Computer Ontology of Mathematical Models of Cyclic Space-Time Structure Signals

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Abstract

The work is devoted to the development of formal and machine-interpretive models of computer ontology of mathematical models of signals of cyclic space-time structure as the core knowledge base of onto-oriented expert decision support system in solving problems of reasonable choice of mathematical models of cyclic signals in the theory of cyclic functional. Based on the obtained theoretical results, a procmdtotype of computer ontology of mathematical models of signals of cyclic space-time structure is constructed, which contains the set and taxonomy of names of classes of cyclic functional relations, their attribute and definition vectors.

Keywords

computer ontology, expert system, ontological modeling, mathematical modeling, signal processing, cyclic signals

1. Introduction

Many scientific works have been devoted to the development of computer systems for automated analysis, forecasting, classification, clustering, regression, simulation (generation) of cyclic signals [1-7]. The class of cyclic includes such types of signals as cyclic heart signals (electrocardiographic signals, magnetocardiographic signals, phonocardiographic signals, sphygmocardiographic signals, etc.), cyclic economic processes, cyclic processes of relief formation on the surface of materials, cyclic processes of gas consumption, energy consumption and electricity consumption. water consumption), cyclical processes in telecommunications systems and computer networks. The accuracy, reliability, informativeness and computational complexity of the functioning of these information systems significantly depends on and is determined by the properties of the relevant mathematical models and methods of processing signals of cyclic structure, which underlie their mathematical support.

In the last two decades, the theory of cyclic functional relations has developed significantly, which is a fundamental theory of mathematical, computer modeling and processing of cyclic signals, and significantly generalizes, expands, systematizes known mathematical models and methods of signal processing and processes of cyclic structure [8, 9]. Within the framework of this theory, new mathematical models, methods of processing (statistical estimation, spectral analysis, sampling) and

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methods of computer simulation of cyclic signals of biological, economic, and technical origin are built. The theory of cyclic functional relations has the means of mathematical description and processing of cyclic signals in the framework of deterministic, stochastic, fuzzy and interval approaches to modeling cyclic signals. Within the framework of the stochastic approach mathematical models in the form of cyclic random processes and vectors, as well as conditional cyclic random processes are intensively applied and developed, which generalize periodic (periodically correlated and periodically distributed) random processes and vectors and have formal means of considering the variability and stochasticity of the rhythm of the studied cyclic signals. These mathematical models and their corresponding methods of cyclic signal processing have become the core of mathematical software for several software systems for analysis and prediction of cyclic signals (processes) in medical cardio diagnostics, econometrics, biometric authentication, non-destructive diagnostics, and energy consumption.

It is known that the development or reasonable choice of a mathematical model of the studied cyclic signals is the first difficult but important step in building a whole set of mathematical tools for automated processing and computer simulation of cyclic signals in modern information systems. Given the large number of existing mathematical models of signals of spatiotemporal structure, which describe them in the framework of deterministic, stochastic, fuzzy and interval approaches, there is a need to develop an expert system to support decision-making in the problems of reasonable choice of optimal (quasi-optimal) mathematical model of cyclic signals, within which they will be processed in the appropriate automated information systems. The need to develop such an expert system becomes even more obvious, because often the collective developers of appropriate automated information systems do not have a direct highly qualified specialist in the field of mathematical modeling and processing of cyclic signals. Users of such an expert system can be researchers, engineers who are not direct highly qualified specialists in the field of modeling and processing of cyclic signals, but who need to solve problems in this field using information system for modeling and processing of cyclic signals.

The process of building its knowledge base is central to the process of developing any expert system. Given the rapid development of knowledge engineering technologies of ontological modeling of various subject areas, it is appropriate to use the computer ontology of the corresponding mathematical models as the core of the knowledge base of the expert decision support system in the problems of choosing mathematical models of cyclic signals. The expediency of the ontological approach is also justified by the fact that ontology allows to specify the knowledge and automate the procedures of logical inference (proof), which are contained in the theory of modeling and processing of cyclic signals, enables the presentation of the theory of cyclic functional relations in machine-interpretive form as a basis for the development of onto-oriented information systems for modeling, generation, processing (analysis, forecasting, decision-making) of cyclic signals. In addition, the ontological approach is well coordinated with the axiomatic-deductive strategy of modeling theory and processing of cyclic signals based on cyclic functional relations, which significantly increases its structure, rigor, and formalism, facilitates the identification of new directions and regions of cyclical functional theory.

2. Review of literature sources

Ontologies as a means of presenting and preserving knowledge have been actively used in various subject areas. Thus, in the field of medicine, well-known computer ontologies are GO [10], a systematized multilingual thesaurus with the properties of SNOMED CT ontology [11], domain ontology FMA Ontology [12], ontology-like reference terminology dictionary NCI [13], ontology Malaria Ontology, which covers all aspects of malaria and measures to combat it; Hypertension Ontology to present clinical data on hypertension; Antibiotic Resistance Ontology, which describes genes and mutations that are resistant to antibiotics [14].

Computer ontologies are actively used for folk and alternative medical systems in projects such as CLINMED, TCM-Grid, TCMLARS, TCMID, Database of Chinese Medical Formula, TCM Electronic Medical Record Database, China Hospitals Database, Venomous Chinese Herb Database Platform, TCDBASE, Database of Chemical Composition from Chinese Herbal Medicine, TCM

Herbal Medicine Database, Chinese Materia Medica, TCMGeneDIT, Chinese Herbal Medicine Ontology and others. [15-19].

Ontology has also found wide application in the problems of materials design and computational materials science. An example of such an ontology is the MDO (Materials Design Ontology) ontology [20]. In the field of economics, in the field of textual data in economics, computer ontologies are also actively used. An example of such a well-known ontology is the Ontology-based multi-label classification of economic articles, which is designed to automatically classify documents in the field of economics, allowing their automatic description and search [21]. For problems in mathematics and mathematical modeling, the OntoMath ontology is fruitfully used, and in the subject area of signal and image processing - the computer ontology ODSPTB (Ontology-Directed Signal Processing Toolbox) [22].

In [23, 24] a generalized conceptual model of ontology and a formal model of ontology of the subject area "Modeling and processing of cyclic signals" were developed. The ontology studied in these works includes the ontology of mathematical models of cyclic signals as its subontology. Also, an important result of research, the results of which are presented in [23, 24] is the application of the method of induction to form the main components of the computer ontology of mathematical models of cyclic signals for the formation of many names and definitions of classes of cyclic functional relations, their taxonomy. This method consists of a combinatorial ordered combination of names of types of regions of values, types of attributes of cyclicity, types of domains of definition and types of rhythm functions in the definition of abstract cyclic functional relation as a generalized mathematical model of signals of cyclic space-time structure. mathematical models of cyclic signals.

Given the above material, the aim of this work is to develop the known results obtained in [23, 24], namely, the development of a formal model of ontology of mathematical models of cyclic signals and the development of a prototype of the corresponding computer ontology, which is the core knowledge base of the expert system of support of model decision-making in problems of modeling and processing of signals of cyclic space-time structure.

3. Main part

3.1. Formal model of computer ontology of cyclic signal models

Let us concentrate on the construction of computer ontology of mathematical models of signals of cyclic space-time structure, namely, ontology O. Ontology O - ontology of models of cyclic signals (ontology of cyclic functional relations) at the formal level is given by the following relational system:

$$\boldsymbol{O} = \left\{ \begin{matrix} \boldsymbol{A} = \boldsymbol{B} \cup \boldsymbol{C},\ \boldsymbol{R} = \left\{ \mathbf{AKO}, \mathbf{IS-A}, \overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n}), \overline{\boldsymbol{L_{imp}}} = (\mathrm{l}_1, \mathrm{l}_2, \dots, \mathrm{l}_8) \right\}, \\ \mathbf{F} = \{\mathrm{f}(\cdot)\} \end{matrix} \right\} \quad (1)$$

where: A is a finite set of terms (concepts), which defines the lexical stock of the ontology O.

B is a finite set (names) of classes of cyclic functional relations. C is a finite set of 4-element vectors, each element of which is a term, which derive their values from the corresponding sets $\boldsymbol{X_\Psi}$,$\boldsymbol{X_A}$, $\boldsymbol{X}_{T(t,n)}$, $\boldsymbol{X_W}$, and has the domain of predicate $P(x_1, x_2, x_3, x_4)$. Sets $\mathbf{X_\Psi}$, is a set of predefined classes (types) of linear spaces $\mathbf{\Psi}$ in which the corresponding cyclic functional relations gain the values; plural $\boldsymbol{X_A}$ is a set of predefined classes (types) of possible attributes $p{:}\,\boldsymbol{\Psi} \to \boldsymbol{A}$ or sets of attributes $\left\{p_k{:}\,\boldsymbol{\Psi}^{n_k} \to \boldsymbol{A}_k,\ k = \overline{1, K}\right\}$, in which the cyclical structure of the functional relation is postulated (reflected); Sets $\boldsymbol{X}_{T(t,n)}$ is a set of predefined classes (types) of rhythm functions $T(t,n)$ cyclic functional relations, and the set $\boldsymbol{X_W}$ is a set of predefined types of definition areas $\boldsymbol{W}$ cyclic functional relationship. Identically true 4-local predicate $P(x_1, x_2, x_3, x_4)$ is a function-expression, which is set on sets$\boldsymbol{X_\Psi}$,$\boldsymbol{X_A}$,$\boldsymbol{X}_{T(t,n)}$,$\boldsymbol{X_W}$ ($x_1 \in \boldsymbol{X_\Psi}$,$x_2 \in \boldsymbol{X_A}$,$x_3 \in \boldsymbol{X}_{T(t,n)}$,$x_4 \in \boldsymbol{X_W}$) and which derives its meanings from the set $\boldsymbol{Def}_{cf}$ all possible definitions of specific subclasses of cyclic functional relations.

F – a one-element set that contains an interpretation function f(x_1, x_2, x_3, x_4), the domain of which is the set C, and the domain of values is the set B. Interpretation function $f(x_1, x_2, x_3, x_4)$ identical 4-local predicate $P(x_1, x_2, x_3, x_4)$ and, in fact, for specific sets $x_1 \in \boldsymbol{X_\Psi}$,$x_2 \in \boldsymbol{X_A}$,$x_3 \in \boldsymbol{X}_{T(t,n)}$,$x_4 \in \boldsymbol{X_W}$

sets the definition of the corresponding classes of cyclic functional relations with B, forming a glossary of ontology O - the set of all definitions of cyclic functional relations.

R - a finite set of relations$\{\mathbf{AKO}, \mathbf{IS-A}, \overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n}), \overline{\boldsymbol{L_{\imath mp}}} = (\mathrm{l}_1, \mathrm{l}_2, \dots, \mathrm{l}_8)\}$, namely:

1. AKO genus-species subordination relationship, which connects a set (class) and a subset (subclass) of cyclic functional relationships, defining the $\boldsymbol{Tax\_of\_Cf}$ taxonomy (hierarchy) between these classes as a taxonomic tree.
2. The IS-A membership relationship, which corresponds to a specific cyclic functional relationship (specific model of cyclic signals) to their corresponding class (class of mathematical models of cyclic signals).
3. $\overline{\boldsymbol{P}}$ - vector = $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ unary relations $(\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$, which define the properties (features, attributes) of the corresponding class of cyclic functional relations. The domain of the unary relation $\boldsymbol{P}_\mathrm{i}$ is the set of models A, and the domain of values is the set $\boldsymbol{P}_\mathrm{i}$ of the values of the corresponding property.
4. $\overline{\boldsymbol{L_{\imath mp}}}$ – vector $\overline{\boldsymbol{L_{\imath mp}}} = (\mathrm{l}_1, \mathrm{l}_2, \dots, \mathrm{l}_8)$, components, which characterize the state (level) of elaboration (implementation, development) of the corresponding information technologies of processing and computer simulation (generation) of cyclic signals within the framework of this mathematical model.

3.2. Substantiation of the choice of language and software for the development of the ontology of mathematical models of cyclic signals

The formal ontology model developed above requires a reasonable choice of machine-implemented languages and development environments for their presentation in modern onto-oriented information systems. Currently, we have so many ontology management tools, such as Protégé, OntoEdit, the Ontolingua ontology development environment, Chimaera and OntoGen. Given the results of a comparative analysis of ontology development tools, it is appropriate to use the OWL ontology description language and the Protégé environment [25].

OWL (Web Ontology Language) is a standard in the World Wide Web Consortium and is currently the world's most widely used ontology description language. There are three types of OWL. The OWL DL language is the most acceptable for solving the problems of developing the ontology of the subject area "Modeling and processing of cyclic signals", which allows, on the one hand, achieving the maximum expressiveness of the descriptive logic that underlies it, and on the other - to ensure the solvability of the system of logical inferences with its use. OWL DL language is provided with standardized language constructions for adequate expression of terms-concepts of the theory of cyclic functional relations, their taxonomies and other relations, logical operations on classes of models, methods and means of modeling and processing of cyclic signals.

Due to the inconvenient for human perception syntax of the OWL language in the development of ontologies, it is necessary to use the graphical tools of specialized software systems for the development of ontologies. These software tools include a graphics editor and a reasoner machine, which allows both automation of logical derivation based on ontology knowledge and automatic verification of the correctness of the developed ontology. Protégé is the most popular ontology editor that supports the OWL DL language. This graphics editor is a freely distributable Java application that contains many plug-ins. In general, the Protégé editor allows you to design, view, edit, integrate, populate, and adapt ontologies to different data formats (text, XML, RDf (s), OWL, etc.).

The formation of the set B of names of classes of cyclic functional relations must be unified. The names of the classes of cyclic functions are derived from the corresponding names of the elements of the sets $\boldsymbol{X_\Psi}$, $\boldsymbol{X_A}$, $\boldsymbol{X_{T(t,n)}}$, $\boldsymbol{X_W}$ according to the rules of the relevant national language (Ukrainian, English, etc.), ie from the names of the relevant types of areas of definition, attributes, functions of rhythm and areas of definition of the cyclical functional relationship. To simplify the names of cyclic functional relationships, we will use a shorter version instead of the name "Cyclic functional relationship" - "Cyclic function".

The name of the cyclic functional relation can be conditionally divided into the following four parts. The first part of the name of the cyclic functional relationship reflects the type of attribute cyclicity of this function, namely, contains the name of the attribute $\boldsymbol{p}: \boldsymbol{\Psi} \rightarrow \boldsymbol{A}$ (чи $p: \boldsymbol{\Psi}^{n} \rightarrow \boldsymbol{A}$) or a set of attribute names $\{p_k: \boldsymbol{\Psi}^{n_k} \rightarrow \boldsymbol{A}_k,\ k = \overline{1,K}\}$) from a certain, predefined set of names of possible attributes of cyclicity (sets of names of elements from $\boldsymbol{X_A}$). The second part of the name of the cyclic functional relation derives its verbal meanings from the set of possible, pre-defined, names of general approaches to considering (or not considering) uncertainties in modeling the studied signals, namely, from the set {deterministic, random, fuzzy, interval}, as well as from the names of the types of domains of values of the cyclic functional relation (sets of names of elements from$\boldsymbol{X_\Psi}$). The third part of the name of the cyclic functional relationship reflects the type of domain of the cyclic function, i.e gets its values from the set of names of elements from$\boldsymbol{X_W}$. The fourth part of the name of the cyclic functional relation reflects the type of rhythm of the cyclic function, that is, it derives its values from the set of names of elements from $\boldsymbol{X}_{T(t,n)}$.

Here are some examples of the names of cyclical functional relationships formed in accordance with the above unified approach, namely:

- cyclic value-determined deterministic real function of a real argument with a constant rhythm;
- cyclic values of deterministic real-valued function of a valid argument with variable piecewise-cubic rhythm;
- cyclic value-determined significant function of many real arguments with variable piecewise-linear rhythm;
- cyclic modulo deterministic real function of a valid argument with a variable periodic rhythm;
- cyclic squared value determined deterministic real function of a real argument with a variable piecewise-square rhythm;
- cyclic for many autocorrelations and intercorrelation functions vector random function of a valid argument with a constant rhythm;
- cyclic in the trapezoidal membership function fuzzy function of a discrete argument with a variable rhythm;
- cyclic with respect to the system of intervals interval function of a discrete argument with a variable piecewise linear rhythm.

Each class of cyclic functional relations is defined by its definition, which should be contained in the glossary of ontology O mathematical models of cyclic signals. Therefore, the next stage in the formation of the glossary of ontology of mathematical models of cyclic signals is the formation of a set of definitions of classes of cyclic functional relations, which according to the ontology model O, the interpretation function is set $f_1(x_1, x_2, x_3, x_4)$, which is identical 4-local predicate $P(x_1, x_2, x_3, x_4)$ and for specific sets $x_1 \in \boldsymbol{X_\Psi}$,$x_2 \in \boldsymbol{X_A}$,$x_3 \in \boldsymbol{X}_{T(t,n)}$,$x_4 \in \boldsymbol{X_W}$ defines the corresponding classes of cyclic functional relations, forming a glossary of ontology O.

As stated above, the definition of the cyclic functional relation is considered as an identically true - local predicate, namely, as a function-expression$P(x_1, x_2, x_3, x_4)$, which is given on sets $\boldsymbol{X_\Psi}$,$\boldsymbol{X_A}$,$\boldsymbol{X}_{T(t,n)}$,$\boldsymbol{X_W}$ ($x_1 \in \boldsymbol{X_\Psi}$,$x_2 \in \boldsymbol{X_A}$,$x_3 \in \boldsymbol{X}_{T(t,n)}$,$x_4 \in \boldsymbol{X_W}$),and which derives its meanings from the set $\boldsymbol{Def}_{cf}$ all possible definitions of specific subclasses of cyclic functional relations. Because the predicate $P(x_1, x_2, x_3, x_4)$ is identically true, then for any set of values x_1, x_2, x_3, x_4 from sets $\boldsymbol{X_\Psi}$,$\boldsymbol{X_A}$,$\boldsymbol{X}_{T(t,n)}$,$\boldsymbol{X_W}$, it always turns into a true statement, namely, the definition of a particular subclass of cyclical functional relations. Also, given that with classes $\boldsymbol{X_\Psi}$,$\boldsymbol{X_A}$,$\boldsymbol{X}_{T(t,n)}$,$\boldsymbol{X_W}$ related taxonomies are related $\boldsymbol{T_\Psi}$,$\boldsymbol{T_A}$,$\boldsymbol{T}_{T(t,n)}$,$\boldsymbol{T_W}$, then it can be argued that for any set of values x_1, x_2, x_3, x_4 from any nodes (classes, sets) $\boldsymbol{X_\Psi}$,$\boldsymbol{X_A}$,$\boldsymbol{X}_{T(t,n)}$,$\boldsymbol{X_W}$ taxonomies $\boldsymbol{T_\Psi}$,$\boldsymbol{T_A}$,$\boldsymbol{T}_{T(t,n)}$,$\boldsymbol{T_W}$, predicate $P(x_1, x_2, x_3, x_4)$ always turns into a true statement, which will be automatically generated (generated) definition of a particular subclass of cyclical functional relations, and will be the appropriate node of the taxonomy (classification tree) $\boldsymbol{Tax\_of\_Cf}$ models of cyclic signals within the theory of cyclic functional relations. Figures 1 - 4 show fragments of the glossary of cyclic functional relations as components of the ontology of mathematical models of cyclic signals, built in the Protégé environment.

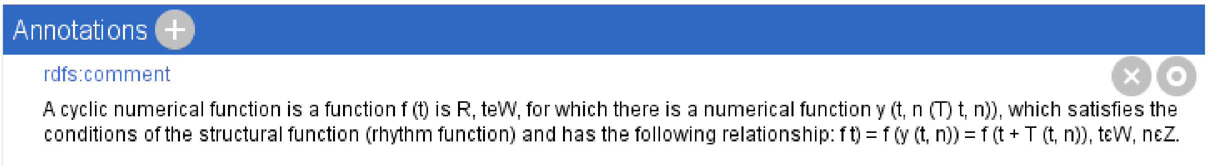

Figure 1: Graphical representation in the Protégé environment of a glossary fragment - the definition of a cyclic numerical function

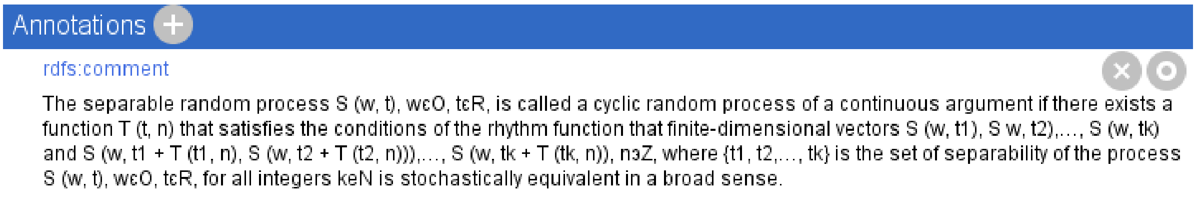

Figure 2: Graphical representation in the Protégé environment of a glossary fragment - definition of a cyclic random process of a continuous argument

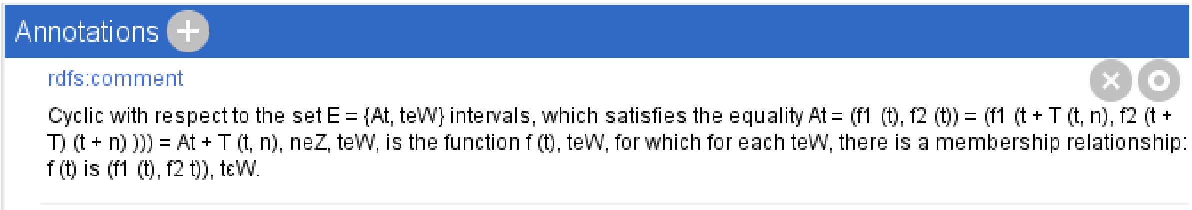

Figure 3: Graphical representation in the Protégé environment of a glossary fragment - the definition of cyclic relative to the set of interests of the function

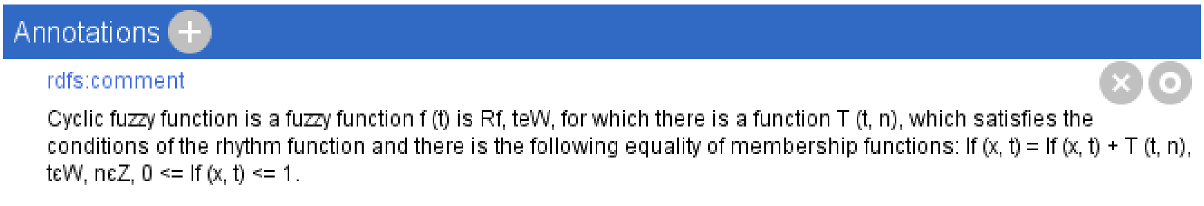

Figure 4: Graphical representation in the Protégé environment of a glossary fragment - definition of cyclic relative to the set of function intervals

3.3. Method of forming vector of properties of classes of cyclic functional relations in the framework of computer ontology of mathematical models of cyclic signals

In addition to outlining the set of names and definitions of classes of mathematical models of cyclic signals in the theory of cyclic functional relations, an important component of the ontology of mathematical models of cyclic signals is the vector $\overline{\boldsymbol{P}}$, namely, the vector $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ unary relations $(\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$, which specify the properties (features, attributes) of the corresponding class of cyclic functional relations, which specify the properties (features, attributes) of the corresponding class of cyclic functional relations. As mentioned in the second section of the dissertation, the area of definition of the unary ratio $\mathrm{p}_\mathrm{i}, i = \overline{1, n}$ is a set $\mathbf{B}_1$ of the names of mathematical models of cyclic signals, and the range of values is the set $\boldsymbol{P}_\mathrm{i}$ values of the corresponding property.

Thus, each class of cyclic functional relations must have its own vector $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ properties (features, attributes), which contains the properties of the corresponding class of cyclic functions, and which fully characterizes it and underlies the procedure of classification of cyclic functional relations. To each such vector of properties $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$we put in correspondence the vector of numerical variables $\overline{\boldsymbol{I}} = (i_1, i_2, \dots, i_\mathrm{n})$, which take values from finite subsets of natural numbers. Vector $\overline{\boldsymbol{I}} = (i_1, i_2, \dots, i_{\mathrm{n}})$ encodes in numerical format the vector of properties $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_{\mathrm{n}})$ and underlies the numerical coding of classes of cyclic functional relations.

Based on the constructed taxonomies $\boldsymbol{T_\Psi}$,$\boldsymbol{T_A}$,$\boldsymbol{T}_{T(t,n)}$,$\boldsymbol{T_W}$and their defined priorities, as well as applying the approach that underlies the method of induction of classes of cyclic functional relations, let us construct a property vector $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_{\mathrm{n}})$ for each class of cyclic functional relations as mathematical models of cyclic signals. Note that the type of ordering of properties $\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_{\mathrm{n}}$ in the vector $\overline{\boldsymbol{P}}$is determined by the order of nodes and priorities of taxonomies $\boldsymbol{T_\Psi}$,$\boldsymbol{T_A}$,$\boldsymbol{T}_{T(t,n)}$,$\boldsymbol{T_W}$.

Firstly, highest priority property in the vector of properties $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_{\mathrm{n}})$ of classes of cyclic functional relations concerns the type of uncertainty of values of cyclic signal. Namely, this property p_1 can take values from the set $\{d, s, f, i\}$, where d denotes a deterministic approach (determined); s - stochastic approach (stochastic); f - fuzzy approach (fuzzy); i - interval approach (interval).

The number i_1 can take values from one to four. One $(i_1 = 1, \mathrm{p}_1 = d)$will encode a deterministic approach to the description of cyclic signal values, two $(i_1 = 2, \mathrm{p}_1 = s)$ will encode a stochastic approach to the description of cyclic signal values, three $(i_1 = 3, \mathrm{p}_1 = f)$will encode something approach to the description of cyclic signal values, and four $(i_1 = 4, \mathrm{p}_1 = i)$ will encode an interval approach to the description of cyclic signal values.

The second priority property p_2 (encoded by the variable i_2) indicates such a property of the class of cyclic functional relations as the type of value of the cyclic signal. Namely, this property p_2 can take values from the set

$$\left\{\begin{matrix} real, complex, vector_{real}, vector_{complex}, matrix_{real}, matrix_{complex}, tensor_{real}, \\ tensor_{complex}, \dots \end{matrix}\right\}$$

and the number i_2 can take values from 1 to 12. One $(i_2 = 1, \mathrm{p}_2 = real)$ will encode cyclic signals whose values are real numbers; two $(i_2 = 2, \mathrm{p}_1 = \ complex)$ will encode cyclic signals, whose values are complex numbers, three $(i_2 = 3, \mathrm{p}_2 = vector\_real)$ will encode cyclic signals whose values are vectors of real numbers, four $(i_2 = 4, \mathrm{p}_2 = vector\_complex)$ will encode cyclic signals whose values are vectors of complex numbers, five $(i_2 = 5, \mathrm{p}_2 = matrix\_real,)$ will encode cyclic signals whose values are matrices of real numbers, six $\left(i_2 = 6, \mathrm{p}_2 = matrix_{complex}\right)$ will encode cyclic signals whose values are matrices of complex numbers, seven $(i_2 = 7, \mathrm{p}_2 = tensor)$ will encode cyclic signals whose values there is a tensor, and so on.

The third priority property p_3 (encoded by the variable i_3) indicates the type of cyclicity attribute of this class of cyclic functional relations. As a rule, $i_3 = 1$, when the cyclicity attribute of the function is its value. For other cyclicity attributes, i_3 is set to 2 or more.

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

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

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

The seventh priority property p_7 (encoded by the variable i_7) 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 variable i_8) specifies the type of variable rhythm of the cyclic function, namely, whether the cyclic function is with a piecewise-linear type of rhythm or with a piece-square type of rhythm or a piece-cubic type of rhythm or with a periodic type of rhythm, etc. That is, this property specifies the type of rhythm variability of the cyclic function.

In general, the number of properties n (i.e., the dimension of the vector $\overline{\boldsymbol{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n}))$ that characterizes the class of cyclic functional relations may be different for different classes. However, it is necessary to follow the rule according to which all the properties of a super-class of cyclic functional relations, which are components of its property vector, are part of the property vectors of all its subclasses.

Given that four possible approaches to uncertainty, namely, deterministic, stochastic, fuzzy and interval, are used to describe the values and elements of the domain (and, accordingly, rhythm functions) of cyclic functions, namely, a total of 16 approaches to mathematical description of the uncertainty of cyclic signals. A summary of these 16 approaches is given in Table 1.

Table 1

Approaches to the mathematical description of the uncertainty of cyclic signals

№ approach	The name of the approach to the description of the uncertainty of the values of cyclic signals	The name of the approach to the description of the uncertainty of the elements of the domain and the rhythm of cyclic signals	The name of a generalized approach to describing the uncertainty of cyclic signals
1	Deterministic $(\mathrm{p}_1 = d, i_1 = 1)$	Deterministic $(\mathrm{p}_4 = d, i_4 = 1)$	Deterministic
2	Deterministic $(\mathrm{p}_1 = d, i_1 = 1)$	Stochastic $(\mathrm{p}_4 = s, i_4 = 2)$	Deterministic-stochastic
3	Deterministic $(\mathrm{p}_1 = d, i_1 = 1)$	Vague $(\mathrm{p}_4 = f, i_4 = 3)$	Deterministic-fuzzy
4	Deterministic $(\mathrm{p}_1 = d, i_1 = 1)$	Interval $(\mathrm{p}_4 = i, i_4 = 4)$	Deterministic-interval
5	Stochastic $(\mathrm{p}_1 = s, i_1 = 2)$	Deterministic $(\mathrm{p}_4 = d, i_4 = 1)$	Stochastic-deterministic
6	Stochastic $(\mathrm{p}_1 = s, i_1 = 2)$	Stochastic $(\mathrm{p}_4 = s, i_4 = 2)$	Stochastic
7	Stochastic $(\mathrm{p}_1 = s, i_1 = 2)$	Vague $(\mathrm{p}_4 = f, i_4 = 3)$	Vague
8	Stochastic $(\mathrm{p}_1 = s, i_1 = 2)$	Interval $(\mathrm{p}_4 = i, i_4 = 4)$	Stochastic-interval
9	Vague $(\mathrm{p}_1 = f, i_1 = 3)$	Deterministic $(\mathrm{p}_4 = d, i_4 = 1)$	Vague-Deterministic
10	Vague $(\mathrm{p}_1 = f, i_1 = 3)$	Stochastic $(\mathrm{p}_4 = s, i_4 = 2)$	Vague-Stochastic
11	Vague $(\mathrm{p}_1 = f, i_1 = 3)$	Vague $(\mathrm{p}_4 = f, i_4 = 3)$	Vague
12	Vague $(\mathrm{p}_1 = f, i_1 = 3)$	Interval $(\mathrm{p}_4 = i, i_4 = 4)$	Vague-interval
13	Interval $(\mathrm{p}_1 = i, i_1 = 4)$	Deterministic $(\mathrm{p}_4 = d, i_4 = 1)$	Interval-Deterministic
14	Interval $(\mathrm{p}_1 = i, i_1 = 4)$	Stochastic $(\mathrm{p}_4 = s, i_4 = 2)$	Interval-stochastic
15	Interval $(\mathrm{p}_1 = i, i_1 = 4)$	Vague $(\mathrm{p}_4 = f, i_4 = 3)$	Interval-Vague
16	Interval $(\mathrm{p}_1 = i, i_1 = 4)$	Interval $(\mathrm{p}_4 = i, i_4 = 4)$	Interval

Figures 5-10 show examples of the vector of properties for a few classes of cyclic functional relations, namely, as attributes of the corresponding classes of ontology of mathematical models of cyclic signals built in Protégé.

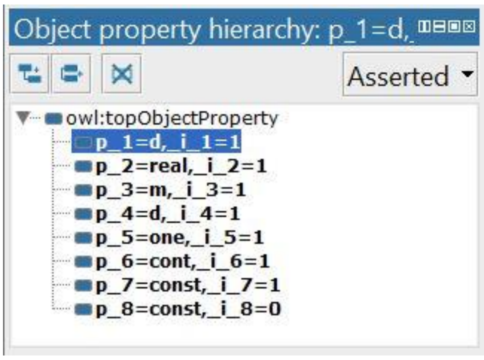

Figure 5: Graphical representation in the Protégé environment of the property vector $\overline{\mathrm{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ for the class "Cyclic values of a deterministic real-valued function of a real argument with a constant rhythm"

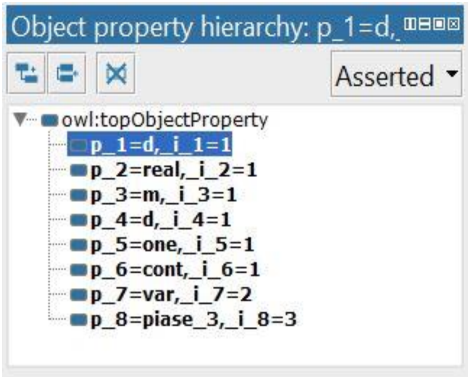

Figure 6: Graphical representation in the Protégé medium of the property vector $\overline{\mathrm{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ for the class "Cyclic values of a deterministic real-valued function of a real argument with a variable piecewise-cubic rhythm"

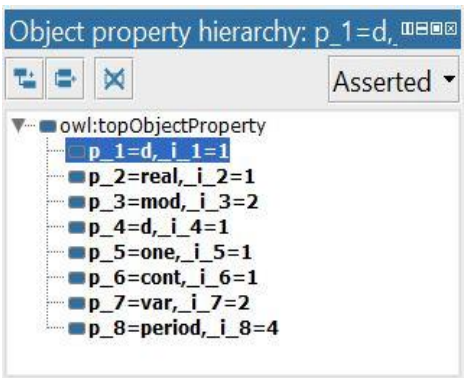

Figure 7: Graphical representation in Protégé medium of the vector of properties $\overline{\mathrm{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ for the class "Cyclic modulo deterministic real function of a valid argument with variable periodic rhythm"

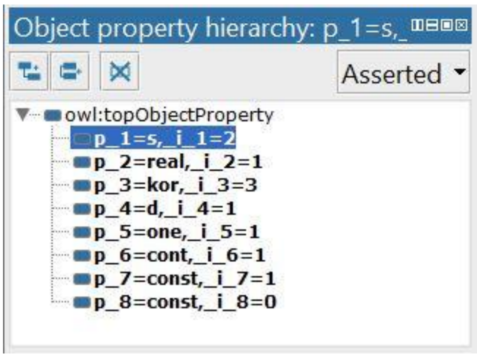

Figure 8: Graphical representation in Protégé medium of the vector of properties $\overline{\mathrm{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ for the class "Cyclic in the set of autocorrelations and intercorrelation functions vector random function of a real argument with a constant rhythm"

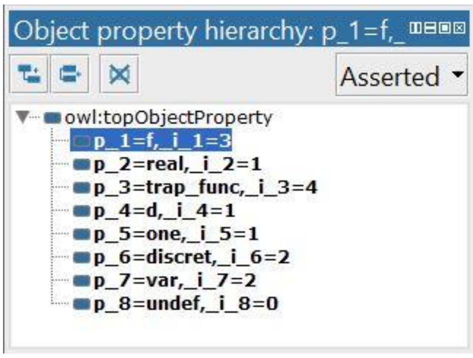

Figure 9: Graphical representation in Protégé medium of the vector of properties $\overline{\mathrm{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ for the class "Cyclic trapezoidal membership function fuzzy function of a discrete argument with variable rhythm"

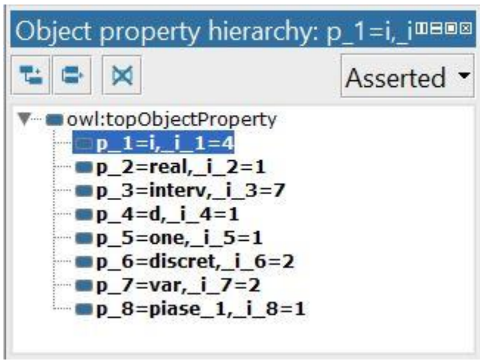

Figure 10: Graphical representation in Protégé medium of the vector of properties $\overline{\mathrm{P}} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$ for the class "Cyclic with respect to the system of intervals interval function of a discrete argument with variable piecewise linear rhythm"

3.4. Method of forming a vector of levels of development of mathematical and software for processing and simulation of cyclic signals within the corresponding class of cyclic functional relations

Since each class of cyclic functional relations is associated with the relevant information technologies (methods and means) of processing and computer simulation (generation) of cyclic signals, mathematical model of which is this class of cyclic functions, in addition to the vector $\bar{\boldsymbol{P}} =$

$(p_1, p_2, \dots, p_n)$, which contains the properties of the corresponding class of cyclic functions, it is correct to enter the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$, components, which characterize the state (level) of elaboration (implementation, development) of the corresponding information technologies of processing and computer simulation (generation) of cyclic signals within the framework of this mathematical model. That is, the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$ is a vector of levels of development of mathematical and software for processing and imitation of cyclic signals within the corresponding class of cyclic functional relations. The information contained in the components of the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$ is important in solving problems of reasonable choice of mathematical model and processing technologies (transformation, analysis (evaluation of cyclicity attributes and rhythm attributes), clustering, classification, forecasting, regression), technologies of simulation (generation) of cyclic signals.

Let us briefly consider each component of the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$.

The first component l_1 of the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$ takes its values from a subset of integers from 0 to 3 and characterizes the level of development of the class of cyclic functional relations as a mathematical model of cyclic signals, namely:

$l_1 = 0$, when there are no definitions, inference properties (lemmas and theorems) that relate to this class of cyclic functional relations, and there are no examples of successful application of this class of cyclic functions as mathematical models of cyclic signals (processes, phenomena);

$l_1 = 1$, When there is a clear mathematically correct definition of the class of cyclic functional relations as a subclass of abstract cyclic functional relations, but there are no derivational properties (lemmas and theorems), relating to this class of cyclic functional relations and there are no examples of successful application of this class of cyclic functions as mathematical models of cyclic signals (processes, phenomena);

$l_1 = 2$, When there is a clear mathematically correct definition of the class of cyclic functional relations as a subclass of abstract cyclic functional relations, there are derivational properties (lemmas and theorems), relating to this class of cyclic functional relations, but there are no examples of successful application of this class of cyclic functions as mathematical models of cyclic signals (processes, phenomena);

$l_1 = 3$, When there is a clear mathematically correct definition of the class of cyclic functional relations as a subclass of abstract cyclic functional relations, there are inference properties (lemmas and theorems) related to this class of cyclic functional relations and there are examples of successful application of this class of cyclic functions as mathematical models of cyclic signals phenomena).

Components $l_2, \dots, l_7$ characterize the level of development of technologies (methods and tools) for processing cyclic signals to solve typical problems within their mathematical model in the form of a corresponding class of cyclic functional relations. These components derive their values from a subset of integers from 0 to 2, namely:

$l_j = 0$ $(j \in \overline{[2{,}7]})$, When there is no method for solving the corresponding typical problem within their mathematical model in the form of this class of cyclic functional relations;

$l_j = 1$ $(j \in \overline{[2{,}7]})$, When there is a method for solving the corresponding typical problem within their mathematical model in the form of this class of cyclic functional relations, but there is no software (hardware, hardware, hardware) that implements this method;

$l_j = 2$ $(j \in \overline{[2{,}7]})$, When there is a method for solving the corresponding typical problem within their mathematical model in the form of a given class of cyclic functional relations, as well as available software (hardware, software, and firmware) that implements this method.

The component l_2 of the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$ characterizes the level of development of technologies (methods and means) of cyclic signal processing to solve the problem of estimating cyclicity attributes (morpho analysis problem) of cyclic signals within their mathematical model in the form of the corresponding class of cyclic functional relations.

The component l_3 of the vector $\overline{\boldsymbol{L_{imp}}} = (l_1, l_2, \dots, l_8)$characterizes the level of development of technologies (methods and means) of cyclic signal processing to solve the problem of estimating rhythm attributes (rhythm analysis problem) of cyclic signals within their mathematical model in the form of a corresponding class of cyclic functional relations.

The component l_4 of the vector ($\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$ characterizes the level of development of technologies (methods and means) of cyclic signal processing to solve the problem of classification (recognition) of cyclic signals within their mathematical model in the form of a corresponding class of cyclic functional relations.

The component l_5 of the vector $\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$ characterizes the level of development of technologies (methods and means) of cyclic signal processing to solve the problem of clustering (construction of diagnostic space) of cyclic signals within their mathematical model in the form of the corresponding class of cyclic functional relations.

The component l_6 of the vector $\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$ characterizes the level of development of technologies (methods and tools) for processing cyclic signals to solve the problem of predicting cyclic signals within their mathematical model in the form of a corresponding class of cyclic functional relations.

The component l_7 of the vector $\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$ characterizes the level of development of technologies (methods and means) of cyclic signal processing to solve the problem of regression of cyclic signals within their mathematical model in the form of a corresponding class of cyclic functional relations.

The component l_8 of the vector $\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$ characterizes the level of development of technologies (methods and tools) for processing cyclic signals to solve the problem of computer simulation (generation) of cyclic signals within their mathematical model in the form the corresponding class of cyclic functional relations.

Thus, the vector $\overline{\boldsymbol{P}} = (p_1, p_2, \dots, p_n)$ (or the vector ($\overline{\boldsymbol{I}} = (i_1, i_2, \dots, i_n)$)) together with the vector $\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$ completely characterize both each specific class of cyclic functional relations and the level of development of technologies (methods and tools) for processing and simulation of cyclic signals within their mathematical model in the form of a corresponding class of cyclic functional relations.

3.5. Coding of classes of cyclic functional relations and their taxonomy

Based on the vectors $\overline{\boldsymbol{P}} = (p_1, p_2, \dots, p_n)$, $\overline{\boldsymbol{I}} = (i_1, i_2, \dots, i_n)$ and $\overline{\boldsymbol{L_{\iota mp}}} = (l_1, l_2, \dots, l_8)$, we form a coding system for classes of cyclic functional relations and information technologies (methods and means) of processing (analysis (estimation of cyclicity attributes and rhythm attributes)), clustering, classification, forecasting, regression), technologies of simulation (generation) of cyclic signals within this mathematical model. Such a coding system enables a unified numerical representation of each class of cyclic functional relations and makes it possible to organize all these classes into their taxonomy $\boldsymbol{Tax\_of\_Cf}$.

Thus, for each class of cyclic functional relations from the vector $\overline{\boldsymbol{I}} = (i_1, i_2, \dots, i_n)$ it is possible to form a unique code vector that has the form: $i_1.i_2., \dots, .i_n$, i.e., which is a sequence of components of the vector $\overline{\boldsymbol{I}} = (i_1, i_2, \dots, i_n)$, separated by a dot (".").

To organize (structure) the set of definitions $\boldsymbol{Def_{cf}}$classes of cyclic functional relations), as well as to develop a general classification of cyclic functional relations, we construct a taxonomy $\boldsymbol{Tax\_of\_Cf}$ definitions of classes of cyclic functional relations, elements (nodes) of which are predicate definitions from $\boldsymbol{Def_{cf}}$. To do this, we apply the method of induction of taxonomy $\boldsymbol{Tax\_of\_Cf}$ from taxonomies $\boldsymbol{T_\Psi}$,$\boldsymbol{T_A}$,$\boldsymbol{T}_{T(t,n)}$,$\boldsymbol{T_W}$.

It should be noted that the type of ordering of different classes of cyclic functional relations within their taxonomy is determined by the types of ordering of the respective sets within the taxonomies $\boldsymbol{T_\Psi}$,$\boldsymbol{T_A}$,$\boldsymbol{T}_{T(t,n)}$,$\boldsymbol{T_W}$, and the ordering of mutual priorities between these taxonomies.

Figures 11 - 16 show examples of taxonomy fragments of cyclic deterministic functional relations constructed in the Protégé environment.

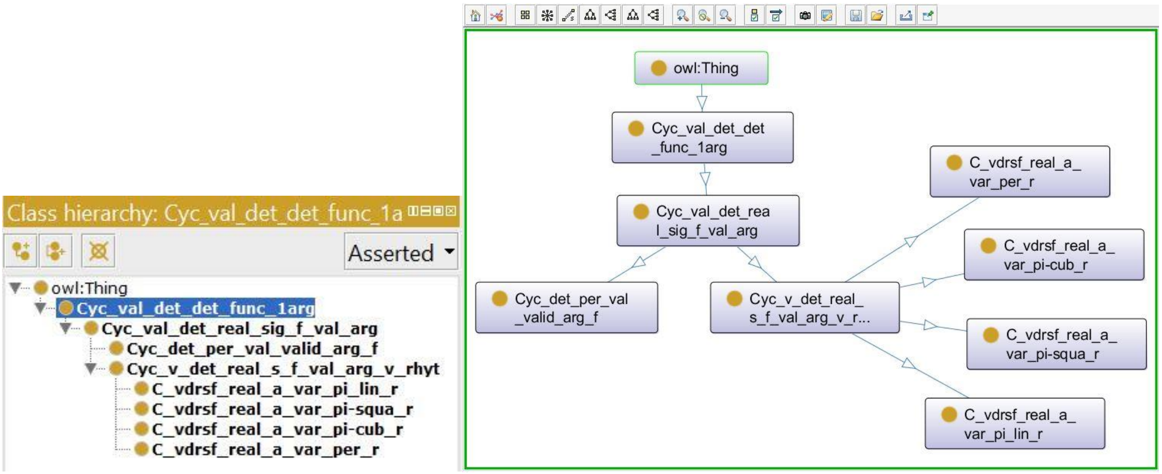

Figure 11: Graphical representation in the Protégé environment for the class "Cyclic value-determined real-value function of one argument"

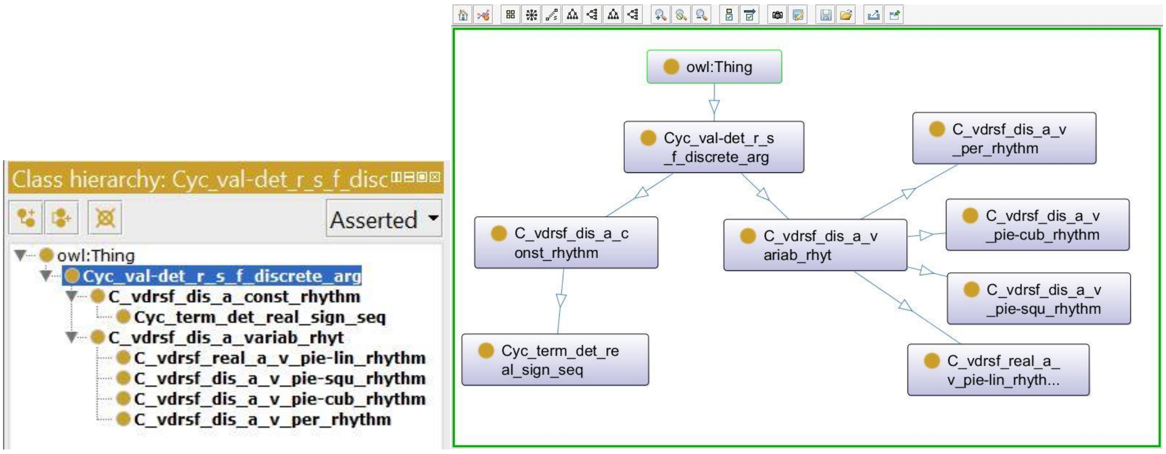

Figure 12: Graphical representation in the Protégé environment for the class "Cyclic value-determined real-valued function of a discrete argument"

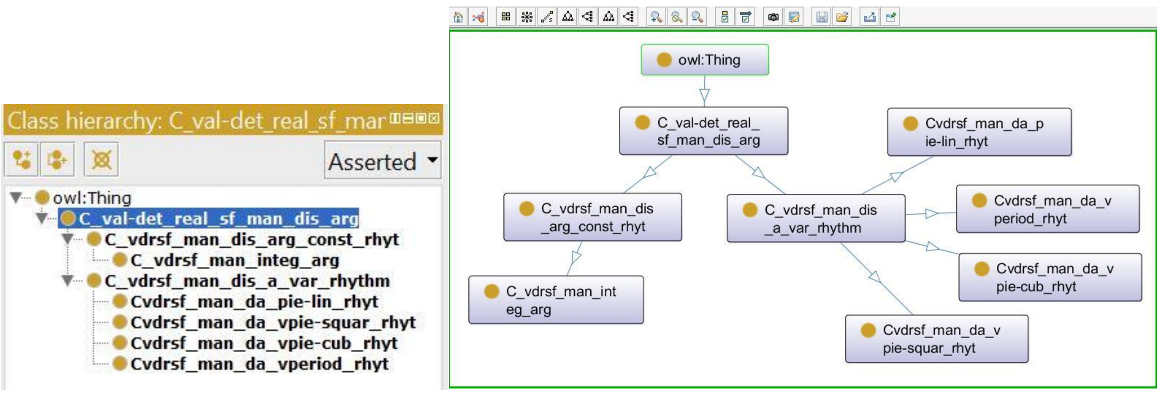

Figure 13: Graphical representation in the Protégé environment for the class "Cyclic value-determined real-valued function of many discrete arguments"

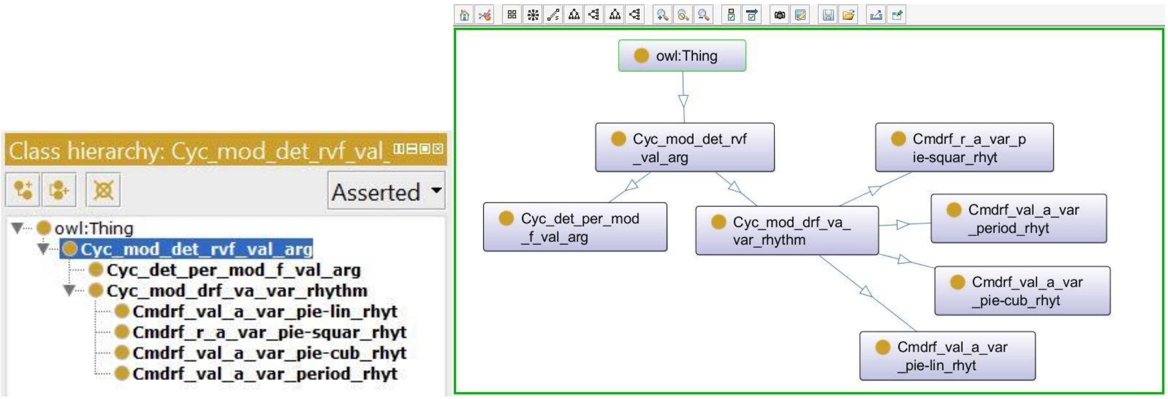

Figure 14: Graphical representation in the Protégé environment for the class "Cyclic modulo deterministic real function of a valid argument"

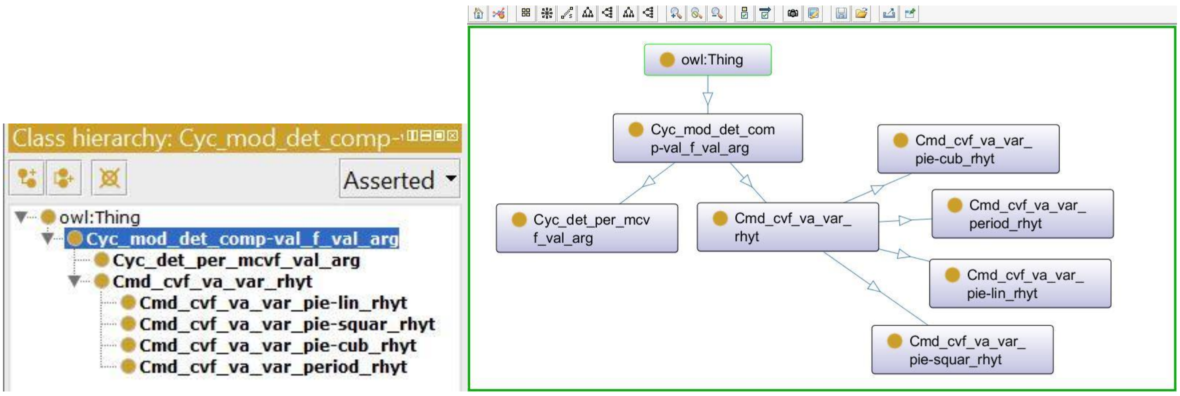

Figure 15: Graphical representation in the Protégé environment for the class "Cyclic modulo deterministic complex function of a valid argument"

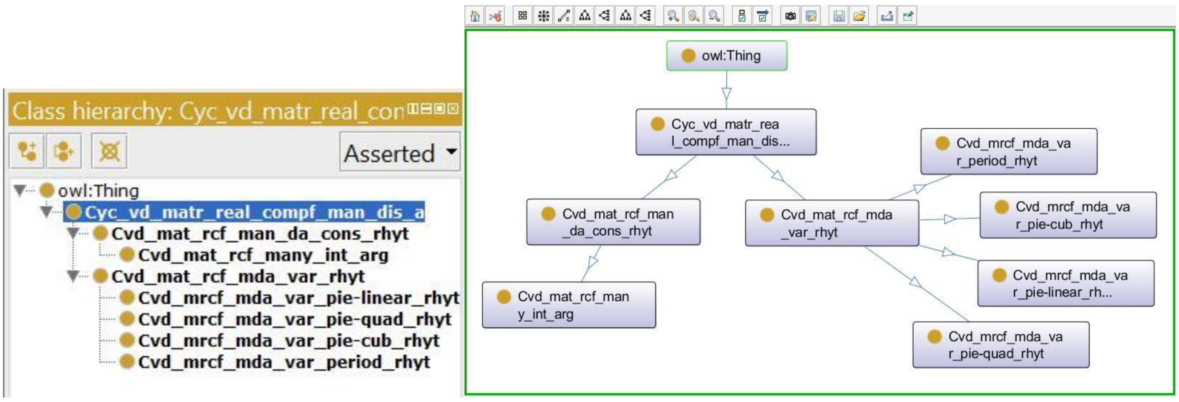

Figure 16: Graphical representation in the Protégé environment for the class "Cyclic value-determined matrix real-component function of many discrete arguments"

4. Conclusions

A formal model of computer ontology of cyclic signal modeling is developed in the work. This formal model is presented as a relational system, which includes a finite set of names of classes of cyclic functional relations; the function of interpretation, which defines the corresponding classes of cyclic functional relations as components of the glossary; the relationship of genus-species subordination, which determines the taxonomy (hierarchy) between different classes of cyclical functional relations; vector of unary relations that define the properties (features, attributes) of the corresponding class of cyclic functional relations, and eight-component vector, the elements of which characterize the state (level) of elaboration (implementation, development) of relevant information technologies for processing and computer simulation (generation) of cyclic signals within the corresponding class of cyclic functional relations.

Based on the developed formal model of computer ontology of mathematical models of cyclic signals in the Protégé environment, a prototype of this ontology was built, which lays a solid technological foundation for creating an onto-oriented knowledge base of expert decision support system in correct and reasonable choice solving specific problems of research of cyclic signals within the framework of deterministic, stochastic, fuzzy and interval model approaches (paradigms).

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