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ЛИНГВИСТИЧЕСКОЕ ОПИСАНИЕ МНОГОЭТАПНЫХ НЕСТАЦИОНАРНЫХ ПРОЦЕССОВ

THE LINGUISTIC DESCRIPTION OF MULTI-STAGE NON-STATIONARY PROCESSES

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Аннотация. *Рассмотрена проблема формализации лингвистического описания социально-экономических и организационно-технологических процессов на основе построения периодизации, дающей возможность разбить их на этапы для более детального изучения.*

Материалы и методы, результаты и обсуждения. *Методологической основой исследования является понятийный аппарат теории лингвистической переменной Л. Заде в сочетании с экспертными технологиями оценивания.*

С учетом специфики описания нестационарных социально-экономических и организационно-технологических процессов разработана лингвистическая переменная, значения которой (темпоральные термы) соответствуют этапам процесса. Предложен новый тип темпоральных термов, семантически описываемых битрапециевидными функциями принадлежности, и указана экспертная процедура построения этих термов. Предложена и обоснована (утверждениями о свойствах) система алгебраических операций над темпоральными термами, позволяющая формулировать синтаксические и семантические правила преобразования термов. Для описания зависимости характеристик многоэтапных процессов от времени предложено использовать пары лингвистических переменных, первая из которых соответствует исследуемой характеристике, а вторая – этапу процесса.

Заключение. *Предложенное формальное лингвистическое описание многоэтапных процессов позволяет проводить анализ и прогнозирование функционирования социально-экономических и организационно-технологических систем с использованием инструментальных средств интеллектуальной поддержки научных исследований (в частности применяя процедуры нечеткого логического вывода на основе нечеткой продукционной модели знаний о предметной области), что может способствовать повышению научной обоснованности управленческих решений.*

Ключевые слова: многоэтапный процесс, лингвистическая переменная, темпоральный терм.

Abstact. *The problem of formalizing the linguistic description of socio-economic and organizational-technological processes based on the construction of periodization, which makes it possible to break them into stages for a more detailed study, is considered.*

Materials and methods, results and discussions. *The methodological basis of the study is the conceptual apparatus of the theory of the linguistic variable L. Zadeh in combination with expert assessment technologies.*

Taking into account the specifics of the description of unsteady socio-economic and organizational-technological processes, a linguistic variable has been developed, the values of which (temporal terms) correspond to the stages of the process. A new type of temporal terms that are semantically described by bitrapezoid membership functions is proposed, and an expert procedure for constructing these terms is indicated. A system of algebraic operations on temporal terms is proposed and justified (by assertions about properties), which makes it possible to formulate syntactic and semantic rules for the transformation of terms. To describe the dependence of the characteristics of multi-stage processes on time, it is proposed to use pairs of linguistic variables, the first of which corresponds to the studied characteristic, and the second to the stage of the process.

Conclusion*. The proposed formal linguistic description of multi-stage processes allows us to analyze and predict the functioning of socio-economic and organizational-technological systems using tools for the intellectual support of scientific research (in particular, using fuzzy inference procedures based on a fuzzy production model of knowledge about the subject area), which can contribute to increase the scientific validity of management decisions.*

Key words: multi-stage process, linguistic variable, temporal term.

Introduction. One of the general methodological approaches in the analysis of complex non-stationary processes of a very different nature is the division of the time interval of consideration (the lifetime of the process) into sub-intervals (stages, periods), each of which is determined by its own set of indicators, its own limitations and its own evaluation criteria [1]. At the same time, the process conditions characteristic of the considered temporal (temporal) subinterval can be inherent at specific points in time to varying degrees, which causes the application of the formal apparatus of fuzzy logic ([2]) to the temporal description of processes. The aim of this work is to formalize the linguistic description of non-stationary processes based on fuzzy temporal modeling of stages.

Materials and methods, results and discussions. The methodological basis of the research is the conceptual apparatus of the theory of linguistic variable L. Zadeh ([3]) in combination with expert assessment technologies (for example, [4]). To formalize operations on temporal terms, the apparatus of context-free grammars was used ([5]).

Temporal description of multistage processes

By the lifetime of the process TL we mean its projection onto the time continuum. If the lifetime of the process is limited, then it is a length of time

$$TL = [t_{start}, t_{stop}],$$

where t_{start} corresponds to the start of the process, and t_{stop} the moment it ends. In this case, it is convenient to consider the lifetime as a pair $<\tau, \delta>$, where $\tau = t_{start}$, and $\delta = t_{stop} - t_{start}$ - the duration of the lifetime.

The lifetime of a process (as a set of stages and the relationship between them) can be formalized using a linguistic variable

$$< Stage\ , T, TT_{Base}, GT\ , MT >,$$

where *Stage* the name of the linguistic variable "Stage of the life of the process"; *T* - time continuum; TT_{base} – is the base vector of temporal terms; *GT* - is a syntactic rule allowing to generate the names of temporal terms from the names of elements TT_{Base}; *MT* - a semantic rule establishing a correspondence between temporal terms and fuzzy subsets of *T*.

We will assume that the semantics of the temporal term tt (corresponding to the stage of the process) is determined by a fuzzy interval having a bit-trapezoidal membership function (Fig. 1). The proposed type of semantics of temporal terms makes it possible to describe the stages of the process more accurately (in comparison with terms, the semantics of which is determined by the usual trapezoidal membership function), taking into account the transition processes between the stages.

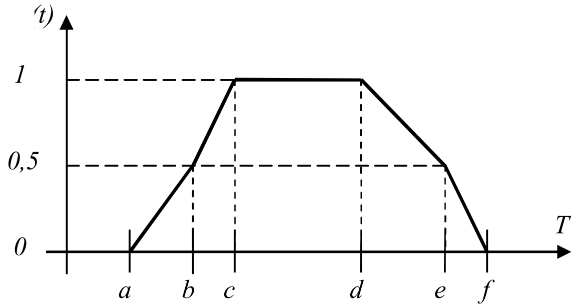

Fig. 1. Bi-trapezoidal membership function of a temporal term

Formally, the bi-trapezoidal membership function is a 6-parameter piecewise linear function $\mu_{a,b,c,d,e,f} : T \to [0,1]$, where T - is a continuum; $a,b,c,d,e,f \in T$ - are parameters ($a < b < c < d < e < f$) определяется формулой:

$$\mu_{a,b,c,d,e,f}(t) = \begin{cases} 0, \ if\ t < a \\ \dfrac{0,5}{b-a} \cdot t + \dfrac{-0,5 \cdot a}{b-a}, \ if\ a \le t < b \\ \dfrac{0,5}{c-b} \cdot t + \dfrac{0,5 \cdot c - b}{c-b}, \ if\ b \le t < c \\ 1, \ if\ c \le t < d \\ \dfrac{-0,5}{e-d} \cdot t + \dfrac{e - 0,5 \cdot d}{e-d}, \ if\ d \le t < e \\ \dfrac{-0,5}{f-e} \cdot t + \dfrac{0,5 \cdot f}{f-e}, \ if\ e \le t < f \\ 0, \ if\ f \le t \end{cases}$$

It is important to note that the parameters $a,b,c,d,e,f \in T$ have a natural interpretation and can be obtained as a result of a survey of experts:

- the parameters *a, f* correspond to the moments in time - the boundaries of the temporal region, which in no way can be attributed to the considered stage of the process (the segment *[a, f]* is the carrier of a fuzzy interval);

- the parameters c, d correspond to the moments of time - the boundaries of the temporal region, which can be fully attributed to the stage of the process under consideration (the segment *[c, d]* is the core of the fuzzy interval);

parameters *b* and *e* correspond to points in time - the boundaries between the considered and adjacent (previous and next) stages (transition points of the membership function).

At the same time, the issues of organizing team examinations and analysis to assess the stability of the results to possible changes in expert judgments (for example, [6]) require additional research.

For further formalization, it is convenient to use the characteristics of the duration of the temporal term tt (process stage):

- optimistic duration: $\delta_{opt} = d - c$;
- standard duration: $\delta_{norm} = e - b$;
- pesimistic duration: $\delta_{pes} = f - a$.

The durations of transient processes correspond to the lengths of the segments [*a*, *b*], [*b*, *c*], [*d*, *e*] and [*e*, *f*], which we denote as δ_{e_pre}, δ_{i_pre}, δ_{i_post}, δ_{e_post}. These values will be called the durations of the external pre-stage, internal pre-stage, internal post-stage, and external post-stage, respectively. Fig. 2 illustrates the concepts introduced

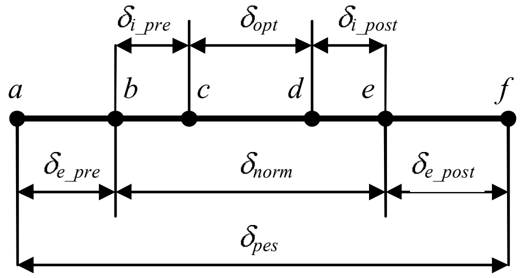

Fig. 2. The relationship of durations and parameters of the bi-trapezoidal membership function of the temporal term *tt*

Thus, the membership function for a temporal term tt_N can be redefined in terms of durations as a 6-component vector

$$\mu_N = <\tau^{(N)}, \delta^{(N)}_{e\_pre}, \delta^{(N)}_{i\_pre}, \delta^{(N)}_{norm}, \delta^{(N)}_{i\_post}, \delta^{(N)}_{e\_post}>$$

Here N - the name of the temporal term, τ the initial moment of time coinciding with the parameter a. The base vector of temporal terms is a finite linearly ordered set $\{tt_b,\ldots,tt_i,\ldots,tt_e\}$, in which tt_b - an initial stage, tt_i - some intermediate stage, and tt_e - a final stage. The membership functions of these temporal terms must satisfy the requirements clearly shown in Fig. 3.

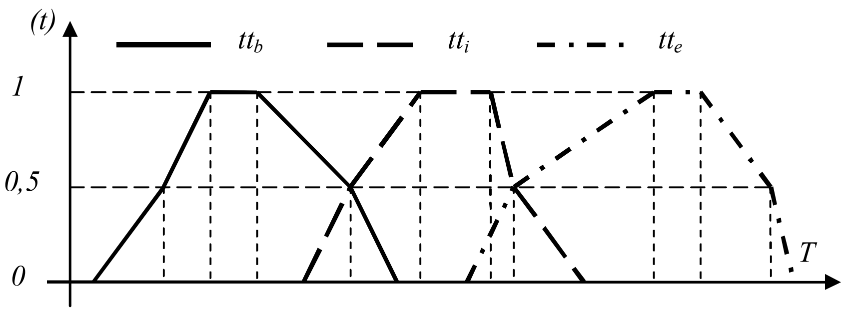

Fig. 3. Membership functions of elements of the base vector of temporal terms TT_{Base}

The syntactic rule *GT* and the semantic rule *MT,* which make it possible to pass from the basic vector of temporal terms TT_{BASE} to the set of all terms *TT,* will be built on the basis of the introduced operations on temporal terms *O1 ÷ O10.*

The entered operations have a general syntax:

1. The alphabet (set of terminal metacharacters) includes the following subsets:

– N_{Base} - names of elements of the base vector of temporal terms;

– R_+ - a set of rational numbers greater than 0, written in the 10th number system;

– Z_+ - a set of integers greater than 0, written in the 10th number system;

$-\ \{*, e\_pre*, i\_pre*, e\_post*, i\_post*, >>, +, /, :, .1, .2, (,)\}$ - a set of special characters.

2. The grammar of the syntactic rule, presented in the Backus-Naur form:

$prop := n:m.1 \mid n:m.2$, where $n, m \in Z_+$;

$term := N$, where $N \in N_{Base}$;

$$term := (term)*\alpha \mid (trem)e\_pre*\alpha \mid (term)i\_pre*\alpha \mid (term)e\_post*\alpha \mid (term)i\_post*\alpha \mid$$
$$(term)>>\alpha \mid (term+term) \mid (term)/prop$$

where $\alpha \in R_+$.

Semantically introduced operations are determined by setting / changing the values of the parameters of the bit-trapezoidal membership function of the temporal term: *O1*.

The operation of initiating a basic temporal term:

$$\mu_N = <\tau^{(N)}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>$$

where the values $\tau^{(N)}$, $\delta_{e\_pre}^{(N)}$, $\delta_{i\_pre}^{(N)}$, $\delta_{norm}^{(N)}$, $\delta_{i\_post}^{(N)}$, $\delta_{e\_post}^{(N)}$ for the base temporal term and name N are set in a dialogue with the expert.

O2. Time shift operation of a temporal term:

$$\mu_{(N)>>\alpha} = <\tau^{(N)}+\alpha, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>$$

O3. The operation of multiplying (increasing / decreasing the standard duration) of a temporal term:

$$\mu_{(N)*\alpha} = <\tau^{(N)}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}\cdot\alpha, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>,$$

when $\alpha \ge \dfrac{\delta_{i\_pre}^{(N)}+\delta_{i\_post}^{(N)}}{\delta_{norm}^{(N)}}$.

O4. Operation of changing the duration of the external pre-stage of a temporal term:

$$\mu_{(N)e\_pre*\alpha} = <\tau^{(N)}+\delta_{e\_pre}^{(N)}\cdot(1-\alpha), \delta_{e\_pre}^{(N)}\cdot\alpha, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>$$

O5. Operation of changing the duration of the internal pre-stage of a temporal term:

$$\mu_{(N)i\_pre*\alpha} = <\tau^{(N)}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}\cdot\alpha, \delta_{norm}^{(N)}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>,$$

when $\alpha \le \dfrac{\delta_{norm}^{(N)}-\delta_{i\_post}^{(N)}}{\delta_{i\_pre}^{(N)}}$

O6. Operation of changing the duration of the internal post-stage of a temporal term:

$$\mu_{(N)i\_post*\alpha} = <\tau^{(N)}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}, \delta_{i\_post}^{(N)}\cdot\alpha, \delta_{e\_post}^{(N)}>$$

when $\alpha \le \dfrac{\delta_{norm}^{(N)}-\delta_{i\_pre}^{(N)}}{\delta_{i\_post}^{(N)}}$

O7. Operation of changing the duration of the external post-stage of a temporal term:

$$\mu_{(N)e\_post*\alpha} = <\tau^{(N)}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}\cdot\alpha>$$

O8. The operation of allocating the initial substage of a temporal term in the proportion $n:m$:

$$\mu_{(N)/n:m.1} = <\tau^{(N)}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}\cdot\frac{n}{n+m}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>,$$

when $\dfrac{n}{n+m} \ge \dfrac{\delta_{i\_pre}^{(N)}+\delta_{i\_post}^{(N)}}{\delta_{norm}^{(N)}}$

O9. The operation of allocating the final sub-stage of a temporal term in the proportion $n:m$:

$$\mu_{(N)/n:m.2} = <\tau^{(N)}+\frac{\delta_{norm}^{(N)}\cdot n}{n+m}, \delta_{e\_pre}^{(N)}, \delta_{i\_pre}^{(N)}, \delta_{norm}^{(N)}\cdot\frac{m}{n+m}, \delta_{i\_post}^{(N)}, \delta_{e\_post}^{(N)}>,$$

when $\dfrac{m}{n+m} \ge \dfrac{\delta_{i\_pre}^{(N)}+\delta_{i\_post}^{(N)}}{\delta_{norm}^{(N)}}$

O10. The operation of combining temporal terms:

$$\mu_{(N1+N2)} = <\tau^{(N)}, \delta_{e\_pre}^{(N1)}, \delta_{i\_pre}^{(N1)}, \delta_{norm}^{(N1)}+\delta_{norm}^{(N2)}, \delta_{i\_post}^{(N2)}, \delta_{e\_post}^{(N2)}>$$

when $\tau^{(N1)}+\delta_{e\_pre}^{(N1)}+\delta_{norm}^{(N1)} = \tau^{(N2)}+\delta_{e\_pre}^{(N2)}$

For the operations introduced, the following statements are true:

Statement 1. Any temporal term $tt \in TT$ can be generated using the unary operations $O2 \div O7$ from an arbitrary basic temporal term $tt^* \in TT_{BASE}$, initiated by the operation $O1$. Exclusion of any operation from the $O2 \div O7$ list will result in the loss of this property.

Statement 2. The order of performing unary operations $O2 \div O7$ irrelevant.

Statement 3. Application of the operation of combining temporal terms $O10$ to the terms obtained by applying the operations $O8$ (selection of the initial substage) and $O9$ (selection of the final substage) to the same term $tt \in TT$ with the same parameters of the operations will lead to the same term.

Obvious statements presented without proof can serve as a justification for the type of operations introduced.

Linguistic description of the temporal dependence of the characteristics of multistage processes.

Consider a set of characteristics of the considered non-stationary process:

$$CHR = < Chr_1, Chr_2, \dots , Chr_s>,$$

taking (after reduction to dimensionless form) values in the segment [0, 1].

We will assume that the characteristics under consideration are functions of time, determined over the entire interval of the process lifetime TL:

$$Chr_i = Chr_i\ (t),\ t \in TL,\ i=1,2,\dots,s.$$

and for the values of $Chr_i(t)$ fuzzification can be carried out with the traditional trapezoidal type of membership functions of the terms "low", "medium", "high" corresponding to the linguistic description of the levels of values of these characteristics at times t. Thus, to characterize Chr_i a linguistic variable is constructed

$$< Characteristic_i, C, TC_{Base}, GC\ , MC >,$$

Where $Characteristic_i$ - the name of the linguistic variable "characteristic"; C = [0, 1] – universal set; TC_{base} = {"low", "medium", "high"} base set of terms common for all characteristics of Chri Chr_i ($i=1,2,\dots, s$); GC - GC is a syntactic rule that allows generating the names of the Chr_i haracteristic terms from the names of TC_{base} ; MC - is a semantic rule establishing a correspondence between terms and fuzzy subsets.

The proposed temporal fuzzification allows us to describe the functional dependence of the characteristics of the process Chr_i ($i=1,2,\dots, s$) on time in the form of a pair of linguistic variables:

$$< Characteristic_i, Stage >$$

For linguistic variable $Characteristic_i$ syntactic and semantic rules are defined in the usual way (eg [3]) (GC и MC) extending the base term-set TC_{base} to the set of all terms of this variable. In this case, strengthening / weakening of the terms "low", "medium", "high" to represent the value $Characteristic_i$ does not change the second element of the pair $< Characteristic_i, Stage >$.

However, the use of logical connectives $\wedge$ ("and") and $\vee$ ("or") as rules requires (to ensure adequacy) a change in the value of the linguistic variable included in the pair *Stage*.

The type of such change is determined by the specifics of the subject area. For example, one option is to use the T-norm / S-conorm: min / max. In this case:

$$< (Characteristic - tc_1, \alpha_1), (Stage - tt, \beta_1) > \wedge$$
$$\wedge < (Characteristic - tc_2, \alpha_2), (Stage - tt, \beta_2)> =$$
$$= < ((Characteristic - tc_1 \wedge tc_2), \min(\alpha_1, \alpha_2))\ , (Stage - tt_1, \min(\beta_1, \beta_2)>$$

where tc_1, $tc_2 \in TC_{base}$, α_1, α_2 – the degree of correspondence of the values of the characteristic Chr to the terms tc_1, tc_2, tt – is the temporal term (the stage of the process at which the characteristic Chr was estimated), β_1, β_2 – are the degrees of correspondence of the moments of time at which the characteristic Chr was measured to the term tt (the stage of the process under consideration). Depending on the subject area, it is possible to use other T-norms / S-conorms (intersection / union of Gamacher, product / sum of Einstein and Werner functions, etc.). In this case, it is possible to use different T-norms / S-conorms for different elements of the linguistic pair

Conclusion. Thus, in the work, taking into account the specifics of the description of non-stationary socio-economic and organizational-technological processes, a linguistic variable has been developed, the values of which (temporal terms) correspond to the stages of the process. A new type of temporal terms is proposed, semantically described by bit-trapezoidal membership functions, and an expert procedure for constructing these terms is indicated. A system of algebraic operations on temporal terms, which allows formulating syntactic and semantic rules for transforming terms, is proposed and substantiated (with statements about properties). To describe the multistage processes under consideration, it is proposed to use pairs of linguistic variables, the first of which corresponds to the studied characteristic, and the second to the stage of the process. Further development of the developed toolkit can be associated with its use in solving problems of analysis of interrelated non-stationary processes ([7]) using expert technologies ([7]).

The proposed formal linguistic description of multi-stage processes makes it possible to analyze and predict the functioning of socio-economic and organizational-technological systems using tools for intellectual support of scientific research (in particular, using fuzzy inference procedures based on a fuzzy production model of knowledge about the subject area), which can contribute to increasing the scientific validity of management decisions.

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