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Development of Conceptual Modeling Method to Solve the Tasks of Computer-Aided Design of Difficult Technical Complexes on the Basis of Category Theory

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Abstract

Background/Objectives: Today much attention is paid to the investigations in the sphere of computer-aided design (CAD), as the automation of difficult technical complexes (DTC) helps improve efficiency, quality and reliability.

Methods: Over the recent years a great number of CAD methods other than classical have been developed. They become more complex and formalized; their implementation is associated with a large number of calculations; they are characterized by invariance in terms of the complexity of the designed system, etc. However, it has to be noted that modern requirements to DTC operations have set principally new problems that have to be solved in the process of DTC design. Thereat, to meet these requirements, it is often necessary to stand back from the classical principles of DTC design that have been formulated over half a century ago. In this context there is a great interest in applying the DTC development technologies that would help meet the set requirements.

Findings: Founded on the category theory, this study suggests an approach to representing different-type DTC development technologies in a unified form convenient for their integration and coordination within the framework of DTC CAD cycle. Universal theoretical-categorical semantic mathematical models of those technologies have been suggested. According to the category theory, the systemic units (components, subsystems, systems, etc.) are the objects of the relevant categories; the operations are morphisms, the complex technological procedures are diagram structures. In the course of establishing structural alignment of different-type procedures that are predetermined within different categories the relevant functors of the categories have to be determined. Thus, the construct of the category theory enables clear and compact formalization of DTC CAD task.

Applications/Improvements: The materials of the study are of practical value for the specialists engaged in solving DTC CAD tasks.

Keywords: Computer-Aided Design; Category Theory; Information Technologies; Mathematical Model; Conceptual Modeling

INTRODUCTION

Nowadays, the scientific investigations aimed at development and implementation of new information technologies (IT) in the sphere of computer-aided design (CAD) of difficult technical complexes (DTC) are extremely important [1]. This is explained by the fact that DTC CAD is believed to be one of the fundamental ways to improve the labor efficiency of designers and to boost quality and reliability of the obtained results simultaneously.

Modern requirements to DTC operations have stipulated the utterly new problems that have to be resolved in the course of DTC development. Thereat, the activities aimed at meeting these requirements often have to deviate from classical DTC development principles established as long back as half a century ago. In this regard much attention is now paid to the application of such DTC design technologies that could help meet these requirements. These technologies are founded on the idea of creating a sufficiently large number of mathematical models (MM) [2]. Besides, these technologies necessarily contain the tools enabling fast stepwise transformation of MM. Such technologies include the following: domain engineering; aspect-oriented software development (AOSD); model-driven engineering (MDE); distributed computing [3-6]. To employ these technologies for DTC CAD purposes, they have to be scaled or adjusted to become capable of manipulating a great number of complex and different-type models [7]. And this is what comprehensive automation is intended for. In this context, to create DTC CAD technologies, a single theoretical basis should be developed to describe the mechanisms of scaling, to formulate and to prove their basic properties, without having to “mess” with the details of particular MM structures.

It should be noted that the bases of many formal methods of modern engineering are represented by miscellaneous “heavy” mathematical means which have been adjusted to different isolated paradigms employed in programming. Due to this reason they often are poorly compatible with each other.

The abovementioned general purpose technologies that can generate satisfactory typical solutions usually evolve ad hoc (i.e. they are designed for solving some particular task and are not capable of generalization or adaptation to solve other tasks) [8, 9]. Consequently, establishment and development of theoretical basis of DTC CAD technologies that would be spared from the abovementioned disadvantages is now a very important scientific problem. In other words it is crucial to find the universal formal way to describe different technologies which would be convenient for designing complex heterogeneous systems to integrate and coordinate these technologies.

The solution to this task depends on the choice of mathematical tools to be used for modeling and analyzing the abovementioned technologies.

CONCEPT HEADING

Classical way of using for mathematical modeling differential equations and minimizing composite functions that are usually used, for example, to solve physical tasks in this case will be of no avail, inasmuch as there are not any suitable analogues of statistical regularities, no conservation laws, no variation principles, etc [10]. However, there is an alternative approach founded on the “observation that the majority of systems possess (or can reconstruct) the history of their being made from some certain initial components” [11]. Knowing MM components and the technological operations that are required for the development of the system, the designer can calculate the integral characteristics of the designed system using the formal analogs of assembly drawings or “megamodels” that formally represent the directed graphs (diagrams). In these graphs, the nodes correspond to the components and the edges correspond to technological operations. Large graphs have to be generated and processed. However, in some cases it is impossible to reflect these graphs in full, and only some structural limitations can be described. The powerful tools for synthesis and analysis of such graphs have been developed on the basis of the category theory that represents a subsection of higher algebra [11]. According to classical postulates this theory “starts with the observation that many properties of mathematical systems can be presented simply and uniformly by means of diagrams” [12]. According to this theory, the systemic units (components, subsystems, systems, etc.) are objects for the relevant categories; the operations are morphisms; the complex technological procedures are diagram structures [8]. In the course of structural alignment of different-type procedures predetermined within different categories the relevant functors of the categories are determined.

Besides, modern universal algebra is formally a part of the theory of heterogeneous (many-sorted or polybasic) algebraic systems that possess random signature and form the aggregate of suitable mathematical categories. This approach combines the theory of abstract types of data with the theory of CAD. Algebraic systems make it possible to develop a great number of MMs and the methods to design them [11]. The logic theory provides the tools for constructing these MMs. Hence, the category-focused perspective makes it possible to perceive the family of polybasic algebraic systems not as a random aggregate, but as a new reasonably structured algebraic system.

Thus, in view of the above, the tools of the category theory enable clear and compact formalization of DTC CAD task [13].

RESULTS

Application of Category Theory to Solve DTC CAD Tasks

Dialectic principle that is applied within the category theory and that requires that mathematical objects should be perceived through their relations to other objects (i.e. the properties of the objects are predetermined by setting the family of object’s connections with other objects, by contrast to the approach when the properties of the object are determined through its elements, i.e. by specifying its internal structure) made it possible to apply categorical approach in representing the system of knowledge in DTC CAD task.

Specific objects can represent different aggregates-categories; therefore, any selected object can be regarded from different perspectives. Hence, the task of knowledge representation can be solved using the methods of the category theory.

Today it is believed that knowledge can be represented as a conglomerate of the areas, correlation and reflection systems that possess fewer limitations in terms of the requirements to the completeness of information about the object.

The task of knowledge representation based on categorical approach assumes that the represented knowledge about the subject area is structured as systemic notions related to the definitions and to the knowledge that follows from those definitions.

The category theory provides mathematical tools to reflect the logic of notions and semantics [14]. To represent the selected notion, algebraic object (category) is constructed which potentially most fully represents the knowledge about the subject of the notion that follows from the definition of this notion. Besides, the finite approximation is built for the category that reflects the already existing knowledge about the represented notion and that is really reflected in the system of representations.

Thus, when categorical approach is used for the purposes of knowledge representation, the algebras featuring larger set of operations are applied; thereat, this set of operations predetermines a certain topos structure and reflexive category of this algebra [15]. Hence, these tools can be applied not only for the purposes of reflecting the knowledge about external objects, but also for reflecting the knowledge about the means and methods of knowledge representation, i.e. it is possible to obtain the knowledge about the whole system of knowledge representation.

The objects of suitable category (formal models) can be correlated with technological artifacts, and the morphisms that reflect the objects-areas (inputs) into the objects-co-areas (outputs) can be correlated with technological processes [16]. Different shifts from one technology to another can be represented as functors, provided that the structures of the processes remain the same. In these categories the diagrams (“megamodels”) are responsible for the procedures of complex model synthesis [17]. Hence, based on their analysis, rational typical solutions can be obtained. For this purpose automated tools can be applied [18]. Thus, theoretical-categorical constructions have to be built and they should correspond most precisely to the key procedures. Then their principal properties that are most important from practical perspective have to be proved. Generalized models of this type are very rare in public domain literature. Individual categories described with particular formal methods are much more common.

Development of Conceptual Simulation Method

The efficiency of automation of intellectual production processes, for example, of research and development activity, cannot be improved without identifying the fundamental laws based on which these processes operate. The required solutions should be searched based on the correlations between automation and technical production evolutions.

One of the solutions to the task of intellectual production process automation is represented by gradual development of the methodology of intellectual labor automation based on semiotic approach.

Application of semiotic approach to solve the principal task of automation that implies the transition from natural language representation of specialist's knowledge toward their formal language representation in computing environment made it possible to formulate the adequacy of this transition as synonymy of character representations.

The principal idea of the methodology of intellectual labor automation implies generation of the sequence of representations from initially formed conceptual models that possess three levels of abstraction (abstract, object, specific) into the formalized models (infological and datalogical). Figure 1 shows the schematic of automation methodology for intellectual production process.

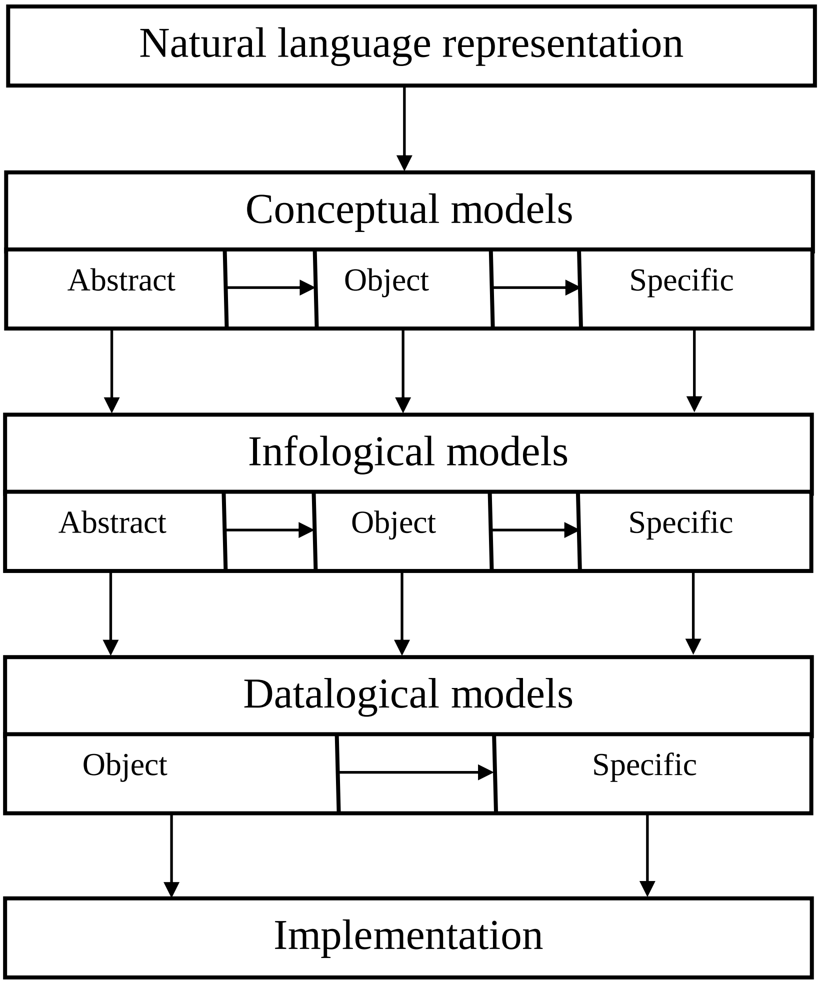

Figure 1. Schematic methodology of intellectual production process automation

This study presents the method of developing models at the stage of general conceptual representation.

Initial conceptual representation of the applied task makes it possible to determine the basis for interpreting the data that are used in the process of its automated solution. Besides, it also solves the problem of establishing the unity of sense for any formal language representations in this task.

Development of the categories for the stage of conceptual simulation which is the basis for the representation of system of knowledge of research and development tasks (R&D T) includes the solutions to the tasks as follows:

- establishing methodological, theoretical and practical foundations;
- identifying the contents and the structure of conceptual models;
- revealing the regularities occurring in the course of formation and integration of conceptual models.

The results of the investigations show that methodological foundations are as follows:

- methodology of DTC formation founded on the assumption that the quality of creation of any DTC depends on the quality of and coordination between design, technological and production environments of its development. Besides, there should be alignment between different-type objects, for example, DTC and its components, organizational and other elements;
- structure of an abstract task of DTC which is the minimal notional structure that makes it possible to represent any process in DTC to the preset degree of details by means of adding different objects to the components of the task;
- cognitive theory.

The investigations also show that theoretical foundations are as follows:

- category theory;
- artificial intellect theory, particularly, the law of cyclic cognition formulated within this theory;
- concept theory.

The investigations revealed the specific characteristics of research and development activities that establish practical foundations.

The results of DTC conceptual simulation supported by the methodology of industrial DTC development are split in three levels of abstraction: abstract, object and specific.

Abstract level is responsible for general representation of knowledge systems.

Object level ensures the representations of specific subject area (SA) knowledge systems.

Specific level operates with factual information.

A set of morphisms of representations (morphisms, arrows) of conceptual models at any level includes the family of structural connections with the objects.

According to the developed approach, in this study the model at any level of abstraction represents principal initial information. The models themselves are represented as mathematical categories defined earlier.

The set of the representations of conceptual models consists of two parts: common conceptual representation (CCR) and conceptual representation of subject task (CRST). CCR predetermines the structure of the knowledge system at different levels of abstraction, and CRST predetermines the construction of the knowledge system of some specific SA. CCR covers the conceptual models of all three levels of abstraction that are connected to each other through their components. CRST covers the conceptual models of object and specific levels of abstraction that are also connected through their components. This study considers the representations of CCR. The representations of CRST will be analyzed in the next study.

Development of Categories at the Stage of Common Conceptual Representation

Common conceptual representation includes a set of formally written categories (models) at three levels (abstract, object and specific) which can be described using CCR structure. There are non-member connections between all categories.

Schematically, at i – level of abstraction category CCR_i is written as shown in Figure 2.

Formally, CCR shall be presented as follows:

$$CCR = \left(CCR_1, CCR_2, CCR_3\right),$$

Where CCR_1 – abstract level;

CCR_2 – object level;

CCR_3 – specific level.

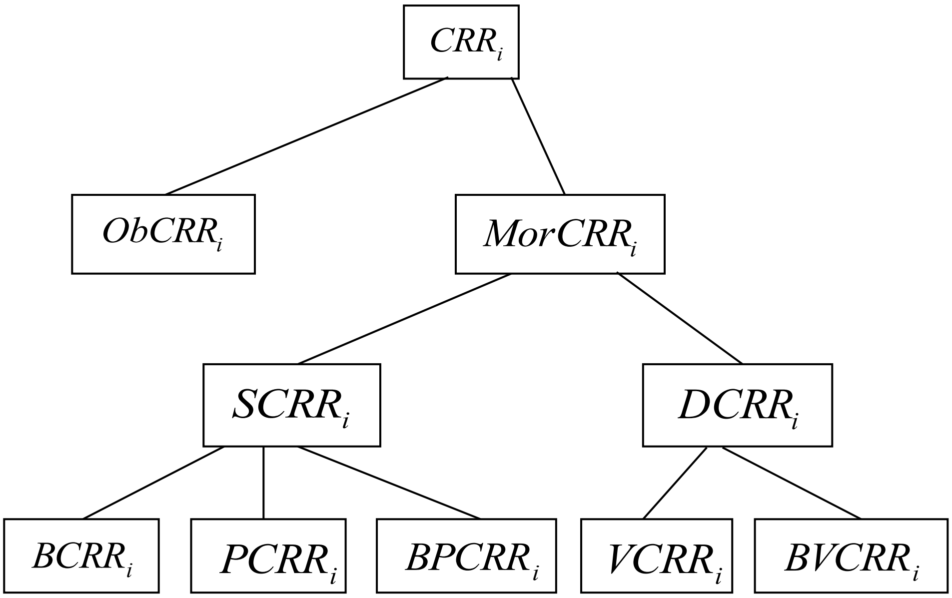

Figure 2. Conceptual model of CCR_i at i – level of abstraction

Then, at i – level of abstraction CCR_i will be formally written as follows:

$$CCR_i = \left(ObCCR_i, MorCCR_i\right);$$

Where $ObCCR_i$ – a set of models (objects) at i – level;

$MorCCR_i$ – a set of morphisms (relations) at i – level;

$MorCCR_i = SCCR_i \cup DCCR_i$;

$SCCR_i = \left(BCCR_i, PCCR_i, BCCR_i\right)$– static relations at i – level;

$BCCR_i \subset ObCCR_i \times ObCCR_i$ – binary relations at $ObCCR_i$;

$PCCR_i$ – schematics at $ObCCR_i$;

$BPCCR_i \subset PCCR_i \times PCCR_i$ – binary relations at $PCCR_i$;

$DCCR_i = \left(VCCR_i, BVCCR_i\right)$ – dynamic relations at objects;

$VCCR_i$ – limitations of i – level of abstraction;

$BVCCR_i \subset VCCR_i \times VCCR_i$ – binary relations at $VCCR_i$.

The limitations reflect the existence of representations (morphisms):

$$f : ObCCR_i \to VCCR_i.$$

Consider the elements of CCR structure in more detail.

The leading role of conceptual simulation at abstract level is illustrated in Figure 1.

$ObCCR_1$ represents a set of Information Objects (IO): $ObCCR_1 = \left\{m_{1,i}\right\}$. Set of IO is created based on the results of the analysis of all specific features observed in the course of knowledge and information representation during DTC CAD.

$ObCCR_2$ represents a set of Subject Objects (SO): $ObCCR_2 = \left\{m_{2,i}^{(j)}\right\}$.

$ObCCR_3$ represents a set of Representative Subject Objects (RSO): $ObCCR_3 = \left\{m_{3,i}^{(j,k)}\right\}$.

$BCCR_1 \subset ObCCR_1 \times ObCCR_1$ is a set of binary relations at $ObCCR_1$ which helps determine the composition, align and arrange set IO: $BCCR_1 = \left\{m_{1,i}, m_{1,j}\right\}$.

$BCCR_2 \subset ObCCR_2 \times ObCCR_2$ is a set of binary relations at $ObCCR_2$ which helps determine the composition, align and arrange set SO: $BCCR_2 = \left\{m_{2,i}^{(j)}, m_{2,i}^{(k)}\right\}$.

$BCCR_3 \subset ObCCR_3 \times ObCCR_3$ is a set of binary relations at $ObCCR_3$ which helps determine the composition, align and arrange set RSO: $BCCR_3 = \left\{m_{3,i}^{(j,k)}, m_{3,i}^{(k,n)}\right\}$.

$PCCR_1$ is a set of schematics IO at $ObCCR_1$: $PCCR_1 = \left\{p_{1,i}\right\}$.

$PCCR_2$ is a set of schematics SO at $ObCCR_2$: $PCCR_2 = \left\{p_{2,i}^{(j)}\right\}$.

$PCCR_3$ is a set of schematics RSO at $ObCCR_3$: $PCCR_3 = \left\{p_{3,i}^{(j,k)}\right\}$.

$BPCCR_1 \subset PCCR_1 \times PCCR_1$ is a set of binary relations at $PCCR_1$ which helps determine the composition, align and arrange the set of schematics IO: $BPCCR_1 = \left\{p_{1,i}, p_{1,j}\right\}$.

$BPCCR_2 \subset PCCR_2 \times PCCR_2$ is a set of binary relations at $PCCR_2$ which helps determine the composition, align and arrange the set of schematics SO: $BPCCR_2 = \left\{p_{2,i}^{(k)}, p_{2,j}^{(n)}\right\}$.

$BPCCR_3 \subset PCCR_3 \times PCCR_3$ is a set of binary relations at $PCCR_3$ which helps determine the composition, align and arrange the set of schematics RSO: $BPCCR_3 = \left\{p_{3,i}^{(k,l)}, p_{3,j}^{(l,n)}\right\}$.

$VCCR_1$ – is a set of limitations of abstract level and it represents a set of Classes of Dependences (CD): $VCCR_1 = \left\{v_{1,i}\right\}$.

$VCCR_2$ – is a set of limitations of object level and it represents a set of Types of Dependences (TD): $VCCR_2 = \left\{v_{2,i}^{(j)}\right\}$.

$VCCR_3$ – is a set of limitations of specific level and it represents a set of Representative Types of Dependences (RTD): $VCCR_3 = \left\{v_{3,i}^{(j,k)}\right\}$.

$BVCCR_1 \subset VCCR_1 \times VCCR_1$ is a set of binary relations at $VCCR_1$ which helps determine the composition, align and arrange the set of schematics CD: $BVCCR_1 = \left\{v_{1,i}, v_{1,j}\right\}$.

$BVCCR_2 \subset VCCR_2 \times VCCR_2$ is a set of binary relations at $VCCR_2$ which helps determine the composition, align and arrange the set of schematics TD: $BVCCR_2 = \left\{v_{2,i}^{(j)}, v_{2,j}^{(k)}\right\}$.

$BVCCR_3 \subset VCCR_3 \times VCCR_3$ is a set of binary relations at $VCCR_3$ which helps determine the composition, align and arrange the set of schematics RTD: $BVCCR_3 = \left\{v_{3,i}^{(j,k)}, v_{3,q}^{(l,n)}\right\}$.

Determine the dependences between the sets of objects and limitations:

$$\begin{aligned} VCCR_1 &= \left\{v_{1,i}\right\} \\ &= \left(\left\{\left(m_{1,i}\right) \,\&\, \left(m_{1,i}, m_{1,j}\right)\right\} \mid m_{1,i}, m_{1,j} \in ObCCR_1 \,\&\, \left(m_{1,i}, m_{1,j}\right) \in BCCR_1\right) \end{aligned}$$

– a set of limitations at abstract level between IO and CD.

$VCCR_2 = \left\{v_{2,i}^{(j)}\right\} = \left\{m_{2,1}^{(j)}, m_{2,2}^{(j)}, \ldots, m_{2,k}^{(j)}\right\} \& W$ – is a set of limitations at object level between SO and TD;

Where $m_{2,i}^{(j)} \in ObCCR_2, \quad i = 1, \ldots k; \quad k = \left|ObCCR_2\right|$.

W – conditions that predetermine connections of SO:

$$W = \left\{\begin{aligned} &\left(\left\{m_{2,i}^{(j)}\right\} \in ObCCR_2\right), \left(\left\{m_{2,i}^{(j)}, m_{2,l}^{(k)}\right\} \in BCCR_2\right), \\ &\left(\left\{p_{2,i}^{(j)}\right\} \in PCCR_2\right), \left(\left\{p_{2,i}^{(j)}, p_{2,l}^{(k)}\right\} \in BPCCR_2\right) \end{aligned}\right\}$$

$VCCR_3 = \left\{v_{3,i}^{(j,k)}\right\} = \left\{m_{3,1}^{(j,l)}, \ldots, m_{3,k}^{(j,l)}\right\} \& Q$ – is a set of limitations at specific level between RTD,

Where $m_{3,i}^{(j,l)} \in ObCCR_3, \quad i = 1, \ldots k; \quad k = \left|ObCCR_3\right|$,

Q – conditions that predetermine the connections between structural and contextual specific objects:

$$\begin{aligned} Q = \Big\{&\left(\left(\left\{m_{3,i}^{(j,l)}\right\} \in ObCCR_3\right), \left(\left\{m_{3,i}^{(j,l)}, m_{3,u}^{(s,r)}\right\} \in BCCR_3\right),\right. \\ &\left.\left(\left\{p_{3,i}^{(j,l)}\right\} \in PCCR_3\right), \left(\left\{p_{3,i}^{(j,l)}, p_{3,u}^{(s,r)}\right\} \in BPCCR_3\right)\right)\Big\}. \end{aligned}$$

The availability of the non-empty set of dependences for developing CCR models is based on the fundamental principles as follows:

- direction of cognition processes, from individual (specific) observations (assisted by generalization) to abstract thinking; from general to the selected, from abstract to individual (specific) [19].
- a set of limitations at specific level between RTD,

Where $m_{3,i}^{(j,l)} \in ObCCR_3, \quad i = 1, \ldots k; \quad k = \left|ObCCR_3\right|$,

Q – conditions that predetermine the connections between structural and contextual specific objects:

- negation of negation law, analysis of the specific, synthesis of a single unit;

- the law of cyclicality of scientific cognition [19].

$$W=\left\{\left(\left\{m_{2,i}^{(j)}\right\}\in ObCCR_2\right),\left(\left\{m_{2,i}^{(j)},m_{2,l}^{(k)}\right\}\in BCCR_2\right),\right.$$
$$\left.\left(\left\{p_{2,i}^{(j)}\right\}\in PCCR_2\right),\left(\left\{p_{2,i}^{(j)},p_{2,l}^{(k)}\right\}\in BPCCR_2\right)\right\}.$$

$$VCCR_3=\left\{v_{3,i}^{(j,k)}\right\}=\left\{m_{3,1}^{(j,l)},\ldots,m_{3,k}^{(j,l)}\right\}\&\,Q$$

$$Q=\left\{\left(\left\{m_{3,i}^{(j,l)}\right\}\in ObCCR_3\right),\left(\left\{m_{3,i}^{(j,l)},m_{3,u}^{(s,r)}\right\}\in BCCR_3\right),\right.$$
$$\left.\left(\left\{p_{3,i}^{(j,l)}\right\}\in PCCR_3\right),\left(\left\{p_{3,i}^{(j,l)},p_{3,u}^{(s,r)}\right\}\in BPCCR_3\right)\right\}.$$

Given the fact that a conceptual model at any level includes both static and dynamic relations, there is a task to identify the regularities that occur in the process of formation of conceptual structures at the elements and schematics of the objects. Besides, there is another task to formulate the systems of limitations.

Any regularity includes the process of structure formation at any level of abstraction unifying all structures into a single whole.

The regularities discovered in the course of static relation formation include the requirements that the morphisms should be formed between the objects and between the schematics of the objects. As a result, binary connections are established for the selected pair of objects and for the selected pair of schematics.

In the course of the process of binary relation formation between the objects at any level of abstraction the effect of repetitive abstraction has been discovered that follows from the effects of the cyclicality law.

The set of objects can be split into elementary schematics due to the repetitive nature of abstractions.

As a result of the process of static relation formation, the conceptual structures emerge that reflect the “pedigree” of the attributes of the real world objects with their meanings and their structure at any level of abstraction.

Methodological basis (foundations) of the availability (existence) of the limitations in conceptual structures is represented by the ideas of fundamental and applied laws (regularities) that have been implemented within the concrete task of DTC CAD in the form of the limitations on the abstract task. Based on the cyclicality law, such limitations also act at other levels of complexity of semantic representations.

In conceptual models the levels of complexity in semantic representation create the regularities of the formation of limitations (Figure 3).

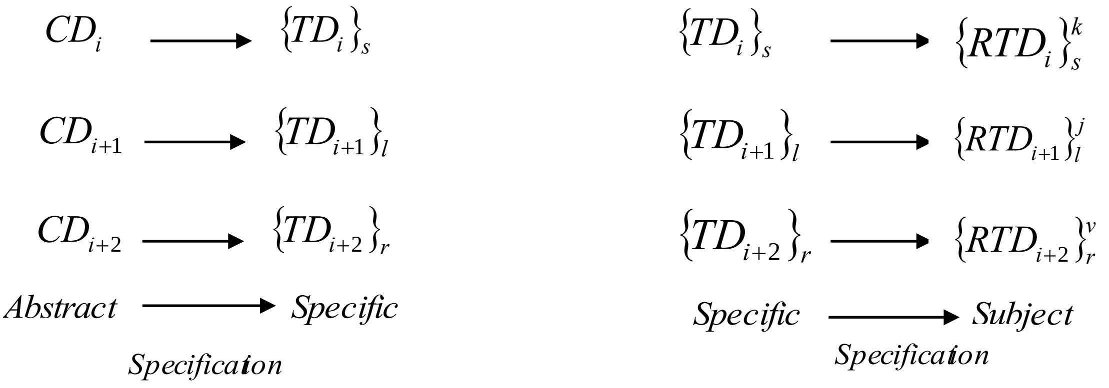

Figure 3. Basic assumptions for designing morphisms for *CCR* limitations

The mechanism of abstraction serves as the basis of the existing interrelations between the models at different level.

Given the fact that the transition from general level (abstract) toward individual (specific) level occurs based on the results of the analysis, in any pair of the models the interrelations are predetermined by such abstraction as “specification” for all component elements. This process can be presented schematically as follows:

$CCR_i \to CCR_{i+1} \quad (i=1,2)$ т.е.

$$ObCCR_i \to ObCCR_{i+1},\ BCCR_i \to BCCR_{i+1},$$
$$PCCR_i \to PCCR_{i+1},\ BPCCR_i \to BPCCR_{i+1},$$
$$VCCR_i \to VCCR_{i+1},\ BVCCR_i \to BVCCR_{i+1}.$$

The formal justification of the interrelations between the categories at different levels is represented by the methods of relational algebra. In this case the operation “natural connection” has been applied [11] which, for any correlation between A_1 and A_2, will be put as $A = A_1 \bullet A_2$. This operation makes it possible to obtain new information from the initial correlations. Consequently, based on the above, it would be safe to write down the following:

$$BCCR_{i+1} = ObCCR_i \bullet ObCCR_{i+1} \bullet BCCR_i,$$

$SCCR_{i+1} = SCCR_i \bullet BCCR_i \bullet BCCR_{i+1},$ – for a set of static operations,

$BVCCR_{i+1} = VCCR_i \bullet VCCR_{i+1} \bullet BVCCR_i,$ – for a set of dynamic operations.

Based on the above, the laws can be formally defined that regulate the transition from the models belonging to the abstract level toward the models that belong to object level; and from the models that belong to object level toward the models that belong to specific level for CCR, i.e. the required functors can be determined.

CONCLUSION

The investigation of the problem of unified representation of different-type models that reflect different levels of generalization or abstraction for applied tasks enabled the formulation of general definition of the models that reveals their composition.

The undertaken investigations of the implementation of the developed method of conceptual simulation to solve the tasks of DTC CAD are founded on modern IT that made it possible to identify a single semantic basis in the form of generalized conceptual models for the tasks in this SA and to estimate the degree of their formalization.

The upcoming investigations in this area will further develop the suggested conceptual simulation method including mathematical categories (models) for conceptual representation of subject-related tasks.

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