DOI: 10.31471/2311-1399-2021-1(15)-8-17

Models, methods and means of ontology development of cyclic signal processing

[1]S.A. Lupenko, [1]Ia.V. Lytvynenko*, [2]A.M. Zozulya, [1]Nnamene K. Chizoba, [2]O.V. Volyanyk

[1]*Ternopil Ivan Puluj National Technical University;*
56, Ruska Str., Ternopil, 46000, Ukraine

[2]*Institute of Telecommunications and Global Information Space of the National Academy of Sciences of Ukraine;*
25, Chokolivskiy bulv., ap. 13, Kyiv, 03186, Ukraine

Received: 20.06.2021 Accepted: 27.06.2021

Abstract

The paper presents the construction of conceptual and formal models of ontology in the subject area "Modeling and processing of cyclic signals based on the theory of cyclic functional relations". There is implemented the ontology of mathematical modelling of cyclic signals, namely, the ontology of cyclic functional relations in the OWL DL language in Protégé.

The proposed ontology has allowed to present the theory of cyclic functional relations in machine-interpretive form, which allows to serve as a basis for the development of onto-oriented information systems for modeling, generation, processing (analysis, forecasting, decision making) of cyclic signals.

Keywords: *cyclic signals, modeling, ontology, processing methods.*

Cyclicity takes an important place in the processes and phenomena of reality. In particular, the processes of energy consumption (electricity, oil and gas consumption), relief formation on the surface of materials, the development of the economy of enterprises and industries, homeostasis of biological systems, etc. are of a cyclical nature [1–9].

Today the problem of energy resources efficient use is urgent. In particular, this concerns the consumption of natural gas by the population. In addition to ensuring economical consumption, it is important to efficiently supply and distribute natural gas by gas supply companies. This, in turn, requires the use of new or modernization of old hardware and software systems (information systems) through the use of effective software in decision-making systems. The use of new software is possible provided that new approaches are used to build mathematical models. Therefore, an important stage in the development and simulation of cyclic signals is the creation of information systems based on the corresponding mathematical models of these signals. Such models should adequately reflect the aspects of their spatio-temporal structure that are important from the point of view of research tasks. The quality (adequacy, constructiveness) of mathematical models of cyclic signals significantly determines the accuracy and reliability of methods for their processing and imitation in the information system, predetermines the level of information content and representativeness of diagnostic (authentication, prognostic) features, which are characteristics (parameters) of the mathematical model, affects the reliability of the adopted solutions and, to a certain extent, determines the structure of the software and hardware components of the projected information system.

Many scientific works [1–22] are devoted to the development of mathematical models, methods of computer modeling and processing of signals of a cyclic structure, as well as the creation on their basis of appropriate information systems for analysis, forecasting, classification, clustering, regression, forecasting, imitation (generation) of cyclic signals. There are many mathematical models of cyclic signals developed within the framework of both deterministic and stochastic approaches to their description. Among the deterministic models, the most famous are harmonic and quasi-harmonic functions, periodic and almost periodic polyharmonic functions that describe the temporal structure of cyclic signals, as well as models in the form of a number of linear and nonlinear differential equations or their difference analogs that describe the mechanisms of formation (generation) of such signals. Among the stochastic mathematical models of cyclic signals, periodically correlated and periodically distributed random processes, periodic white noises (processes with independent periodic values), linear periodic random processes and fields, periodic Markov

* Corresponding author: iaroslav.lytvynenko@gmail.com

random processes, almost periodic, and in particular, polyperiodic random processes have already become classical.

The theory of modeling and processing of cyclic signals received significant development and systematization within the framework of the theory of cyclic functional relations, which substantially generalized the known mathematical models of signals and processes of cyclic structure [1–9]. The theory of cyclic functional relations contains all the necessary prerequisites for creating a unified methodology for the development of new, substantiation, structural and parametric identification of mathematical and computer models, methods of transformation, analysis and forecasting of cyclic signals in modern intellectualized information systems within the framework of deterministic, stochastic, fuzzy and interval approaches.

On the basis of this approach, there have been built new mathematical models, processing methods (statistical estimation, spectral analysis, discretization) and computer simulation methods of cyclic signals of biological, economic and technical origin. On the basis of these mathematical models and methods for processing cyclic signals, a number of software systems have been created for analyzing and predicting cyclic signals (processes) in the field of medical cardiology, econometrics and non-destructive testing of materials [3–9].

Such a wide variety of mathematical models, methods of processing and computer simulation of cyclic signals, as well as software that automate these methods, on the one hand, provides significant opportunities for the development of effective information systems for diagnostics, forecasting and assessment of systems state based on cyclic signals generated by them, and on the other hand, it significantly complicates the choice of mathematical support (models, methods and algorithms) and software for the developer of such systems, which underlie the functioning of such a class of information systems. This situation is further complicated by the fact that often there is no direct specialist in the field of mathematical modeling and processing of cyclic signals in the team of developers, and also by the fact that software development often needs to be done from scratch.

Considering the above, it is relevant to develop an intellectualized (in particular, onto-oriented) information environment for inductive and deductive modeling (mathematical and computer) and processing (analysis, forecasting, recognition, diagnostics, authentication) of cyclic signals (phenomena, processes) in conditions of interval, stochastic and fuzzy uncertainty with guaranteed accuracy and reliability, minimum complexity (structural and computational) and interpretation.

Ontology allows us to formalize knowledge and automate inference (proof) procedures, which are contained in the theory of modeling and processing of cyclic signals.

Representation of the theory of cyclic functional relations in machine-interpreted form using the ontological approach as the basis for the development of onto-oriented information systems for modeling, generation, processing (analysis, forecasting, decision-making) of cyclic signals is an important and urgent task.

The ontological approach is well coordinated with the axiomatic-deductive strategy of organizing modeling and processing of cyclic signals, which significantly increases the level of its structuring, rigor and formalization, facilitates the identification of new directions and regions for the development of the theory of cyclic functional relations (new models, methods, means, full disclosure-actualization potential of this theory).

Generalized requirements for ontology

It is advisable to start the development of the ontology of the subject area "Modeling and processing of cyclic signals based on the theory of cyclic functional relations" with the formulation (specification) of the requirements for it, which allows us to explicitly prescribe necessary properties (characteristics) that determine the quality of the corresponding ontology, and to set clear guidelines at all stages of its creation. Primary requirements:

the structure of the ontology must be consistent with the axiomatic-deductive strategy of organizing the theory of cyclic functional relations as a theory of models of cyclic signals;

ontology should serve as the basis for an integrated information ontoorientated environment for modeling, processing and computer simulation (generation) of cyclic signals. That is, the structure of ontology should determine the architectures of each information system that are part of this information environment: the architecture of the information reference system is determined by the structure and content components of the ontology, the Expert Decision Support System in the field of modeling and processing of cyclic signals as the core of its knowledge base uses the ontology, as well as the structure of the information system for modeling and processing of cyclic signals is determined by this ontology (it has the onto-oriented architecture);

ontology should contain the following four general objects:

1) a glossary (models, methods, algorithms, programs and results of application in applied research);

2) a system of five interrelated taxonomies (mathematical models; tasks; methods (computer simulation of cyclic signals, processing of cyclic signals (analysis, forecasting, transformations, classification, clustering, regression, discretization, etc.)); programs and application results;

3) slots that contain vectors of attributes for each class of cyclic functional relations (these attributes should characterize the corresponding class of cyclic functional relations in terms of features and the possibilities of its use as a model of cyclic signals, taking into account the capabilities of the corresponding methods);

4) a set of expert descriptions of each class of cyclic functional relations from the point of view of the

characteristic conditions of applicability of this class as a model of cyclic signals.

The presence of a set of expert descriptions of each class of cyclic functional relations in the ontology from the point of view of characteristic conditions of applicability of this class as a model of cyclic signals allows the expert decision support system, in addition to recommending a certain class of cyclic functional relations as a model of the signals under study, to provide the user with a justification for this recommendation. Such descriptions are formed on the basis of a survey of several highly qualified experts in the field of mathematical modeling and methods of cyclic signals processing.

Ontology-driven conceptual modeling

The semantic space $\boldsymbol{S}$ of modeling, processing and computer simulation of cyclic signals within the framework of the theory of cyclic functional relations will be an ordered and consistent with logical and semantic priority set of five meaningful subspaces, namely: 1) the meaningful subspace $\boldsymbol{S_1}$ of mathematical models of cyclic signals (meaningful space of cyclic functional relations); 2) meaningful subspace $\boldsymbol{S_2}$ of typical tasks of processing and computer modeling (generation, imitation, simulation) of cyclic signals corresponding to specific classes of cyclic functional relations as their mathematical models; 3) meaningful subspace $\boldsymbol{S_3}$ of methods (algorithms) of processing (transformation, analysis (assessment of cyclicity and rhythm attributes), clustering, classification, forecasting, regression) and computer modeling (generation, imitation, simulation) of cyclic signals corresponding to specific classes of cyclic functional relationships as their mathematical models; 4) substantial subspace $\boldsymbol{S}_4$ of (software, software and hardware, hardware) means of processing and computer simulation (generation) of cyclic signals; meaningful subspace $\boldsymbol{S}_5$ of corresponding mathematical and software application results (software and hardware, hardware) for solving specific scientific and applied problems in the field of medicine, technology and economics.

According to the axiomatic-deductive strategy of organizing the theory of cyclic functional relations, the logical and semantic core of the meaningful (semantic) space $\boldsymbol{S}$ of this theory should contain two of its fundamental components – the terminological and conceptual apparatus and the system of statements, which in turn are divided into two large groups: an axiomatic group of knowledge (concepts, statements) and an output group of knowledge (concepts, statements). In addition to these components, depending on the level of universality (abstractness) of structural units (concepts and statements) of the theory content space, in the logical and semantic core of modeling, processing and computer simulation of cyclic signals within the framework of the theory of cyclic functional relations, there are distinguished a metadisciplinary logical and semantic core, the abstract logical and semantic core and a set of partial logical and semantic areas of the content space of the theory.

Formal ontology models

Given to the allocation in the subject area "Modeling and processing of cyclic signals based on the theory of cyclic functional relations" of its five subareas (content subspaces), it is fair to develop five subontologies of this subject area. In particular, the $\boldsymbol{O}$ ontology of the subject area, which specifies (submits in machine-interpreted form) the semantic space $\boldsymbol{S}$ of this subject area, will contain its five subontologies, namely:

1) the $\boldsymbol{O}_1$ ontology of mathematical modeling (mathematical structures) of cyclic signals, which, in fact, is an ontology of cyclic functional relations classes;

2) the $\boldsymbol{O}_2$ ontology (specifies the meaningful subspace $\boldsymbol{S}_2$) of typical tasks of processing and computer modeling (generation, imitation, simulation) of cyclic signals corresponding to specific classes of cyclic functional relations as their mathematical models;

3) the $\boldsymbol{O}_3$ ontology (specifies the content subspace $\boldsymbol{S}_3$) of methods (algorithms) of processing (transformation, analysis (assessment of cyclicity and rhythm attributes), clustering, classification, forecasting, regression) and computer modeling (generation, imitation, simulation) of cyclic signals that correspond to specific classes of cyclic functional relations as their mathematical models;

4) the $\boldsymbol{O}_4$ ontology (specifies the content subspace $\boldsymbol{S}_4$) of processing and computer modeling (generation) means (software, firmware, hardware) of cyclic signals;

5) the $\boldsymbol{O}_5$ ontology (specifies the content subspace $\boldsymbol{S}_5$) of results for applying the appropriate mathematical support and software (software and hardware, hardware) to solve specific scientific and applied problems in the field of medicine, technology and economics (Figure 1).

The ontology of mathematical modeling of cyclic signals has the highest priority (1); the ontology of typical tasks for processing and computer simulation of cyclic signals – the second most important priority (2); the ontology of methods for processing and computer simulation of cyclic signals – the third most important priority (3); the ontology of (software, hardware-software, hardware) means for development and computer simulation of cyclic signals – the fourth priority by value (4); the ontology of results for applying models, methods and means of processing and computer simulation of cyclic signals is the fifth priority by value (5). Taking into account the priority of ontology components makes it possible to structure models, typical tasks, methods and tools, as well as the results of their application in practice. The ordering type of ontologies is determined by the ordering type of the symbol indices that denote them. That is, the $\boldsymbol{O}_1$ ontology of models has the highest (1) priority, and the $\boldsymbol{O}_5$ ontology has the lowest (5) priority of application results.

Each of these five interrelated ontologies can be formally represented as such triplets

$$\mathrm{O_i} = \{\mathbf{A}_\mathrm{i},\ \mathbf{R}_\mathrm{i},\ \mathbf{F}_\mathrm{i}\},\ \mathrm{i} = \overline{1,5}, \qquad (1)$$

where $\mathbf{A}_\mathrm{i}$ is a finite set of concepts (terms) that define the lexical stock of the $\mathrm{O_i}$ ontology; $\mathbf{R}_\mathrm{i}$ is a finite set of

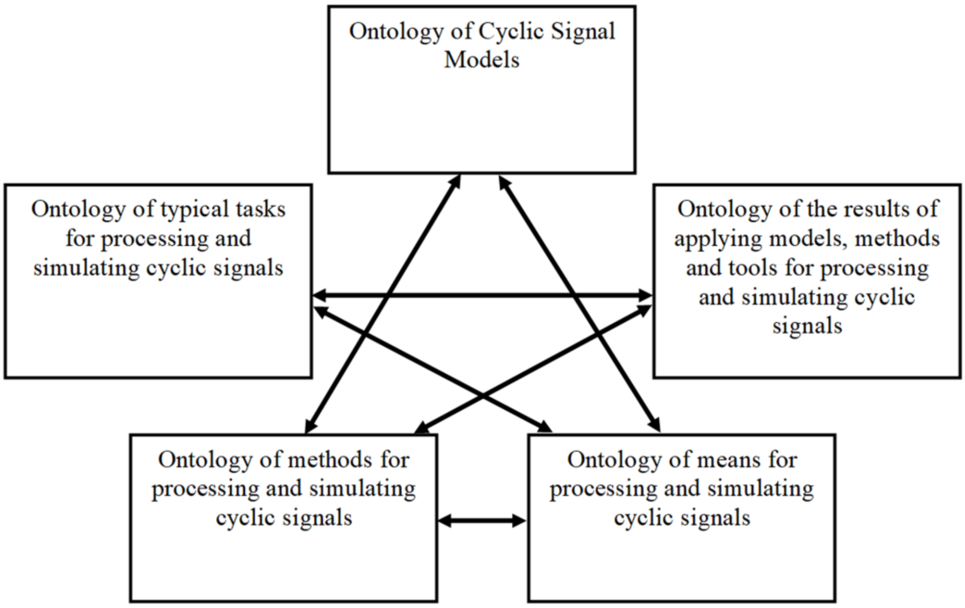

Figure 1 – Conditional representation of structural components of the O ontology of the subject area "Modeling and processing of cyclic signals based on the theory of cyclic functional relations"

relations between concepts, which reflect the relationship between concepts and the properties of concepts (attributes and restrictions on them) within the $\mathrm{O_i}$ ontology; $\mathbf{F}_\mathrm{i}$ is a finite set of interpretation functions defined on concepts and/or relations of the $\mathrm{O_i}$ ontology.

Each set of $\mathbf{R}_\mathrm{i}$ must include relations of genus-specific subordination (denoted by the abbreviation **AKO** – "A Kind Of" or the term "SubsetOf"), which connects a set (class) and a subset (subclass), specifying taxonomies between these classes (concepts), that is, it allows us to organize the hierarchical structure of the $\mathrm{O}_{\boldsymbol{i}}$ ontology concepts in the form of a tree (a hierarchy of concepts).

In addition to the taxonomic relation, the $\mathrm{O}_\mathbf{i}$ ontologies also use the membership relation (denoted by the abbreviation **IS-A** or the terms "MemberOf", "InstanceOf"), which associates an element of the corresponding set with this set (concept) itself.

Each $\mathbf{F}_\mathrm{i}$ set is a singleton set, the only element of which is the $f_\mathrm{i}(x_1, x_2, \ldots, x_n)$ interpretation function with $\boldsymbol{A}_{1i}$ $(x_1, x_2, \ldots, x_n \in \boldsymbol{A}_{1i})$ domain and $\boldsymbol{A}_{2i}(y_1, y_2, \ldots, y_n \in \boldsymbol{A}_{2i})$, range, that is, $\mathbf{F}_\mathrm{i} = \{f_\mathrm{i}(\cdot)\}$

For the $\mathrm{O}_\mathbf{i}$ ontology, the following statement holds:

$$\forall x_i \in \boldsymbol{A}_{1i},\ \exists (y_{1i}, y_{2i}, \ldots, y_{ni} \in \boldsymbol{A}_{2i}),\quad x_i = f_\mathrm{i}(y_{1i}, y_{2i}, \ldots, y_{ni}). \tag{2}$$

That is, the set of $\mathbf{A}_\mathrm{i}$ concepts of the subject area is divided into two subsets: $\boldsymbol{A}_{1i}$ (the set of terms that are interpreted and denoted) and $\boldsymbol{A}_{2i}$ (the set of interpretation terms), ($\mathbf{A}_\mathrm{i} = \boldsymbol{A}_{1i} \cup \boldsymbol{A}_{2i},\ \boldsymbol{A}_{1i} \cap \boldsymbol{A}_{2i} = \emptyset$). Note that the absence of common elements in $\boldsymbol{A}_{1i}$ and $\boldsymbol{A}_{2i}$ sets, which is given by the $\boldsymbol{A}_{1i} \cap \boldsymbol{A}_{2i} = \emptyset$) expression, excludes cyclical interpretations of the terms.

The interconnected concepts from $\boldsymbol{A}_{1i}$ and $\boldsymbol{A}_{2i}$ sets through the interpretation function $f_\mathrm{i}(x_1, x_2, \ldots, x_n)$ formalize the entry in the glossary, which is the definition of the corresponding term (concept).

Ontologies of cyclic functional relationships

Let us consider in more detail the formal model of only the first $\mathrm{O}_\mathbf{1}$ ontology.

The first $\mathrm{O}_\mathbf{1}$ ontology – the ontology of cyclic signals models (an ontology of cyclic functional relations) – is set at the formal level by a relational system as follows:

$$\begin{gathered}\mathrm{O}_1 = \{\mathbf{A}_1 = \boldsymbol{B}_1 \cup \boldsymbol{C}_1,\\ \mathbf{R}_1 = \{\mathbf{AKO}, \mathbf{IS-A}, \overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \ldots, \mathrm{p_n})\},\\ \mathbf{F}_1 = \{f_1(\cdot)\}\}\end{gathered} \tag{3}$$

where $\mathbf{A}_1$ is a finite set of terms (concepts), which specifies the lexical stock of the $\mathrm{O}_\mathbf{1}$ ontology; $\boldsymbol{B}_1$ is a finite set (of names) of cyclic functional relations classes; $\boldsymbol{C}_1$ is a finite set of 4-element vectors, each element of which is a term, entering into their values from the corresponding sets $\boldsymbol{X}_{\boldsymbol{\Psi}}$, $\boldsymbol{X}_{\boldsymbol{A}}$, $\boldsymbol{X}_{T(t,n)}$, $\boldsymbol{X}_{\boldsymbol{W}}$ and is the domain of the $P(x_1, x_2, x_3, x_4)$ predicate.

The set $\mathbf{X}_{\boldsymbol{\Psi}}$ is the set of predetermined classes (types) of linear spaces $\boldsymbol{\Psi}$, in which the corresponding cyclic functional relations acquire their values; the set $\boldsymbol{X}_{\boldsymbol{A}}$ is a set of predetermined classes (types) of possible attributes p: $\boldsymbol{\Psi} \to \boldsymbol{A}$ or sets of attributes $\{p_k\colon \boldsymbol{\Psi}^{n_k} \to \boldsymbol{A}_k,\ k = \overline{1,K}\}$, in which the cyclical structure of a functional relationship is postulated (displayed); the set $\mathbf{X}_{T(t,n)}$ is a set of predetermined classes (types) of functions of the rhythm $T(t,n)$ of the cyclic functional relationship, and the set $\boldsymbol{X}_{\boldsymbol{W}}$ is a set of predetermined types of domains $\mathbf{W}$ for determining the cyclic functional relationship. The identically true 4-digit predicate $P(x_1, x_2, x_3, x_4)$ is a statement function that is defined on the $\boldsymbol{X}_{\boldsymbol{\Psi}}$, $\boldsymbol{X}_{\boldsymbol{A}}$, $\boldsymbol{X}_{T(t,n)}$, $\boldsymbol{X}_{\boldsymbol{W}}$ $(x_1 \in \boldsymbol{X}_{\boldsymbol{\Psi}}, x_2 \in \boldsymbol{X}_{\boldsymbol{A}}, x_3 \in \boldsymbol{X}_{T(t,n)}, x_4 \in \boldsymbol{X}_{\boldsymbol{W}})$ sets, and it takes its values from the $\boldsymbol{Def}_{cf}$ set of all possible definitions of specific subclasses of cyclic functional relations.

$\mathbf{F}_1$ is a one-element set, which contains an interpretation function $f_1(x_1, x_2, x_3, x_4)$, the domain of which is the set $\boldsymbol{C}_1$, and the range of values is the set $\boldsymbol{B}_1$. The interpretation function $f_1(x_1, x_2, x_3, x_4)$ is identical to the 4-digit predicate $P(x_1, x_2, x_3, x_4)$ and, in fact, it defines the definition of the corresponding classes of cyclic functional relations with $\boldsymbol{B}_1$ for specific $x_1 \in \boldsymbol{X_\Psi}$,$x_2 \in \boldsymbol{X_A}$,$x_3 \in \boldsymbol{X}_{T(t,n)}$,$x_4 \in \boldsymbol{X_W}$ sets, forming a glossary of the O_1 ontology – the $\boldsymbol{Set\_of\_Def}_{cf}$ set of all definitions of cyclic functional relations. $\mathbf{R}_1$ is a finite set of $\{\mathbf{AKO}, \mathbf{IS-A}, \overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})\}$ relations, namely:

1) the relation of generic-species **AKO** subordination, which connects a set (class) and a subset (subclass) of cyclic functional relations, specifying the $\boldsymbol{Tax\_of\_Cf}$ taxonomy (hierarchy) between these classes in the form of a taxonomic tree;

2) the **IS-A** relation, which associates a specific cyclic functional relation (a specific model of cyclic signals) with their corresponding class (a class of mathematical models of cyclic signals);

3) $\overline{\boldsymbol{P}}$ is a $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ vector of $(\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ unary relations, which define the properties (signs, attributes) of the corresponding class of cyclic functional relations. The domain of p_i unary relation is the set of $\mathbf{A}_1$, models, and the domain of values is $\boldsymbol{P}_\mathrm{i}$ set of corresponding property values.

The first, the most priority property in the vector of properties of cyclic functional relations classes concerns the type of ambiguity of the cyclic signal values. In particular, this p_1 property can take values from $\{d, s, f, i\}$ set, and the i_1 number can take values from one to four. One $i_1 = 1, \mathrm{p}_1 = d)$ encodes a deterministic approach to describing the values of cyclic signals, two $(i_1 = 2, \mathrm{p}_1 = s)$ encodes a stochastic approach to describing the values of cyclic signals, three $(i_1 = 3, \mathrm{p}_1 = f)$ encodes a fuzzy approach to describing the values of cyclic signals, and four $(i_1 = 4, \mathrm{p}_1 = i)$ encodes an interval approach to describing the values of cyclic signals.

The second p_2 priority property (encoded by the i_2 variable) indicates such a property of the class of cyclic functional relations as the type of the cyclic signal value. In particular, this p_2 property can take values from $\{real, complex, vector_{real}, vector_{complex}, matrix_{real}, matrix_{complex}, tensor_{real}, tensor_{complex}\}$ set, and i_2 number can take values from 1 to 12. One $(i_2 = 1, \mathrm{p}_2 = real)$ encodes cyclic signals, the values of which are real numbers; two $(i_2 = 2, \mathrm{p}_1 = complex)$ encodes cyclic signals, the values of which are complex numbers; triplet $(i_2 = 3, \mathrm{p}_2 = vector\_real)$ encodes cyclic signals, the values of which are vectors of real numbers; four $(i_2 = 4, \mathrm{p}_2 = vector\_complex)$ encodes cyclic signals, the values of which are vectors of complex numbers; five $(i_2 = 5, \mathrm{p}_2 = matrix\_real,)$ encodes cyclic signals, the values of which are matrices of real numbers; six $(i_2 = 6, \mathrm{p}_2 = matrix\_complex)$ encodes cyclic signals, the values of which are matrices of complex numbers; seven $(i_2 = 7, \mathrm{p}_2 = tensor)$ encodes cyclic signals, the values of which are tensor.

The third p_3 priority property (encoded by the i_3 variable) indicates the type of the cyclic attribute of this class of cyclic functional relations. Since, as shown above, the type of the cyclic attribute depends significantly on the type of the value of the cyclic function. That is, for different ranges of values of cyclic functional relations, there may be different attributes of their cyclicity. As a rule, $i_3 = 1$, when the function's cyclicity attribute is its value. For other cyclical attributes, i_3 obtains a value of 2 or more.

The fourth p_4 priority property (encoded by the i_4 variable) indicates the type of ambiguity in the description of the elements of the cyclic function domain. As in the case of p_1 property, p_4 property can take values from the $\{d, s, f, i\}$ set, and i_4 can take values from one to four. One $(i_4 = 1, \mathrm{p}_4 = d)$ encodes a deterministic approach to describing the elements of the cyclic signal definition domain; two $(i_4 = 2, \mathrm{p}_4 = s)$ encodes a stochastic approach to describing elements of the domain of cyclic signals; three $(i_4 = 3, \mathrm{p}_4 = f)$ encodes the fuzzy approach to describing the elements of the domain of cyclic signals, and four $(i_4 = 4, \mathrm{p}_4 = i)$ encodes the interval approach to the description of the elements of cyclic signals domain.

The fifth priority property p_5 (encoded by i_5 variable) indicates the dimension of the domain of the cyclic function, namely, whether the cyclic function is a function of one or many (several) arguments (a cyclic field).

The sixth priority property p_6 (encoded by the i_6 variable) indicates the type of power (continuous or discrete) of the cyclic function domain, namely, whether the cyclic function is a function of real arguments or a function of discrete arguments.

The seventh priority property p_7 (encoded by the i_7 variable) indicates the type of rhythm (constant or variable) of the cyclic function, namely, whether the cyclic function is a cyclic function with a variable rhythm or with a constant rhythm (periodic function).

The eighth priority property p_8 (encoded by the i_8 variable) specifies the type of alternating rhythm of a cyclic function, namely, a cyclic function with a piecewise linear type of rhythm or with a piecewise quadratic type of rhythm or a piecewise cubic type of rhythm or with a periodic type of rhythm and etc. That is, this property specifies the type of rhythm change of the cyclic function.

In general, the number of properties n (that is, the dimension of the vector $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$), characterizing the class of cyclic functional relations can be various for different classes. However, it is necessary to adhere to the rule according to which all properties of the superclass of cyclic functional relations, which are components of its vector of properties, are included in the vectors of properties of all its subclasses.

Given the fact that both to describe the values and elements of the definitional domain (and, accordingly, the rhythm functions) of cyclic functions, there are applied four possible approaches to taking into account uncertainty, namely, deterministic, stochastic, fuzzy and interval; in general, 16 approaches can be distinguished

Table 1 – Approaches to the mathematical description of the cyclic signals uncertainty

Approach	The name of the approach to describing the uncertainty of the values of cyclic signals	The name of the approach to describing the uncertainty of the elements of the definitional domain and the rhythm of cyclic signals	The name of the generalized approach to describing the uncertainty of cyclic signals
1	Deterministic ($p_1 = d, i_1 = 1$)	Deterministic ($p_4 = d, i_4 = 1$)	Deterministic
2	Deterministic ($p_1 = d, i_1 = 1$)	Stochastic ($p_4 = s, i_4 = 2$)	Deterministic and stochastic
3	Deterministic ($p_1 = d, i_1 = 1$)	Fuzzy ($p_4 = f, i_4 = 3$)	Deterministic and fuzzy
4	Deterministic ($p_1 = d, i_1 = 1$)	Interval ($p_4 = i, i_4 = 4$)	Deterministic and interval
5	Stochastic ($p_1 = s, i_1 = 2$)	Deterministic ($p_4 = d, i_4 = 1$)	Stochastic and deterministic
6	Stochastic ($p_1 = s, i_1 = 2$)	Stochastic ($p_4 = s, i_4 = 2$)	Stochastic
7	Stochastic ($p_1 = s, i_1 = 2$)	Fuzzy ($p_4 = f, i_4 = 3$)	Stochastic and fuzzy
8	Stochastic ($p_1 = s, i_1 = 2$)	Interval ($p_4 = i, i_4 = 4$)	Stochastic and interval
9	Fuzzy ($p_1 = f, i_1 = 3$)	Deterministic ($p_4 = d, i_4 = 1$)	Fuzzy and deterministic
10	Fuzzy ($p_1 = f, i_1 = 3$)	Stochastic ($p_4 = s, i_4 = 2$)	Fuzzy and stochastic
11	Fuzzy ($p_1 = f, i_1 = 3$)	Fuzzy ($p_4 = f, i_4 = 3$)	Fuzzy
12	Fuzzy ($p_1 = f, i_1 = 3$)	Interval ($p_4 = i, i_4 = 4$)	Fuzzy and interval
13	Interval ($p_1 = i, i_1 = 4$)	Deterministic ($p_4 = d, i_4 = 1$)	Interval and deterministic
14	Interval ($p_1 = i, i_1 = 4$)	Stochastic ($p_4 = s, i_4 = 2$)	Interval and stochastic
15	Interval ($p_1 = i, i_1 = 4$)	Fuzzy ($p_4 = f, i_4 = 3$)	Interval and fuzzy
16	Interval ($p_1 = i, i_1 = 4$)	Interval ($p_4 = i, i_4 = 4$)	Interval

to the mathematical description of the uncertainty of cyclic functional relations. A summary of these 16 approaches is presented in Table 1.

There is a close logical and semantic relationship between the ontology of $\boldsymbol{O}_1$ models, ontology of $\boldsymbol{O}_2$ tasks, $\boldsymbol{O}_3$ ontology of methods, $\boldsymbol{O}_4$ ontology of means and $\boldsymbol{O}_5$ ontology of application results, graphically displayed in Figure 2. In particular, at the formal level, this relationship is set by the relationship between concepts from different ontologies $\boldsymbol{O}_1$, $\boldsymbol{O}_2$, $\boldsymbol{O}_3$, $\boldsymbol{O}_4$ and $\boldsymbol{O}_5$ as well as the ordering of ontologies by priority.

Justification of the choice of language and software

The conceptual model and logical-structural (formal) models of the subject area "Modeling and processing of cyclic signals based on the theory of cyclic functional relations" developed above require a reasonable choice of machine-implemented languages and development environments for their representation in modern onto-oriented information systems. Considering the results of a comparative analysis of ontology development tools [24, 25], it is fair to use the OWL ontology description language and the Protégé environment.

OWL (Web Ontology Language) is a standard in the World Wide Web Consotrium and is currently the most widely used ontology description language in the world. There are three sublanguages of the OWL language. The most acceptable language for solving ontology development problems is OWL DL, which makes it possible, on the one hand, to achieve the maximum expressiveness of the descriptive logic

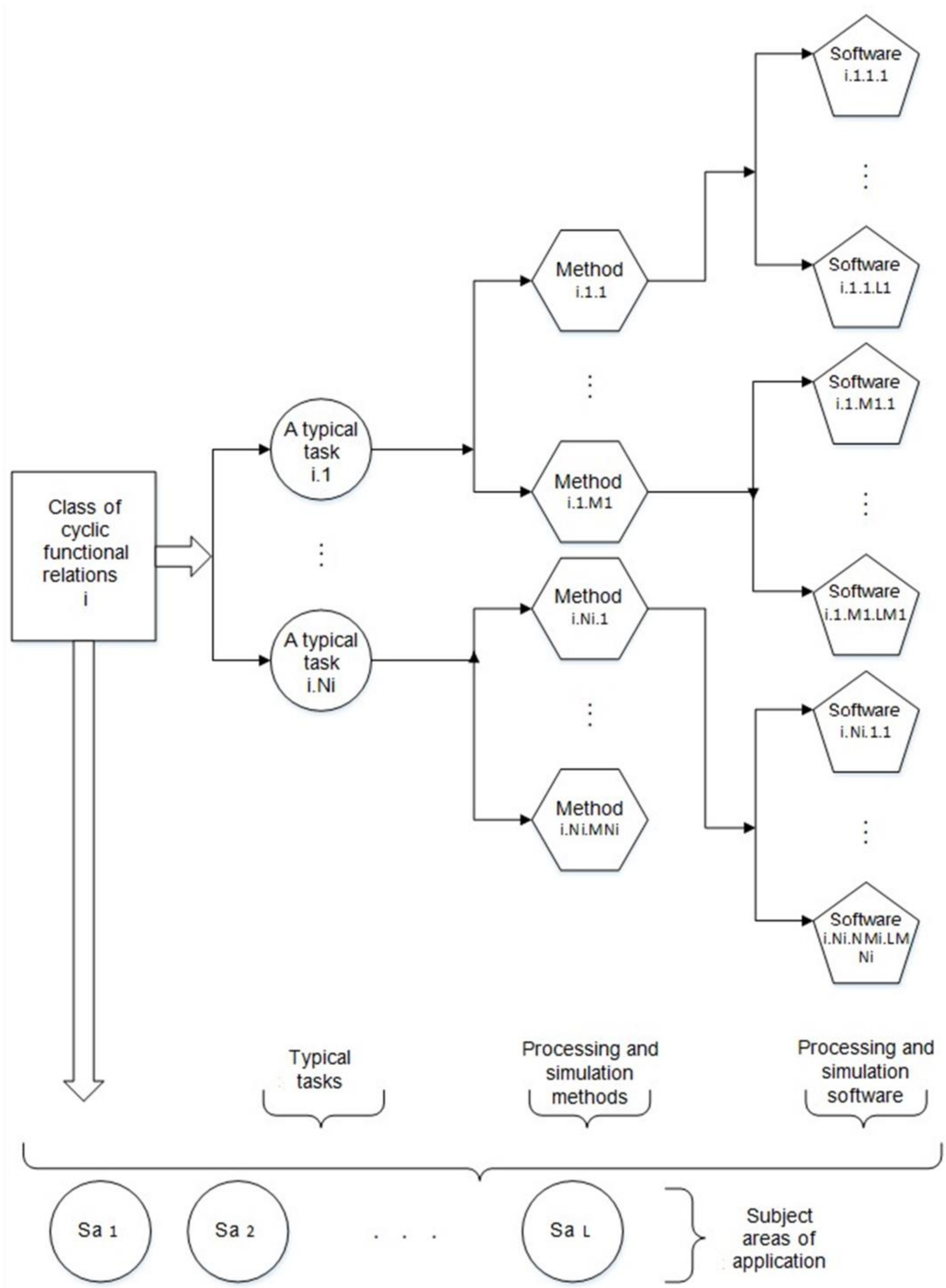

Figure 2 – The scheme of interconnection of models, methods (algorithms), software (software and hardware) and the results of their application to solve problems of modeling, processing and simulation in specific subject areas in the fields of medicine, technology and economics

underlying it, and on the other hand, to ensure the solvability of the inference system using it.

The OWL DL language is provided with standardized language constructs for the adequate expression of terms and concepts of the theory of cyclic functional relations, their taxonomies and other relationships, logical operations on model classes, methods and tools for modeling and processing cyclic signals.

Given the syntax of the OWL language, which is inconvenient for human perception, when developing the ontology, it is necessary to use the graphical tools of specialized software systems for developing ontologies. These software tools include a graphical editor and a Reasoner, which enables both the automation of logical inference based on knowledge in the ontology and automatic validation of the developed ontology. As the most popular ontology editor that supports OWL DL, Protégé should be used. This graphics editor is a freeware Java program that contains a large number of plugins. In general, Protégé allows us to design, view, edit, integrate, replenish and adapt ontologies for various data formats (text, XML, RDf (s), OWL, etc.).

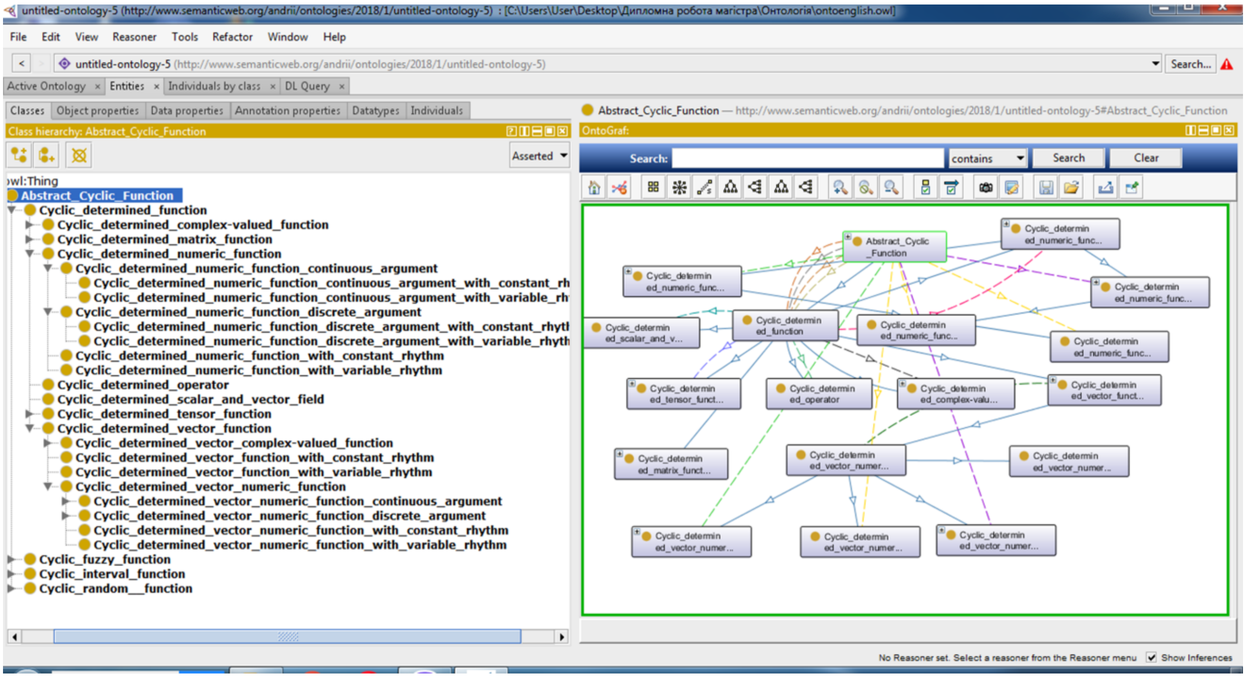

Figure 3 – Screenshot of a fragment of mathematical modeling ontology of cyclic signals in Protégé based environment (subontology of deterministic models of cyclic signals)

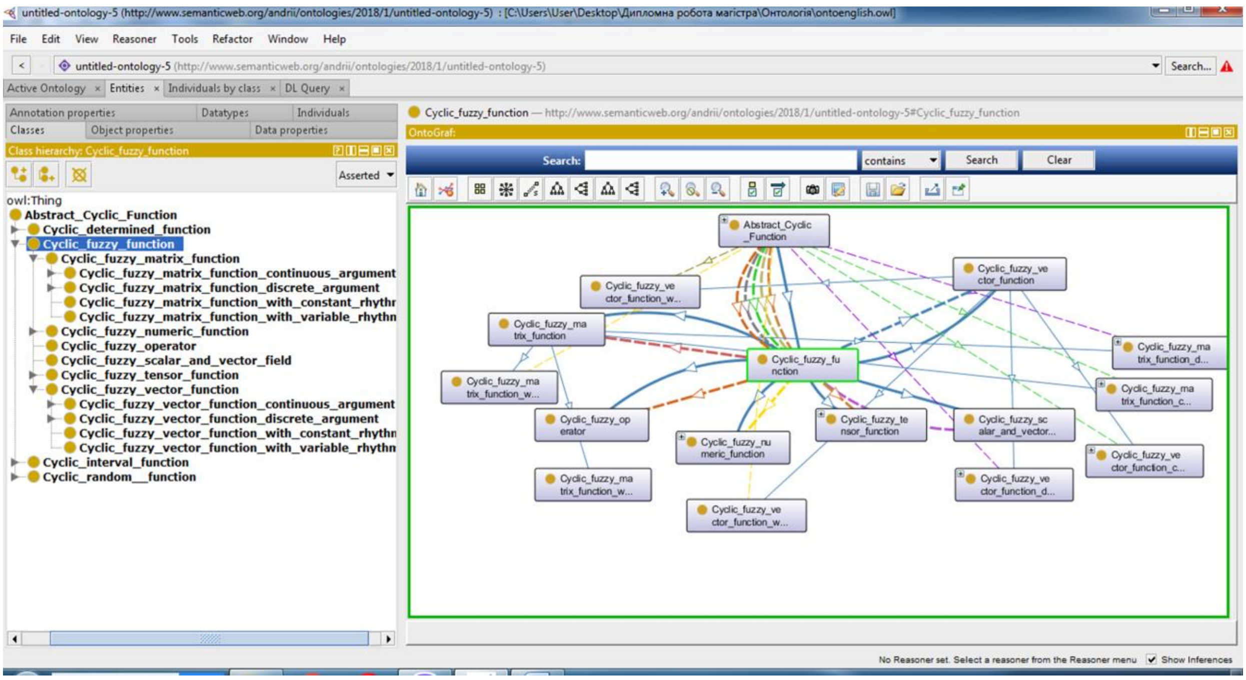

Figure 4 – Screenshot of a fragment of mathematical modeling ontology of cyclic signals in Protégé based environment (subontology of fuzzy models of cyclic signals)

As an example of the developed ontology, Figures 3 and 4 show screenshots of fragments of mathematical modeling ontology of cyclic signals in Protégé based environment.

Conclusions

There is substantiated the urgency of creating the ontology of the subject area "Modeling and processing of cyclic signals based on the theory of cyclic functional relations". Conceptual and formal models of this ontology have been developed. A reasonable choice of the OWL DL ontology description language and Protégé ontology development environment has been made. There has been implemented the ontology of mathematical models of cyclic signals, namely, the ontology of cyclic functional relations in the OWL DL language in Protégé environment.

The developed ontology makes it possible to present the theory of cyclic functional relations in machine-interpreted form and to be the basis for the development of onto-oriented information systems for modeling, generating, processing (analysis, forecasting, decision-making) of cyclic signals. In addition, the ontological approach is well consistent with the axiomatic-deductive strategy of organizing the theory of modeling and processing of cyclic signals; this significantly increases the level of its structurization, rigor and formalization, facilitates the identification of new directions and areas of development of the cyclic functional relations theory.

Based on the results obtained in the work, in the future it is appropriate to develop an expert onto-oriented system for supporting model decision-making in the field of cyclic signals modeling and processing (processes, phenomena), an information reference system and an information system with an onto-oriented architecture for cyclic signals modeling and processing.

References

[1] Lytvynenko, IV, Lupenko, SA Dem'yanchuk, NR & Horkunenko, AB 2011, 'Simulation modeling of interconnected economic processes on the basis of a vector of cyclically rhythmically connected random processes', *Electronics and control systems*, vol. 28, no. 2, pp. 133–141 [in Ukrainian].

[2] Gorkunenko, AB & Lupenko, SA 2012, 'Substantiation of diagnostic and prognostic features in information systems of analysis and forecasting of cyclical economic processes', *Scientific Bulletin of NLTU of Ukraine: collection of scientific and technical works*, no. 22.9, pp. 347−352 [in Ukrainian].

[3] Onyskiv, P, Lupenko, S, Lytvynenko, I & Zozulia, A 2020, 'Mathematical modeling and processing of high resolution rhythmocardio signal based on a vector of stationary and stationary related random sequences. IDDM'2020', *3rd International Conference on Informatics & Data-Driven Medicine*, November 19–21, Växjö, Sweden. CEUR Workshop Proceedings, 2753, pp. 149–155. http://ceur-ws.org/Vol-2753/short8.pdf

[4] Lupenko, S, Lytvynenko, I & Stadnyk, N 2020, 'Method for reducing the computational complexity of processing discrete cyclic random processes in digital data analysis systems', *Scientific Journal of Ternopil National Technical University*, vol. 97, no. 1, pp. 110–121. https://doi.org/10.33108/visnyk_tntu

[5] Lupenko, S, Lytvynenko, I, Stadnyk, N & Zozulia, A 2020, 'Mathematical model of rhythmocardiosignal in vector view of stationary and stationary-related case sequences', *Advanced Information Systems*, vol. 4, no. 2, pp. 42–46. doi:10.20998/2522-9052.2020.2.08

[6] Hutsaylyuk, V, Lytvynenko, I, Maruschak, P & Schnell, G 2020, 'A new method for modeling the cyclic structure of the surface microrelief of titanium alloy ti6al4v after processing with femtosecond pulses', *Materials*, 13(21), pp. 1–8, 4983. doi: 10.3390/ma13214983

[7] Marushak, PO, Lytvynenko, IO, Lupenko, SA & Popovych, PV 2016, 'Modeling of the Ordered Surface Topography of Statically Deformed Aluminum Alloy', *Materials Science*, vol. 52, no. 1, pp. 113–122. DOI: 10.1007/s11003-016-9933-1

[8] Lytvynenko, IV & Marushchak, PO 2015, 'Analysis of the State of the Modified Nanotitanium Surface with the Use of the Mathematical Model of a Cyclic Random Process', *Optoelectronics, Instrumentation and Data Processing*, vol. 51, no. 3, pp. 254–263. DOI: 10.3103/S8756699015030073

[9] Lupenko, S, Lytvynenko, I, Stadnyk, N & Zozulia, A 2020, 'Model of signals with double stochasticity in the form of a conditional cyclic random process', *ICT&ES-2020: Information-Communication Technologies & Embedded Systems*, November 12, 2020, Mykolaiv, Ukraine. CEUR Workshop Proceedings, 2762, pp. 201–208. http://ceur-ws.org/Vol-2762/short1.pdf

[10] Gardner, WA, Napolitano, A & Paura, L 2015, 'Cyclostationarity: Half a century of research', *Signal Processing*, no. 86, pp. 639–697. https://doi.org/10.1016/j.sigpro.2005.06.016

[11] Hurd, HL, *Periodically Correlated Random Sequences: Spectral Theory and Practice*, The University of North Carolina at Chapel Hill Hampton University.

[12] Kochel, P 1980, 'Periodically stationary Markovian decision models', *Elektron. Informationsverarb. Kybernet*, no. 16, pp. 553–567 [in German].

[13] Nematollahi, AR & Soltani, AR 2000, 'Discrete time periodically correlated Markov processes', *Probability and Mathematical Statistics*, no. 20 (1), pp. 127–140.

[14] Ghysels, E, McCulloch, RE & Tsay, RS 1993, 'Bayesian Inference for a General Class of Periodic Markov Switching Models'.

[15] Ghysels, E 1992, 'On the Periodic Structure of the Business Cycle', Cowles Foundation, Yale University, no. 1028. https://doi.org/10.2307/1392085

[16] Bittanti, S, Lorito, F & Strada, S 1991, 'Markovian representations of cyclostationary processes', *Topics in Stochastic Systems: Modelling, Estimation and Adaptive Control*, Springer, Berlin, Germany, vol. 161, pp. 31–46.

[17] Israa Shaker Tawfic, Sema Koc Kayhan 2017, 'Improving recovery of ECG signal with deterministic guarantees using split signal for multiple supports of matching pursuit (SSMSMP) algorithm', *Computer Methods and Programs in Biomedicine*, vol. 139, pp. 39–50. doi.org/10.1016/j.cmpb.2016.10.014

[18] Fumagalli, F, Silver, AE, Tan, Q, Zaidi, N & Ristagno, G 2018, 'Cardiac rhythm analysis during ongoing cardiopulmonary resuscitation using the Analysis During Compressions with Fast Reconfirmation technology', *Heart Rhythm*, 15(2), pp. 248–255. doi: 10.1016/j.hrthm.2017.09.003.

[19] Napoli, NJ, Demas, MW, Mendu, S, Stephens, CL, Kennedy, KD, Harrivel, AR, Bailey, RE & Barnes, LE 2018, 'Uncertainty in heart rate complexity metrics caused by R-peak perturbations', *Computers in Biology and Medicine*, 103, pp. 198–207. doi: 10.1016/j.compbiomed.2018.10.009.

[20] Napolitano, A 2016, 'Cyclostationarity: Limits and generalizations', *Signal Processing*, vol. 120, March 2016, pp. 323–347. DOI: 10.1016/j.sigpro.2015.09.013

[21] Karyotis, V & Khouzani, MHR 2016, 'Malware Diffusion Models for Modern Complex Networks', *Theory and Applications*, p. 324. ISBN 978-0-12-802714-1.

[22] Sericola, B 2013, *Markov Chains: Theory and Applications*, London, 416 p. ISBN: 978-1-848-21493-4.

[23] Shaffer, F & Ginsberg, JP 2017, 'An Overview of Heart Rate Variability Metrics and Norms', *Frontiers in Public Health*, vol. 5, Article 258, pp. 1–17, doi: 10.3389/fpubh.2017.00258.

[24] Gorshkov, S 2016, *Introduction to Ontological Modeling*. TriniData, Yekaterinburg, Russia. [in Russian]

[25] OWL Web Ontology Language Guide. W3C Recommendation. [Online]. Available: http://www.w3.org/TR/owl-guide/. Accessed on: Dec.13, 2019.

УДК 519.216

Моделі, методи та засоби онтології опрацювання циклічних сигналів

[1]С.А. Лупенко, [1]Я.В. Литвиненко, [2]А.М. Зозуля, [1]Ннамене К. Чизоба, [2]О.В. Воляник

[1]Тернопільський національний технічний університет імені Івана Пулюя;
вул. Руська, 56, м. Тернопіль, 46000, Україна

[2] Інститут телекомунікацій і глобального інформаційного простору Національної академії наук України;
Чоколівський бульвар, 25, ап. 13, м. Київ, 03186, Україна

Запропоновано концептуальну та формальну моделі онтології предметної області «Моделювання та опрацювання циклічних сигналів на базі теорії циклічних функціональних відношень». Реалізовано онтологію математичних моделей циклічних сигналів, а саме циклічних функціональних відношень на алгоритмічній мові OWL DL в середовищі Protégé.

Модель онтології дає змогу подати теорію циклічних функціональних відношень у машинно-інтерпретовній формі, яка є основою розроблення онтоорієнтованих інформаційних систем для моделювання, генерування, оброблення (аналіз, прогнозування, прийняття рішень) циклічних сигналів.

Ключові слова: *методи опрацювання, моделювання, онтологія, циклічні сигнали.*