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Research Paper

Integrated Modeling of Complex Objects of Geoinformational Monitoring

[1]Igor Patrakeyev, [2]Victor Ziborov, [3]Yuliia Maksymova, [4]Tetiana Yeremenko
[1,2,3]Kyiv National University of Construction and Architecture, 31, Povitroflotsky prospect, 03680, Kyiv
[4] Vinnytsia National Technical University, Khmelnytsky highway 95, Vinnytsia

ABSTRACT: *Geoinformatics gives a new impetus to the development of monitoring theory. This development is due to the fact that geoinformatics uses integrated information processing systems. Modern geoinformation monitoring (GM) is characterized by the expansion of the range of tasks to be solved, as well as the growing needs for the integration of modern observation technologies. In this regard, there is a need for a fundamentally new approach to the GM process, as well as improving its methodological foundations.*
The article discusses an approach to the integration of various types of models of a geoinformation monitoring object based on the use of methods of categorical-functor analysis. This approach allows you to preserve the integrity of the monitoring object representation due to the invariance of the polymodel method of its description. It becomes possible to reduce the problem of studying one type of model to the problem of another type of model.
The article is devoted to the analysis of the polymodel properties of GM. Polymodel makes it possible to increase the efficiency of the process of monitoring and evaluating complex systems based on a multi-model complex of heterogeneous models.
KEYWORDS: *urban environment; integrated modeling; category; geoinformation monitoring; polymodel method*

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I. INTRODUCTION

Analysis of studies on GM shows that it is advisable to use it for monitoring systems [1], monitoring processes and phenomena [2], factor monitoring and monitoring of one-time situations [1]. Each type of monitoring requires the construction of appropriate models. These models determine the assessment of the state of the object, the dynamics of state changes and the prediction of this state.

Polymorphic modeling of complex objects allows you to mutually compensate for the shortcomings of some models and at the same time enhance the positive qualities of other models [3, 4]. The ideological side of polymodel was laid down by the physicist Niels Bohr (1924-1930) when he formulated the principle of "complementarity" [5, 6]. According to this principle, for a complete description of the phenomena of quantum mechanics, it is necessary to use mutually exclusive "additional" information. This "additional" information ultimately composes complete information about the processes and phenomena under study. Niels Bohr concentrated his principle in the statement "Incompatibility is the essence of complementarity" [5, 7, 8].

II. CATEGORIAL APPROACH TO ANALYSIS OF INTEGRATED MODELING OF COMPLEX OBJECTS OF GEOINFORMATIONAL MONITORING

GM has an important property of polymodel, when the same object of monitoring (OM) (or phenomenon, or process) can be represented by dissimilar models.

This property of the GM preserves the integrity of the OM representation due to the invariance of the object description. This will allow you to bring monitoring tasks of one type to tasks of another type. In this case, the consistency of the heterogeneous models of OM is carried out on the basis of the analysis of belonging to a given category of models. A constructive approach to the integration of various types of OM models in the GM system is the use of methods of categorical-functor analysis.

The mathematical apparatus of the theory of categories makes it possible to formalize the structures of a complex system in the form of sets of morphisms and objects of categories of structured sets. Features of category theory can provide an adequate basis for a theory of the GM system in general. A category is a

*Corresponding Author: Abdalftah Elbori
MODES Department Atilim University Turkey

mathematical structure, a special case of which is partially ordered sets. In many cases, a category is conveniently represented as a "generalized partially ordered set" [9].

In category theory, the category $\boldsymbol{K}$ defines the class of objects $Ob(\boldsymbol{K})$, the elements of which are called objects of the category $\boldsymbol{K}$. It is convenient to represent the category $\boldsymbol{K}$ as a labeled directed graph. The nodes of this graph are called $Ob(\boldsymbol{K})$ objects, and the labeled directed edges are called morphisms. Morphisms form the class $Mor\ \boldsymbol{K}$ [9, 10].

Category $\boldsymbol{K}$ is specified under the following conditions:

– a class of objects $A, B, C, \ldots,$ is given, each of which is a set;

– for each pair of objects A, B of category $\boldsymbol{K}$, a set of morphisms $Mor(A, B)$ of object A into object B is given;

– for each triple of objects A, B, C of category $\boldsymbol{K}$, the **composition** (mapping) law is defined:

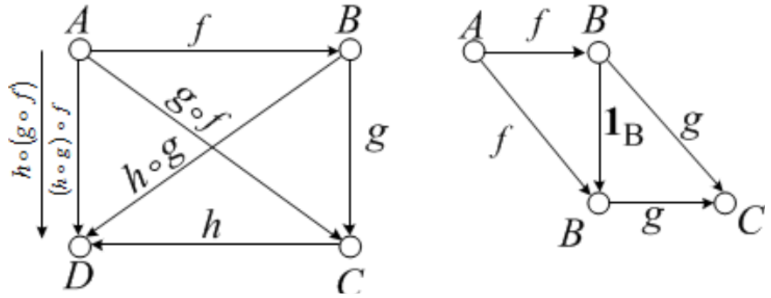
$$Mor(A, B) \circ Mor(B, C) \rightarrow Mor(A, C).$$

The composition of morphisms $f \in Mor(A, B)$ and $g \in Mor(B, C)$ is defined as $f \circ g$ and has the following properties:

— $f \circ (g \circ h) = (f \circ g) \circ h$ the **associativity** law is satisfied, (рис. 1 a);

— for each object of category $\boldsymbol{K}$ ($B \in Ob(\boldsymbol{K})$) there is an element $\mathbf{1}_B \in Mor(A, C)$, such $\mathbf{1}_B \circ f = f \circ \mathbf{1}_B$, $g \circ \mathbf{1}_B = g \circ \mathbf{1}_B$ for any $f \in Mor(A, B)$, $g \in Mor(B, C)$.

That is, for each object of category $\boldsymbol{K}$, we put in correspondence the identical relation. Thus, the **commutativity** law is fulfilled, (Fig. 1. b).



a) b)

Figure 1: Examples of associative (a) and commutative (b) diagrams of morphisms

As objects of category $\boldsymbol{K}$, we define the set of heterogeneous models $M = \{M^i\} \equiv Ob(\boldsymbol{K})$. Here $i = \overline{1, n}$, n is the number of heterogeneous computational models [11]. Such models can be [12, 4]: pattern recognition models, predicate logic models, frame models, georelational models, gravity models, Monte Carlo models, cellular automata models, models based on genetic algorithms, material flow analysis models, footprint analysis models, models of the "goal tree" type, fuzzy optimization models and others. These models are used for various types of monitoring and evaluation of objects, processes and phenomena of the urban environment.

Between each pair of objects $M^i \in Ob(\boldsymbol{K})$ and $M^j \in Ob(\boldsymbol{K})$ we define a set of morphisms:

$\Delta = Mor(M^i, M^j)$, $\delta_k \in \Delta$.

For any triple of objects $M^i \in Ob(\boldsymbol{K})$, $M^j \in Ob(\boldsymbol{K})$, and $M^l \in Ob(\boldsymbol{K})$, a composition of morphisms is defined:

$$\delta \in Mor(M^i, M^j) \circ \varphi \in Mor(M^j, M^l) = \delta \circ \varphi \in Mor(M^i, M^l).$$

For each of the objects M^i, we define a unit morphism:

$\mathbf{1}_{M^i} \in Mor(M^i, M^i)$.

In fig. 2 shows an example of a given category of $\boldsymbol{K}$ heterogeneous models of the monitoring object in the form of a commutative diagram.

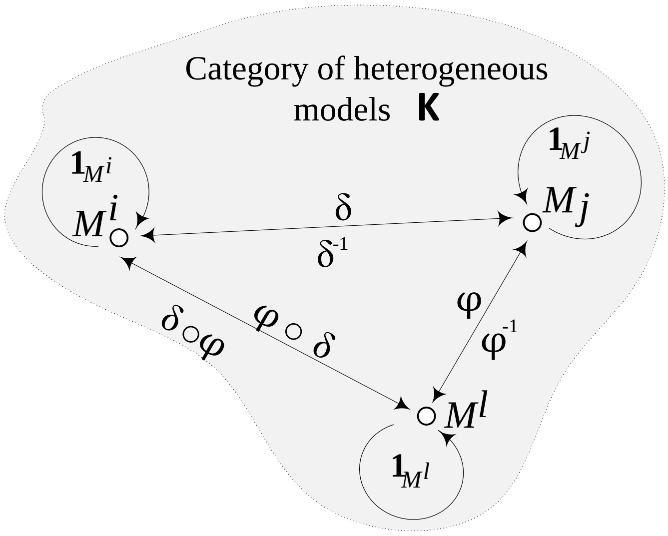


Figure 2: Graphical interpretation of the category $\boldsymbol{K}$ of models of the monitoring object in the form of a commutative diagram

Apply the taxonomy problem to category $\boldsymbol{K}$. Then, on the basis of the feature space [13], it is possible to form a category of small categories (CSC) ***Cat***:

$P^n = \{p_1, p_2, \dots, p_i, \dots, p_n\}$.

As an object of CSC $\boldsymbol{Cat}$, we define classes of heterogeneous models $\mathcal{M} = \{\mathcal{M}^v\} \equiv Ob(\boldsymbol{Cat})$, $v = \overline{1,m}$, where m is the number of generated classes of heterogeneous models based on the feature space of P^n.

An example of classes of heterogeneous models can be: class of relationship models, class of process models, class of object models, semantic model class, dynamic model class, data model class, class of static models, class of multi-agent models and others.

Computational models that belong to the category of one class of heterogeneous models $M^i, M^j \in \mathcal{M}^v \equiv Ob(\boldsymbol{Cat})$ are isomorphic (similar) in a given feature space of P^n. The figure 3 shows the structure, which is formed on the basis of the feature space P^n CSC ***Cat*** classes of heterogeneous models.

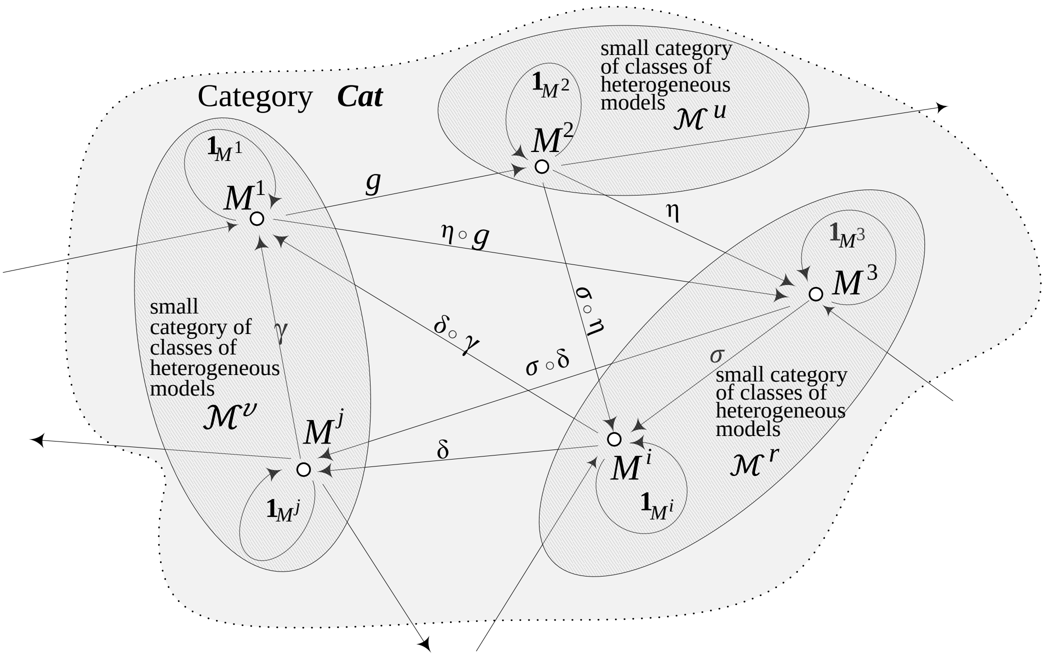


Figure 3: The structure formed on the basis of the feature space P^n of the category of small categories ***Cat*** in the form of a diagram

Classes of heterogeneous models $\{\mathcal{M}^v\} \equiv Ob(\boldsymbol{Cat})$ in the feature space P^n are homomorphic. That is, one class of models has the ability to be replaced by another class of models.

The polymodel property of a GM system (SGM_{poly}) is defined as a set of categories of classes of heterogeneous models $\mathcal{M}^v$. These categories can be used for model representation of objects of observation using geoinformation monitoring:

$SGM_{poly} = \bigcup_{v\in V} \mathcal{M}^v$.

Here the categories of classes of dissimilar models have the form:

$\mathcal{M}^v = \{M^i |\ \exists_{v\in V}, M^i \in \mathcal{M}^v\}$.

Establishing connections between different categories is carried out using functors. The introduction of functors as a system of relations between different categories (between classes of geoinformation monitoring models) guarantees the consistency of categories (models) and the consistency of monitoring results obtained on their basis. Thus, functors allow you to compare models from different classes of categories and establish relationships between them to achieve the following goals [4]:

− revealing the properties of various classes of models using functor transformations;

− reduction of research models for GM objects of one class to another class of models;

− joint study of the results of the study of GM objects by various categories of model classes and the formation of new categories.

Between the objects $\mathcal{M} = \{\mathcal{M}^v\} \equiv Ob(Cat)$ there are regular mappings of one category to another (functors) [9]. Consider two categories of model classes $\mathcal{M}^v$ and $\mathcal{M}^u$. To each model M^i from the category of the class of models $\mathcal{M}^v$ we associate the model M^i from the category of the class of models $\mathcal{M}^u$. Moreover, to each morphism $\varphi \in Mor(F(M^i, M^l))$ we associate the morphism:

$$F(\varphi) \in Mor(F(M^i)\,, F(M^l))$$

subject to the following equalities:

$F(\mathbf{1}_{M^i}) = \mathbf{1}_{F(M^i)};\quad F(f\circ g) = F(g)\circ F(f).$

Then, according to the definitions of [14], we can say that a **covariant functor** from the category of classes of models $\mathcal{M}^v$ in the category of classes $\mathcal{M}^u$ is given in the form of the system:

$$\begin{cases} F: Ob(\mathcal{M}^v) & \rightarrow & Ob(\mathcal{M}^u) \\ F: Mor(\mathcal{M}^v) & \rightarrow & Mor(\mathcal{M}^u) \end{cases}$$

The concept of a contravariant functor can be obtained by changing the equation $F(f\circ g) = F(g)\circ F(f)$ to the equation $F(f\circ g) = F(f)\circ F(g)$ [9].

Formation of rules for mapping models of a GM object of one class in a model of another class requires the construction of a covariant or contravariant functor $F(\mathcal{M}^v, \mathcal{M}^u)$. The kind of functor depends on the relationship between different kinds of models $\langle M^i, M^j\rangle$. When carrying out multi-model studies of a GM object, the operation of the natural transformation of functors is used [15, 16].

In Figure 3, the functor F connects the models and the morphism of the category $\mathcal{M}^v$ with the models and the morphism of the category $\mathcal{M}^{v+1}$. As a result of this connection, the models M^i, M^j and the morphism f (from the category $\mathcal{M}^v$) obtain their images $F(M^i)$, $F(M^j)$ and $F(f)$ in the category $\mathcal{M}^{v+1}$.

Similarly, the functor G connects models and a morphism of the same category $\mathcal{M}^v$ with models and a morphism of a different category $\mathcal{M}^u$. Also, as a result, the same models and morphism get already different images, namely, $G(M^i)$, $G(M^j)$ and $G(f)$ in the category $\mathcal{M}^u$.

In turn, the images $F(M^i)$, $G(M^i)$, $F(M^j)$ and $G(M^j)$ are connected using morphisms h and h'. In this case, the condition for the commutativity of the diagram composed of the mappings h, h', $F(f)$ and $G(f)$ must be satisfied.

That is, the following equality must be satisfied:

$$h' \circ F(f) = G(f)\circ h$$

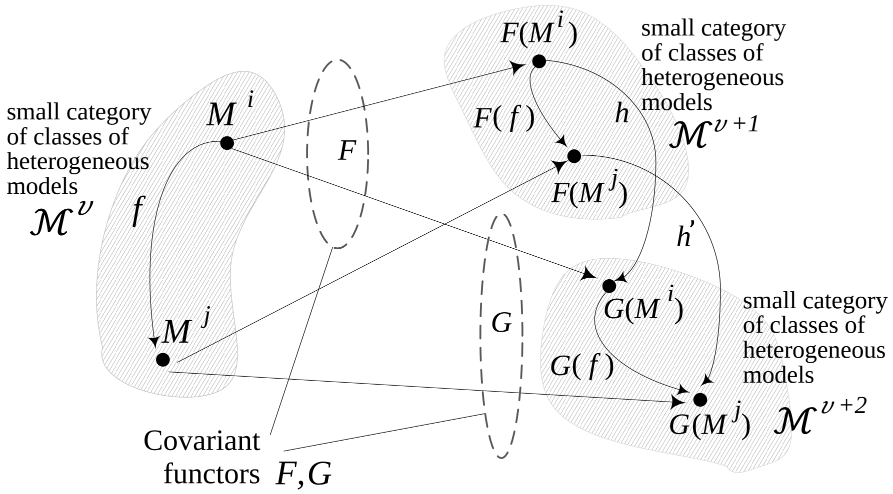


Figure 4: An example of the operation of natural transformation of covariant functors F, G

Now we will illustrate the possibilities of the categorical-functor approach using a simplified example of a poly-model description of the problem of monitoring the state of the urban environment (UE).

Monitoring, assessment and forecasting of the state of the UE are an integral part of the activities of the departments that directly plan the development of the city. For example, the task of modeling and scenario forecasting involves the formation and construction of models based on artificial intelligence methods to overcome information uncertainty in the initial data on the state of the UE components. Further, the constructed information-analytical model can already provide imitation modeling of territorial development based on the use of geographic cellular automata or multi-agent models.

In a polymodel description of the tasks of GM, estimation and forecasting of the state of the UE, the functor $F: \mathcal{M}^{v} \to \mathcal{M}^{v+1}$ provides a transition from the category $\mathcal{M}^{v}$ to its mapping $\mathcal{M}^{v+1}$. The $\mathcal{M}^{v}$ category assigns the class of models based on artificial intelligence methods (these are static models) to the $\mathcal{M}^{v+1}$ category. The category $\mathcal{M}^{v+1}$ defines the class of simulation (dynamic) models.

Thus, the constructed covariant functor $F: \mathcal{M}^{v} \to \mathcal{M}^{v+1}$ establishes a correspondence between the vertices of the graph (static models) $x_i \in Ob(\mathcal{M}^{v})$ and dynamic models $z_i(t) \in Ob(\mathcal{M}^{v+1})$. In addition, the F functor provides a transition between morphisms $\langle x_i, x_{i+1}\rangle \in Mor_{\mathcal{M}^{v}}(X_i, X_{i+1})$ of the $\mathcal{M}^{v}$ category and morphisms $\Omega_{i,i+1} \in Mor_{\mathcal{M}^{v+1}}(F(\langle x_i, x_{i+1}\rangle))$ of the $\mathcal{M}^{v+1}$ category.

Figure 5 shows a graphical interpretation of the functor mapping $F: \mathcal{M}^{v} \to \mathcal{M}^{v+1}$ of the small category $\mathcal{M}^{v}$ of the class of models. This mapping is based on artificial intelligence techniques. As a result, we get a small category $\mathcal{M}^{v+1}$ of the class of simulation models for predicting the state of the UE.

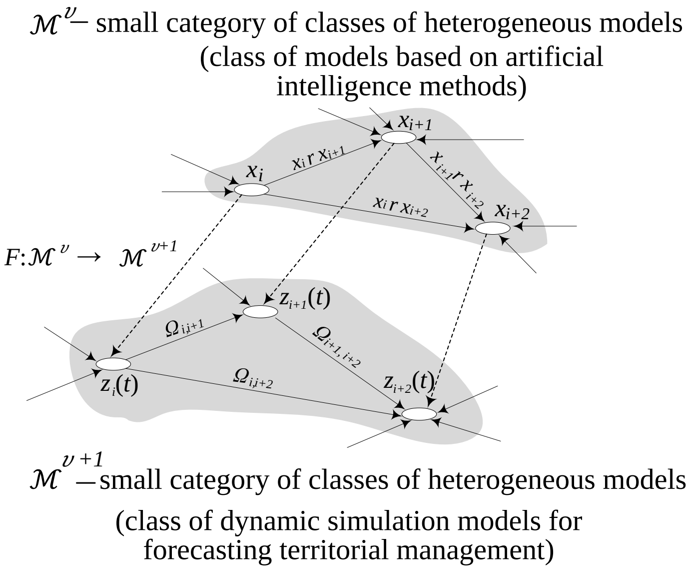


Figure 5: Graphical illustration of the functorial mapping of a small category $\mathcal{M}^{v}$ of a class of models based on artificial intelligence methods into a small category $\mathcal{M}^{v+1}$ of a class of dynamic simulation models for forecasting territorial management

The functor formation procedure $F: Ob(\mathcal{M}^{v}) \rightarrow Ob(\mathcal{M}^{u})$ allows you to build and process hypotheses about the knowledge of one category of a class of models, applied knowledge to another category of a class of models. This fact significantly expands the theoretical and practical possibilities of obtaining geoinformational knowledge about the GM object.

III. EXAMPLES OF PRACTICAL IMPLEMENTATION OF INTEGRATED MODELING OF COMPLEX OBJECTS OF GEOINFORMATION MONITORING

Thus, the polymodel property characterizes GM as a multi-model complex of heterogeneous models. This complex allows you to apply the following strategy of operating with heterogeneous models in the process of GM [17]. If the model of the GM object is the result of deductive inference (that is, it is built from general to specific), then such a model provides the formation of a detailed result of modeling the monitoring object. And if the model of the GM object is the result of inductive inference (the model is built from the particular to the general), then this approach provides a more aggregated simulation result. An example of the consistency of heterogeneous models of a GM object is illustrated in Figure 6.

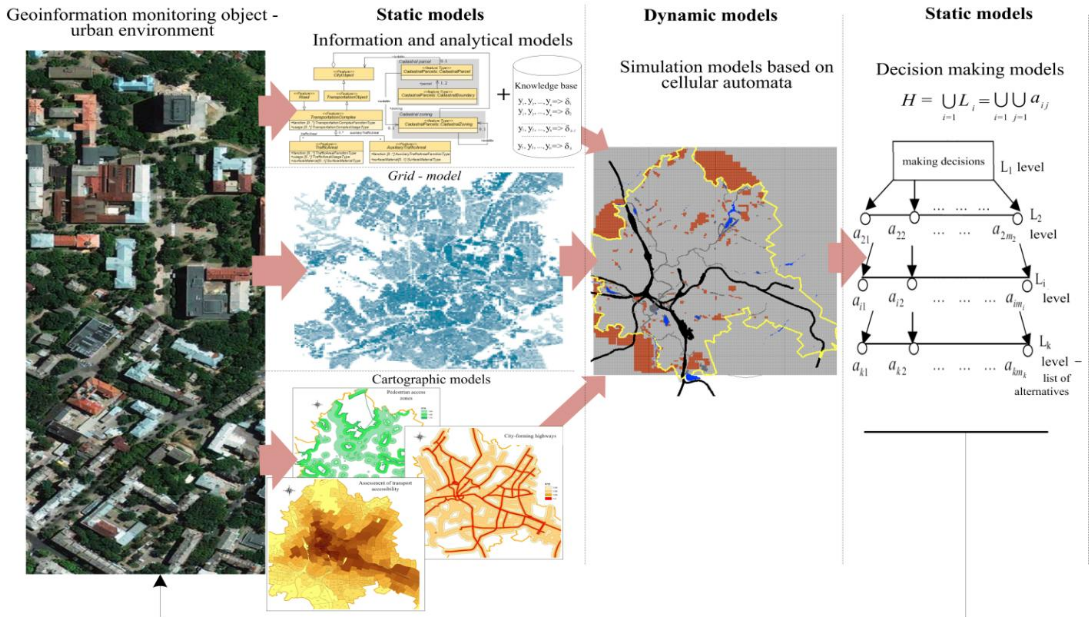
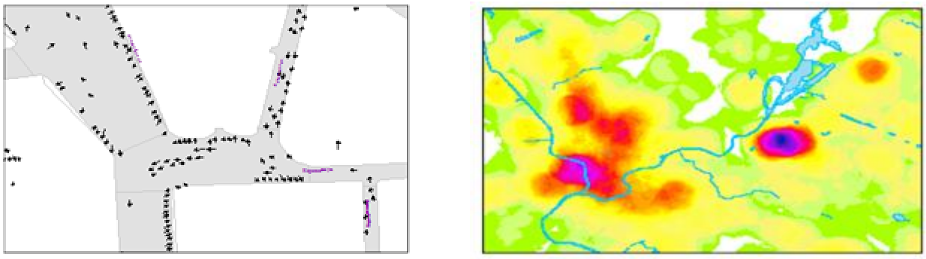


Figure 6: An example of the consistency of heterogeneous models of a GM object

Below we give an example of a GM and an estimate of the density of vehicles in an urban environment based on aerial photography of the territory. Traditional methods of modeling traffic flows rely on local point surveys in separate distributed locations of the road network. Practical experience shows that the use of GM, for example, based on aerial photographs, indicates its high efficiency.

For the city of Kharkov, in order to obtain initial information, an orthophotomap was used based on aerial photography materials. This made it possible to generate a vector linear layer of vehicles for the entire city in the ArcGIS Desktop software environment (Figure 7, a)) [18]. The grid model made it possible to identify the main anomalies in the distribution density of vehicles in the city of Kharkov (Fig. 7, b)), to analyze and classify the road network by the volume of traffic (Fig. 8 a), b)).



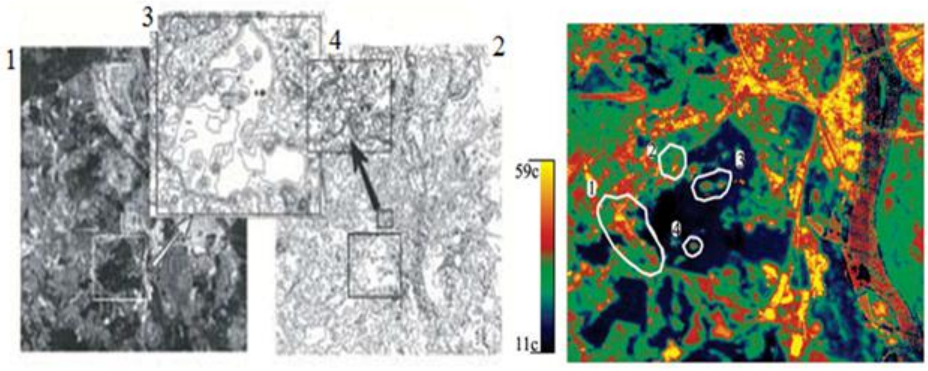
a) b)

Figure 7: Vector model of the distribution of vehicles (a),
grid model of vehicle density (1000, 1500, 2000, 2500, 3000 vehicles / ha (b))

a) b)

Figure 8: Raster model of anomalous zones of vehicle density (a),
classification of the road network according to the volume of
traffic (vehicles / 100 m) (b)

For urbanized areas, the formation of so-called "heat islands" is characteristic [19, 20]. Their formation is associated with the difference in near-surface temperatures between the city center and its periphery. From the processing of space data, raster models are obtained with the subsequent construction of cartographic models of thermal fields. Analysis of thermal fields allows you to identify, for example, the causes of environmental problems in the city (Figure 9).



a) b)

Figure 9: An example of a cartographic model of the surface thermal field in the southern part of the city of Kiev (Landsat 5 TM 05/29/2011). Raster model of the thermal field and underlying surface (a). Thermal field shown using a black to yellow gradient (b) [20]

IV. CONCLUSION

1. The modern urban environment is characterized by increasing complexity. The number of primary indicators assessed is in the tens of thousands. At the same time, topological and morphological indicators about the state of the urban environment are superimposed in real time. In addition, on the one hand, monitoring objects are characterized by heterogeneity, incompleteness and inconsistency of data, and on the other hand, they have information redundancy. All this leads to the understanding that it is necessary to improve the methodological foundations of geoinformation monitoring.

2. The constructed model of the monitoring object is an information basis for obtaining new knowledge about the research object. Meanwhile, each model has a number of fundamental limitations. Such restrictions significantly narrow the scope of application of certain models. At the same time, the geoinformation monitoring system has significant capabilities for the system integration of heterogeneous models. The use of the polymodel property in monitoring complex objects will increase the reliability of the model of the monitored object, and therefore will ensure greater validity of the decisions made.

3. The article shows that the complexation of heterogeneous models of the object of geoinformation monitoring is based on the use of a single information and coordinate space. From the practical point of view the complexation of heterogeneous models is provided on the basis of technologies of spatial databases and knowledge of geoinformation monitoring.

4. In this article, in the language of categorical-functor representation, we substantiated the need for integration and convergence of various categories of models for the intellectualization of the system of geoinformation monitoring of the urban environment. Such models can be, for example, situational, imitation, expert, cognitive, semiotic models and others. We have shown the feasibility of describing the investigated monitoring object with a set of heterogeneous models with the possibility of taking into account the dynamics of the monitoring object. This makes it possible to adapt the models of the object of geoinformation monitoring to changes and allows you to compare the results obtained.

5. The considered and investigated property of polymodel nature of geoinformation monitoring allows to significantly expand the practical possibilities for obtaining new geoinformational knowledge about the state of the urban environment as a hierarchical, spatially distributed system.

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