Integrated Processing of Spatial Information based on Multidimensional Data Models for General Planning Tasks

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ABSTRACT The article presents the development of method of integrated spatial information processing based on multidimensional data models. Joint description of spatial data of different levels of detail (LOD) using a multidimensional model and attribute data using a relational model is difficult and requires the development of modified structures of multidimensional data models. The description of spatial and attribute data based on multidimensional information objects (MIO) is determined. It is proposed to use a new type of MIO − modified multidimensional information objects (MMIO). MIO and MMIO schemes allow describing multidimensional information objects and relationships in the form of a single multidimensional structure. On the basis of the introduced method of joint description of spatial and attributive data using extended multidimensional information objects, a multidimensional data model is built. This approach allows integrating different types of databases and contains a unified description of spatial and attribute data in the form of a multidimensional information object. The developed method is supposed to be used in BIM (Building Information Modeling) technology of computer modeling to solve general planning tasks.

KEYWORDS multidimensional information objects, multidimensional data model, building information modelling, general planning tasks.

I. INTRODUCTION

Spatial information is of great importance in the formation of the initial data for solving CAD-tasks related to the design of master plans and relief on the construction site. There is a need for a unified formalized description of spatial information in order to obtain an integrated BIM of natural and manufactured territorial distributed objects. There are different types of spatial information according to the data, format, description method, distributed to the storage location, belonging to the existing information systems, etc. [1].

Design of master plan is implemented at different organizational levels, each of which requires its own level of detail (LOD). Therefore, information systems for processing spatial information should be built on a hierarchical principle with varying degrees of detailing, integration and generalization of information at each level. It is necessary to determine the types of structures for storing this information in the territories and describe methods for converting them into a one multidimensional model of spatial data on geographically distributed objects.

To solve this problem, a method is proposed for describing large amounts of information using multidimensional information objects (MIO). MIO can describe one parameter, table, feature class, or the entire database. It depends on the MIO dimension.

The authors of the work [2] describe the basic advantages of multidimensional data models and their application. There is given a formalized description of data manipulation operations.

In the work [3], the authors develop the operations of manipulating data stored in different two MIO cubes.

Mathematical formalized procedures for creating multidimensional models are introduced in [4]. The operations of generation, projection, merging and deletion are described to implement the basic data processing functions. The main idea is to generalize the relational approach, in which several different relations with the same structure are proposed to be placed in a certain multidimensional object called MIO.

The article [5] gives a detailed review of the mathematical formalized procedures constructing multidimensional models for spatial objects in the information model of the construction territory. The proposed approach is adapted to describe in a uniform manner geographically distributed heterogeneous spatial data on geographically distributed objects and systems.

The author of the work [6] formalized multidimensional data representation using the theory of relational databases. There are described mathematically main multidimensional data representation concepts, dimension, hypercube and operations with data hypercube.

In works [7-10], there are studied the efficient organization and access of multidimensional datasets on storage information systems. There are analyzed approaches to spatial data and nonparametric modeling of multidimensional systems.

The articles [11] and [12] are devoted to the fast, efficient spatial method of data collection for multidimensional scaling. In work [13], the author shows procedure for selecting dimensionality in multidimensional scaling using the Bayesian network.

The authors of [14] examine dissimilarity structure from multiple item arrangements. The authors in the article [15] consider standardizing the creation of spatial databases to fill with spatial and attribute information.

At the conference [16] it was reported on the parallel coordinates as effective tools for visualizing multidimensional geometry. In works [17-19], the authors study multidimensional data visualization and show details of multidimensional dynamic analysis for data acquisition.

Articles [20, 21] are devoted the problem of joint description of spatial data different types in the composition of the construction territory information model. It is proposed the application of multiplicative theoretical approach to the description of spatial data, which presents in a single formalized form a plurality of spatial objects of different types.

It is necessary to study and describe the geometric and attribute data of the planning objects for design of master plan based on the multidimensional information objects (MIO). This approach meets the modern requirements of information modeling in construction – BIM-technology. It will allow solving tasks related to the design of master plan on the new technological level.

II. MAIN RESEARCH

The spatial planning objects can be modelled by spatial data of various types such as point, linear or polygonal, taking into account their level of detail. This characteristic feature of spatial data is used in GIS and CAD systems. Coordinates *X, Y, Z* characterize a point spatial object. Examples of such objects are water intake, a well, a hatch, a pole, a tree, etc. A linear spatial object is characterized by a set of attribute characteristics of a linear feature and a set of nodal points representing this feature. Examples of such objects are roads, channels, engineering communications, the boundaries of red lines, horizontal contours, etc. A polygonal spatial object is characterized by a set of attribute characteristics of a polygonal object and a set of closed lines bounding its contours. Individual buildings, special natural areas, planting trees and vegetation, lakes, etc. can represent such objects.

Different types of spatial data are described as multidimensional information objects (MIO) of various dimensions. MIO is designated as follows:

$$T_i^n , \qquad (1)$$

where T is the name of MIO, *n* is the dimension of MIO, *i* is characteristic of geometric type (point, line, polygon).

The geometric description of a point spatial object can be represented by MIO T_{point}^1 as follows:

$$T_{point}^1 = \{IDp, X, Y, Z\}, \qquad (2)$$

where *X, Y, Z* are geometric planning coordinates; *IDp* is the point number (identification code).

A complete description (Fig. 1) of the one point spatial object T_{point}^1 is determined:

$$Point = \{T_{point}^1 , A_{point}^1\}, \qquad (3)$$

where A_{point}^1 is a set of point object attribute data.

Points	ID$_1$	X$_1$	Y$_1$	Z$_1$	$\cdots$
	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
	T$^1_{point}$			A$^1_{point}$	

Figure 1. Graphic representation MIO for complete description of the point spatial object

The geometric description MIO of one linear spatial object T_{line}^2 is given by the set of nodes in the line. MIO dimension 2 is determined:

$$T_{line}^2 = \left\{ IDl, \{ T_{point}^1 \}_i \right\} , \ i = \overline{1, k_p}, \qquad (4)$$

where *IDl* is linear spatial object number (identification code), k_p is the number of nodes in the line, representing this spatial object, $\{T_{point}^1\}_i$ is *i*-point spatial object MIO

that defines a set of coordinates values characterizing the location of a nodal point in the space of the coordinate system.

In addition to the set of nodes, a linear spatial object is characterized by a A_{line}^1 as a set of attribute data MIO. So, one linear spatial object *Line* is described as a MIO pair. Its complete description is determined:

$$Line = \{T_{line}^2, A_{line}^1\}. \tag{5}$$

The complete description of one polygonal spatial object *Polygon* is represented as MIO pair: T_{polyg}^3 – a set of lines bounding its contours and A_{polyg}^1 – a set of attributive characteristics. It is determined:

$$Polygon = \{T_{polyg}^3, A_{polyg}^1\}, \tag{6}$$

where, T_{polyg}^3 is MIO of dimension 3 for one polygonal spatial object. It is determined:

$$T_{polyg}^3 = \{IDpl, \{T_{line}^2\}_j\}, \; j = \overline{1, k_l}, \tag{7}$$

where, *IDpl* is polygonal spatial object number (identification code) k_l – the number of bounding polygon lines, $\{T_{line}^2\}_j$ – *j*-linear spatial object MIO, defined by (4).

The complete description of one thematic layer on the master plan is represented as a group of similar objects – point, linear or polygon (for example, a river network or a set of hydrological control posts) and their attributive characteristics.

The description MIO of dimension 2 for one point layer is determined:

$$T_{layer\_point}^2 = \{T_{point}^1\} \cdot S_p, \; i = \overline{1, n_p}, \tag{8}$$

where S_p is a list of point objects, n_p is a number of points.

For a complete description of one linear layer on the master plan, it is necessary to unite the totality of linear objects included in the layer and their attributive characteristics. The description MIO of dimension 2 for set of linear objects attribute data is determined:

$$T_{AL}^2 = \{A_{line}^1\}_j \cdot S_l, \; j = \overline{1, n_l}, \tag{9}$$

where S_l – a list of linear objects, n_l – a number of linear objects.

The description MIO of dimension 3 of one point layer is determined:

$$T_{layer\_line}^3 = \{T_{line}^2\}_j \cdot S_l, \; j = \overline{1, n_l}. \tag{10}$$

Since MIO (9) and (10) are different types, but have a common dimension – identification codes of linear objects

(*IDl*), then according to (4) they can be combined by this common element.

The result is a fan MIO of dimension 4 of one linear layer (Fig. 2). It is determined:

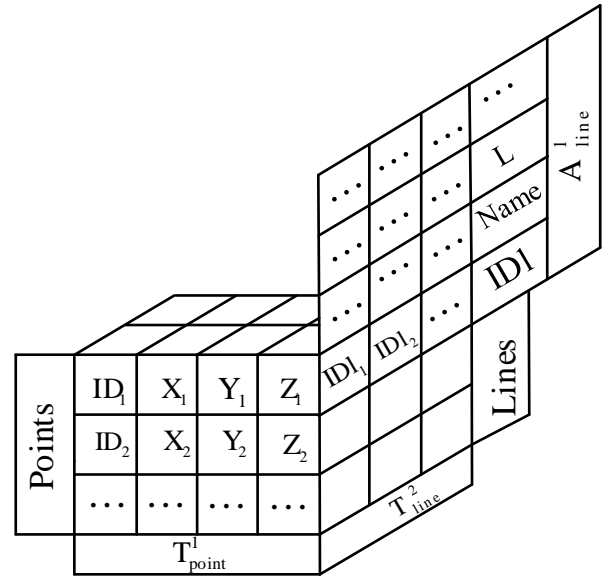$$T_{line}^4 = T_{layer\_line}^3 \cup T_{AL}^2, \; i = \overline{1, n_l}. \tag{11}$$

Figure 2. Graphic representation MIO of dimension 4 for the one linear layer

For a complete description of one polygonal layer of the master plan, it is necessary to unite the totality of polygonal objects included in this layer and their attributive characteristics similarly (9)–(11). An attribute data set for polygonal objects is merged MIO of dimension 2:

$$T_{AP}^2 = \{A_{polyg}^1\}_k \cdot S_{pl}, \; k = \overline{1, n_{pl}}, \tag{12}$$

where S_{pl} is list of polygonal objects identification codes (*IDpl*), n_{pl} is number of polygonal objects identification codes on master plan.

The description MIO of dimension 4 of one polygonal layer is determined:

$$T_{layer\_polyg}^4 = \{T_{polyg}^3\}_i \cdot S_l, i = \overline{1, n_{pl}}. \tag{13}$$

MIO (12) and (13) are combined by common elements – identification codes of polygonal objects *IDpl* according to [6]. The result is a fan MIO of dimension 5 of one polygonal layer. It is determined:

$$T_{polyg}^5 = T_{layer\_polyg}^4 \cup T_{AP}^2, i = \overline{1, n_{pl}}. \tag{14}$$

It is necessary to combine the different MIOs defined by (6), (11) and (14) representing the layers for each type of geometry (point, linear, polygonal), to describe the spatial

objects grouped into layers, with a certain level of detail. It is very difficult to use the operation of combining different types of MIO, described in [5].

It is visibly presented that a complete description of one spatial object may consist of several MIOs of different dimensions and has a complex appearance. For a joint description of various types of spatial objects within a single information data model, it is necessary that the description of each type of spatial object is one MIO. In addition, there is no generality in the description of objects layers of geometry different types, which makes it difficult to perform data transformation operations on them. For a uniform representation of spatial objects of various types, they have necessarily to be of the same form.

Let some MIO of dimension n be denoted as T_0^n and its scheme as $S(T_0^n) = S^n$. MIO of dimension n should be combined with MIO dimension (n+1), which is denoted as T_0^{n+1} and its scheme as $S(T_1^{n+1}) = \{S^n, S_{n+1}\} = S_1^{n+1}$. The data of these MIO differ in one element of the scheme S_{n+1}. In order for the scheme S^n to take the form S_1^{n+1}, it is proposed to use a new type of MIO – modified multidimensional information objects (MMIO), which are denoted as $\tilde{T}^{n,m}$, where *n* is a number of existing dimensions, *m* is a number of extra dimensions. These objects correspond to the MIO of larger dimension according to the scheme and MIO of the same dimension in information content. If m = 1, then MMIO is $\tilde{T}^{n,1}$. The scheme of this object is as follows:

$$S(\tilde{T}^{n,1}) = \{S^n, S_{n+1}\} = S^{n+1}, \qquad (15)$$

where S_{n+1} is an element of the scheme MIO of dimension n, it is different from the scheme MIO with which it needs to be combined. In this case, the MIO, which corresponds to the circuit element S_{n+1} in the $\tilde{T}^{n,1}$, contains an empty data set. This dimension is called fictitious.

The operations of adding a dimension increases dimension I_1 to get a MMIO of dimension n+1:

$$I_1(T^n, S_{n+1}) = T^n \cdot S_{n+1} = \tilde{T}^{n,1}. \qquad (16)$$

This operation is applied simultaneously to only one MIO.

In the general case, to obtain a MMIO, including *m* fictitious dimensions, several operations of adding a dimension are consistently applied:

$$I_1(T^n, S_{n+1}) = T^n \cdot S_{n+1} = \tilde{T}^{n,1},$$
$$I_1(\tilde{T}^{n,1}, S_{n+2}) = \tilde{T}^{n,1} \cdot S_{n+2} = \tilde{T}^{n,2},$$
$$\dots$$
$$I_1(\tilde{T}^{n,m-1}, S_{n+m}) = \tilde{T}^{n,m-1} \cdot S_{n+m} = \tilde{T}^{n,m}. \qquad (17)$$

This is presented:

$$\tilde{T}^{n,m} = I_m(T^n, \{S_{n+i}\}) = T^n \cdot \{S_{n+i}\}, i = \overline{1,m}, \qquad (18)$$

where S_{n+1} determines the entry order $\tilde{T}^{n,i-1}$ in $\tilde{T}^{n,i}$, at the same time $T^{a,0} = T^a$.

The operation of adding a dimension allows getting MMIO of any dimension that exceeds the dimension of the original MIO. To study the operation of adding dimension, consider the process of obtaining MMIO for a uniform description of various types of spatial objects and their presentation as layers of different types (point, linear and polygonal) depending on the level of detail of spatial data on the database.

Let the elementary *i* characteristic of a spatial object of any type (point, line, polygon) be described in the form of MIO T^0.

The point spatial object is proposed to describe MIO T_m^1 as a set of characteristics T_i^0 with scheme S_{point}^1. This scheme describes one point as a set of coordinate values *(X, Y, Z)* characterizing the location of a point in the coordinate system:

$$T_m^1 = \{T_i^0\} \cdot S_m, \ i = \overline{1,k_0}, \qquad (19)$$

where S_m is a list of various characteristics of point object, k_0 is a number of characteristics of the point object.

The linear spatial object is proposed to be described as MIO of dimension 2 T_L^2 with scheme S_L^2, which describes the line as a set of nodal points:

$$T_L^2 = \{T_m^1\}_i \cdot S_2, \ i = \overline{1,k_1}, \qquad (20)$$

where S_2 is a list of nodal points, k_1 is a number of nodal points in the linear object, T_m^1 is MIO with scheme S_m^1.

The polygonal spatial object is proposed to be described as MIO of dimension 3 T_P^3 with scheme S_P^3, which describes the polygon as a set of closed lines:

$$T_P^3 = \{T_L^2\}_i \cdot S_3, \ i = \overline{1,k_2}, \qquad (21)$$

where S_3 is a list of bounding lines, k_2 is a number of bounding lines in the polygonal object, T_L^2 is MIO with scheme S_L^2.

It follows from (19) and (20), that the scheme S_L^2 of MIO T_L^2 differs from scheme S_m^1 by MIO T_m^1 by list S_2. The scheme S_P^3 of MIO T_P^3 differs from scheme S_L^2 of MIO T_L^2 by S_3. It is necessary to apply operation of adding a dimension MIO T_m^1 and T_L^2 to get a common description for any spatial object. Since the maximum dimension equals 3, any spatial object can be represented as a MIO of dimension 3. To apply the operation of adding and obtaining MMIO $\tilde{T}_m^{1,2}$ from T_m^1 describing point spatial objects, it is necessary to enter for MMIO $\tilde{T}_m^{1,2}$ fictitious dimensions $\{S_2, S_3\}$. Two operations of adding dimension defined by (17) are consistently applied:

$$I_1(T_m^1, S_2) = (T_m^1) \cdot S_2 = \tilde{T}_m^{1,1}.$$

$$I_1(\tilde{T}_m^{1,1}, S_3) = (\tilde{T}_m^{1,1}) \cdot S_3 = \tilde{T}_m^{1,2}.$$

The result defined by (18) is:

$$I_1(T_m^1, S_2, S_3) = (T_m^1) \cdot \{S_2, S_3\} = \tilde{T}_m^{1,2}. \tag{22}$$

The scheme of MMIO for point spatial objects is determined:

$$S_m^{1,2} = \{S_m^1, S_2, S_3\}. \tag{23}$$

The MMIO $\tilde{T}_L^{2,1}$ from T_L^2 describes linear spatial objects with fictitious dimensions S_3:

$$I_1(T_L^2, S_3) = (T_m^1) \cdot S_3 = \tilde{T}_L^{2,1}. \tag{24}$$

The scheme of MMIO for linear spatial objects is determined:

$$S_L^{2,1} = \{S_L^2, S_3\}. \tag{25}$$

For a joint description of attribute and spatial data, it is necessary to provide MIO describing attribute information for spatial objects, to the MMIO of dimension 3. In general, the attribute characteristics of spatial object of any type (point, linear, polygonal) describe MIO of dimension 1.

According to (3), the attribute characteristics of a point object is described MIO of dimension $1 - T_{Am}^1$ with scheme S_{Am}^1. According to (5), the attribute characteristics of a linear object is described MIO of dimension $1 - T_{AL}^1$ with scheme S_{AL}^1. According to (6), the attribute characteristics of a polygonal object is described MIO of dimension $1 - T_{AP}^1$ with scheme S_{AP}^1. It is necessary to enter for the attribute characteristics spatial object fictitious dimensions $\{S_2, S_3\}$ that are the same as (3), (4) and (6). Similarly to $(22) - (24)$:

$$I_2(T_{Am}^1, \{S_2, S_3\}) = (T_{Am}^1) \cdot \{S_2, S_3\} = \tilde{T}_{Am}^{1,2}, \tag{26}$$

$$I_2(T_{AL}^1, \{S_2, S_3\}) = (T_{AL}^1) \cdot \{S_2, S_3\} = \tilde{T}_{AL}^{1,2}, \tag{27}$$

$$I_2(T_{AP}^1, \{S_2, S_3\}) = (T_{AP}^1) \cdot \{S_2, S_3\} = \tilde{T}_{AP}^{1,2}. \tag{28}$$

Now, described attribute data MIO is of the same type than described spatial data MIO. Received MIO differs in only one element of the scheme − the list of attributes of a spatial object. It is necessary to perform transformations (22)–(28) to obtain a joint description of spatial and attribute data. The result obtained allows applying the operations of combining MIOs of various types.

A complete description of MMIO for one point spatial object is represented:

$$\tilde{T}_m^3 = \tilde{T}_{Am}^{1,2} \cup \tilde{T}_m^{1,2}. \tag{29}$$

The scheme of complete description of MMIO for one point spatial object is determined:

$$S(\tilde{T}_m^3) = \{S_m, S_2, S_3, S_{Am}\}. \tag{30}$$

A complete description of MMIO for one linear spatial object is represented:

$$\tilde{T}_L^3 = \tilde{T}_{AL}^{1,2} \cup \tilde{T}_L^{2,1}. \tag{31}$$

The scheme of complete description of MMIO for one linear spatial object is determined:

$$S(\tilde{T}_L^3) = \{S_l, S_2, S_3, S_{AL}\}. \tag{32}$$

A complete description of MMIO for one polygonal spatial object is represented:

$$\tilde{T}_p^3 = \tilde{T}_{AP}^{1,2} \cup T_P^3. \tag{33}$$

The scheme of complete description of MMIO for one polygonal spatial object is determined:

$$S(\tilde{T}_P^3) = \{S_p, S_2, S_3, S_{AP}\}. \tag{34}$$

In (27), (29) and (31) there S_m, S_l, S_p are lists of spatial characteristics, S_{Am}, S_{AL}, S_{AP} are lists of attribute characteristics. Combine them for each scheme and denote as S_1. Accordingly, the scheme received MMIO will look like:

$$S(\tilde{T}_m^3) = S(\tilde{T}_L^3) = S(\tilde{T}_P^3) = \{S_1, S_2, S_3\}. \tag{35}$$

Since any spatial data object according to (29), (31) and (33) can be described as a MMIO of dimension 3, a separate thematic layer of the master plan can be represented as a group of similar objects and their characteristics as $\tilde{T}^4$.

The layer of point objects can be represented as MMIO:
$$\tilde{T}_m^4 = \{\tilde{T}_m^3\}_i \cdot S_4, \ i = \overline{1, n_1}, \tag{36}$$

where S_4 is a list of all objects on one layer, n_1 is a number of point objects on the layer.

The layer of linear objects can be represented as MMIO:
$$\tilde{T}_L^4 = \{\tilde{T}_L^3\}_i \cdot S_4, \ i = \overline{1, n_2}, \tag{37}$$

where n_2 is a number of linear objects on one layer.

The layer of polygonal objects can be represented as MMIO:

$$\widetilde{T}_P^4 = \{\widetilde{T}_P^3\}_i \cdot S_4, \ i = \overline{1, n_3}, \tag{38}$$

where n_3 is a number of linear objects on the layer.

The full description of all the spatial objects under consideration grouped into layers with one LOD constituting a construction territory master plan of a certain scale, can be represented as a MMIO of dimension 5:

$$\widetilde{T}^5 = \{\widetilde{T}^4\}_i \cdot S_5, \ i = \overline{1, n_5}, \tag{39}$$

where S_5 is a list of object types (layers), n_5 is a number of object types (layers).

Accordingly, if the master plan of the construction territory is considered as a set of various LOD, then the information base of spatial objects can be described as a MMIO of dimension 6:

$$\widetilde{T}^6 = \{\widetilde{T}^5\}_i \cdot S_6, \ i = \overline{1, n_6}, \tag{40}$$

where S_6 is a list of LOD, n_6 is a number of LOD.

III. RESULTS

The description of spatial and attribute data of general planning objects based on the MIO allows to submit each type of spatial object as one MIO, achieve integrity of the layers description of different types of objects, simplify the structure description of the existing databases on information processing systems, make the information data model observable and understandable.

Figures 3-5 show graphical representations of formulas (29), (31) and (33) for the complete descriptions of spatial data each type. Fig. 3 shows a graphical interpretation of MMIO $\widetilde{T}_m^3$ describing point objects. Fig. 4 shows a graphical interpretation of MMIO $\widetilde{T}_L^3$ describing linear objects. Fig. 5 shows a graphical interpretation of MMIO $\widetilde{T}_p^3$ describing polygonal objects.
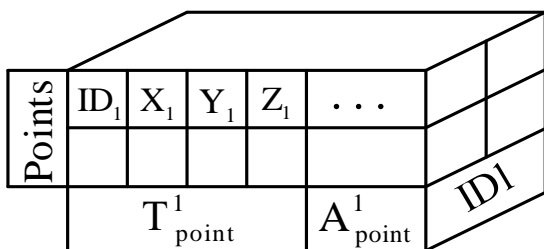

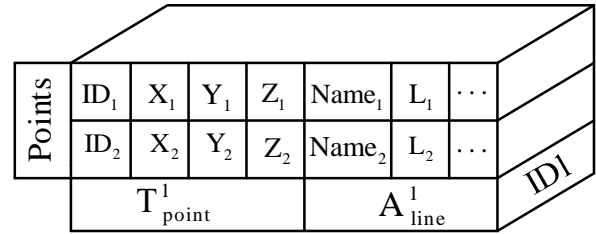Figure 3. Graphic representation $\widetilde{T}_m^3$ – MMIO dimension 3 for description point objects

Figure 4. Graphic representation $\widetilde{T}_L^3$ – MMIO dimension 3 for description linear objects
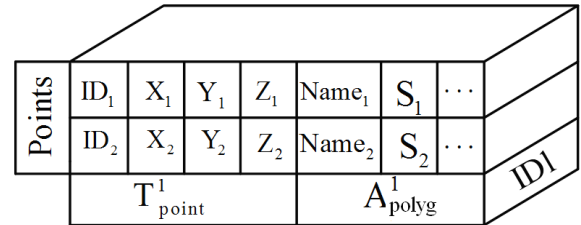

Figure 5. Graphic representation $\widetilde{T}_p^3$ – MMIO dimension 3 for description polygonal objects

Table 1 shows examples of different types of spatial objects.

Table 1. Types of spatial objects

Name/ Type of spatial object	Set of some attributes of the spatial object	Description and Type of MMIO
Tree/ **Point**	ID, planning geometric coordinates, breeD, Height, Age, Growth parameters	(IDt, X,Y,Z), (D, H, A,G) $\widetilde{T}_m^3$
Drainpipe/ **Line**	ID, planning geometric coordinates, Name, Function, Material, Diameter of pipe	(IDd, {X,Y,Z}, (N, F, M, D) $\widetilde{T}_L^3$
Building/ **Polygon**	ID, planning geometric coordinates, Destination status, explication Number, Zero mark	(IDb, {X,Y,Z}), (D, N, Z) $\widetilde{T}_p^3$

Fig. 6 shows a practical example of interpretation of MMIO $\widetilde{T}_m^3$ for describing point object "Tree" from Table 1.
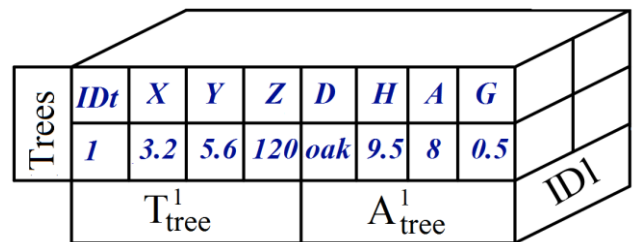

Figure 6. Practical example of interpretation of MMIO $\widetilde{T}_m^3$ for describing point object "Tree"

Figures 7 – 9 show graphical representations of formulas (36)-(38) for the descriptions of a similar objects group, that forms a separate layer of the master plan as MMIO. Hidden dimensions are shown in gray color in schemes.
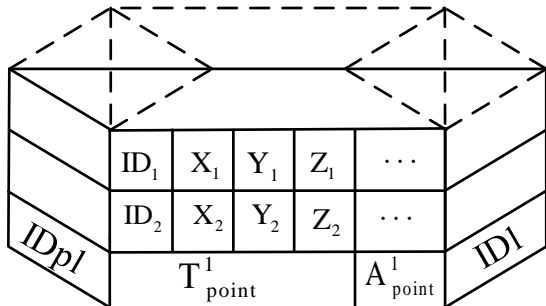

Figure 7. Graphic representation $\widetilde{T}_m^4$ – MMIO dimension 4 for the layer of point objects
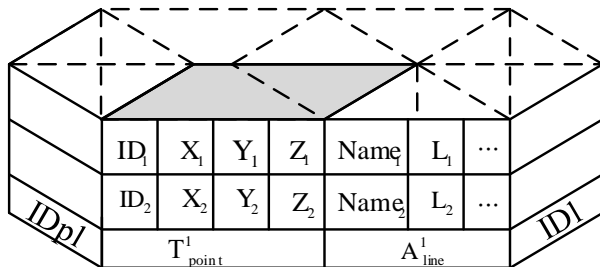

Figure 8. Graphic representation $\widetilde{T}_L^4$ – MMIO dimension 4 for the layer of linear objects
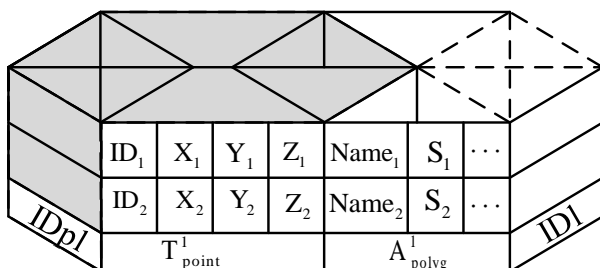

Figure 9. Graphic representation $\widetilde{T}_P^4$ – MMIO dimension 4 for the layer of polygonal objects

IV. CONCLUSIONS

In this work, a description of the spatial and attribute data of the planning objects is based on the multidimensional information objects.

The results of the study have shown that multiplicative theoretical approach allows describing in one mathematical form the sets of various types of spatial objects. The introduction of the additional dimension allows describing each type of spatial planning object as one separate MIO and MMIO.

This makes it possible to achieve the integrity of the description layers of the different type objects and simplifies the description of the existing database for the system information processing.

This approach allows integrating different types of databases and contains a unified description of spatial and attribute data in the form of a multidimensional information object. The developed integrated processing is supposed to be used in computer modeling of BIM-technology to solve general planning tasks.
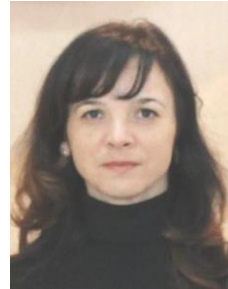
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