)$.

Addition:

$$\tilde{3}+\tilde{2} = \{0/(2+1);\ 0,5/(2,5+1,5);\ 1/(3+2);\ 0,5/(3,5+2,5);$$
$$0/(4+3)\} = \{0/3;\ 0,5/4;\ 1/5;\ 0,5/6;\ 0/7\}.$$

Multiplication:

$$\tilde{3}\times\tilde{2} = \{0/2;\ 0,5/3,75;\ 1/6;\ 0,5/8,75;\quad 0/12\}.$$

Subtraction:

$$-\tilde{2} = \{0/(-3);\ 0,5/(-2,5);\ 1/(-2);\ 0,5/(-1,5);\ 0/(-1)\};$$
$$\tilde{3}-\tilde{2} = \tilde{3}+(-\tilde{2}) = \{0/(2-3);\ 0,5/(2,5-2,5);\ 1/(3-2);\ 0,5/(3,5-1,5);$$
$$0/(4-1)\} = \{0/(-1);\ 0,5/0;\ 1/1;\ 0,5/2;\ 0/3\}.$$

Division:

$$\tilde{2}^{-1} = \{0/(1:1);\ 0,5/(1:1,5);\ 1/(1:2);\ 0,5/(1:2,5);\ 0/(1:3)\} =$$
$$= \{0/1;\ 0,5/0,66;\ 1/0,5;\ 0,5/0,4;\ 0/0,33\} = \{0/0,33;\ 0,5/0,4;\ 1/0,5;\ 0,5/0,66;\ 0/1\};$$
$$\tilde{3}:\tilde{2} = 3\times(2^{-1}) = \{0/0,66;\ 0,5/1;\ 1/1,5;\ 0,5/2,33;\ 0/4\}.$$

Additional subtraction and division operations. When solving fuzzy equations, it is necessary to calculate opposite and inverse numbers [5]. Arithmetic operations considered above, based on the principle of generalization, do not allow to find the opposite A' (which becomes $A+A'=0$) and the opposite number A" ($A\times A''=1$). Also, the following inequalities hold:

$$(A-B)+B\neq A;\quad (A:B)\times B\neq A.$$

Additional subtraction (--) and additional division (33) are used to accurately solve the following equation:

$$AX+B=D, \tag{34}$$

where A, B, D – fuzzy numbers, X- unknown,

In particular, the solution of (34) is as follows

$$X=D—B. \tag{35}$$

The carriers of the set *V* and *D* are the intervals $S_B=[b_1,b_2]$ and $S_D=[d_1,d_2]$, respectively. The carrier of the set *X* determined by additional subtraction has the following form:

$$S_X=[d_1-b_1,d_2-b_2], \tag{36}$$

and its appearance expressed using the relevance function is as follows [5]:

$$\mu_X(x)=\inf_z\begin{cases}1, & if\ \mu_D(z-x)<\mu_D(z);\\ \mu_D, & if\ \mu_B(z-x)\geq\mu_D(z).\end{cases} \tag{37}$$

The considered subtraction operation is determined only when the length of the carrier of the reducer is smaller than that of the subtractor.

Additional divison. The solution of the equation *AX=B* is the set *X=D//A*. If the carriers of sets *A* and *D* are $S_A=[a_1,a_2]$ and $S_D=[d_1,d_2]$, then the carrier of set *X* is defined as follows [5]:

$$S_X=[d_1,d_2]//[a_1,a_2]=\begin{cases}d_1:a_1,d_2:a_2, if & S_A>0;S_D>0,\\ d_1:a_2,d_2:a_1, if & S_A>0;S_D<0,\\ d_2:a_1,d_1:a_2, if & S_A<0;S_D>0,\\ d_2:a_2,d_1:a_1, if & S_A<0;S_D<0,\end{cases}$$

or its appearance expressed through the relevance function:

$$\mu_X(x) = \inf_t \begin{cases} 1, & if\ \mu_A(t/x) < \mu_D(t), \\ \mu_D(t), & if\ \mu_A(t/x) \geq \mu_D(t). \end{cases}$$

This operation is not defined for arbitrary numbers *A* and *D*, it is defined for numbers whose intermediate carriers satisfy certain conditions [5].

3. A computational experiment. We solve the following equation:

$$X+B=D, \qquad (38)$$

where B=$\tilde{8}$ *={0/6; 0,5/7; 1/8; 0,5/9; 0/10),*

D=$1\tilde{4}$ *={0/10; 0,5/12; 1/14; 0,5/16; 0/18}.*

Intermediate carriers for *B* and *D* $S_B = [6,10]; \quad S_D = [10,18]$. According to (36) $S_X = [4,8]$. According to the formula (37), the relevance function 16 $\mu_X(x)$ can be determined as follows.

$$X = (0/4; 0,5/5; 1,0/6; 0,5/7; 0/8) .$$

A=$\tilde{8}$ ={0/6; 0,5/7; 1/8; 0,5/9; 0/10} and *D*=$2\tilde{4}$ ={0/6; 0,5/14; 1,0/24; 0,5/36; 0/50} we solve the following equation:

$$AX=D. \qquad (39)$$

The relevance functions μ_A and μ_D are depicted in Fig. 1.

Intermediate carriers of sets *A* and *D* $S_A = [6,10]; \quad S_D = [6,50]$. According to (36) $S_X = [6:6,50:10] = [1,5]$.

According to (37), the value of the relevance function $\mu_X(x)$ presented in Fig. 1 can be determined.

The solution of the equation:

$$X=\{0/1;\ 0,5/2;\ 1/3;\ 0,5/4;\ 0/5\}.$$

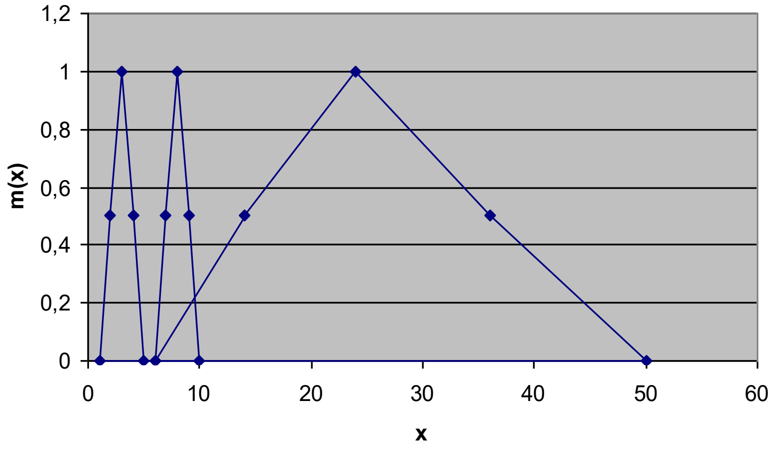

Figure 1
Membership functions of sets for additive division

4. Conclusion. Taking into account uncertainties of various nature and adequate mathematical formulation increases depending on the difficulty level of the problem being solved. In practice, the possibility of reducing the level of uncertainty by deepening the definition of the process of operation of complex systems is quite limited. The fact is that according to L. Zade's principle of incomparability, the more detailed the model, the more uncertain factors are added to it, which directly leads to an increase in uncertainty in the results. As a result, at a certain stage of model complexity, despite the high accuracy based on the detailing of the definition, the model becomes almost meaningless. In general, L. Zade's principle of uncertainty limits the possibilities of mathematical modeling methods, which previously seemed limitless.

The concept of fuzzy sets is an attempt to mathematically describe fuzzy information in order to build mathematical models. This concept is based on the idea that elements with the same characteristic that make up a given set can have this characteristic to different degrees, which means that they can belong to a given set to different degrees. Based on such an approach, statements like "some element belongs to a given set" cease to have meaning, because it is necessary to show to what extent or "how strongly" a specific element satisfies a given set.

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