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The Method of Generalizing Spatial Information into a Single Multidimensional Data Model

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***Abstract**: The study presents innovative method of generalizing spatial information into a single multidimensional data model technology based on multidimensional information objects (MIO). This advanced method is intended to describe various types of spatial information of general planning objects at a construction site and their generalization into a single multidimensional model of general plan data. The method was further developed on the basis of newly introduced operations on multidimensional information objects. The operations of simple and generalized change and spatial generalization make it possible to integrate heterogeneous spatial information into single information space at all organizational levels of management while maintaining its integrity. The paper considers mathematical descriptions and graphic representations of information models of various types of spatial objects of general planning based on multidimensional information objects.*

***Keywords**: spatial data, multidimensional information objects, MIO, multidimensional modeling, spatial generalization.*

I. INTRODUCTION

The spatial information is of great importance in the formation of the source data for making managerial decisions in the tasks of general planning and organization of the territory under construction. It is necessary to single formal description of spatial information to obtain a holistic view of natural and manufactured territorially distributed objects on the construction territory. Such information is heterogeneous in type, format and description method, distributed by storage location and by belonging to existing information systems.

Management of the general planning process is implemented at different organizational levels. Information support should include territorially distributed information processing information systems and be built on a hierarchical basis with varying levels of detail (LOD) and generalization of information at each level. The analysis of the basic functions and tasks in the field of management of the territories of the existing information processing systems shows the following [1-3]. Information flows in the territorial management system are aimed at solving problems at each organizational level and at providing the necessary information to a higher organizational level. The generalization of information for transferring from one organizational level to a higher level in the resource territory management system is called information generalization.

The information that is used to solve the problems of territory management is primarily spatial in nature. It is represented by various types of data and is distributed territorially between organizational levels. There are no integrated processing systems for distributed spatial information in the territorial management system.

There is duplication of data in various independently functioning data processing information systems during the general planning of the construction site.

It is necessary to determine the types of spatial information storage structures for general planning objects and describe the methods of their transformation into a single multidimensional spatial data model. It is supposed to be used for information support of the process of organizing the relief of a construction site.

There is an urgent task of integration and generalization of heterogeneous (by type, format and description method) spatial natural resource and anthropogenic information distributed by territorial storage location (in various organizations, territorial divisions, municipal authorities, etc.) and by belonging to existing information systems.

The special method is proposed for describing large amounts of information to provide a joint description of databases and operations on them. This method is called multidimensional information objects (MIO). MIO can be of any dimension and describe a separate parameter, table, feature class or the entire database.

In works [3, 4] mathematically formalized procedures for constructing multidimensional models are presented. In these works, operations such as generating, projecting, combining, and deleting are described to implement basic data processing functions.

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The main idea of this multidimensional approach is to generalize the relational approach, in which it is proposed to place several different relations with the same structure in some multidimensional object called the MIO. The authors of the works [5-8] describe the generalization relations of the "polygon – point" and "polygon – line" types and the relations of attributive generalization, which determined in accordance with the levels of the hierarchical system. However, the proposed relations take into account only the transfer of information about the object itself, and do not allow describing the transformation of individual characteristics of individual objects or groups of objects.

The articles [9-11] are devoted to integrate processing of spatial information based on multidimensional data models and to develop method of integration and generalization diverse territorially distributed spatial natural resources information.

In works [12] and [13], there are studied the modeling of spatial data on the construction site based on multidimensional information objects and multidimensional space structure for adaptable data model.

But existing operations on MIO are not enough to solve the problems of spatial information generalization. It is necessary to introduce new operations for the transfer of information in a generalized form from one organizational level of management to another.

It is proposed to introduce a new operation to describe the change in the elements of the MIO data and their generalization to solve the problems of generalizing spatial information described using the MIO.

II. MAIN RESEARCH

Consider the first, simplest option, when it is necessary to change one data element in a multidimensional information object. There is some n-element T^n_{input}, containing a data element T^i_{input} whose value must be changed to T^i_{output}. T^i_{output} is the result of applying to T^i_{input} some functional transformation f. The operation C^n_f of simply changing MIO of the element T^n_{input} is determined by the result of applying the same dimension MIO of the element T^n_{output}. T^n_{output} differs from T^n_{input} by the value of some data element T^i_{output} , which is the result of applying the functional transformation f. For example, for MIO of dimension 0, the operation C^0_f of simply changing coincides with the functional transformation f:

$$T^o_{output} = C^0_f\left(T^o_{input}\right) = f\left(T^o_{input}\right), \tag{1}$$

where f is transformation function.

It is necessary to specify i-element that needs to be converted to change MIO T^1 of dimension 1:

$$T^1 = \{T^0_1, T^0_2, \dots, T^0_i, \dots, T^0_k\} \tag{2}$$

Primarily, element T^0_i is removed from T^1 that corresponds to the specified i-element of scheme and contains the value that should be changed. Secondly, operation (1) of a simply changing MIO is applicable to this i-element:

$$T^o_{output} = C^0_f(T^o_i) = f(T^o_i), \tag{3}$$

When one more MIO of dimension *(n-1)* is added to the MIO of dimension *n*, the order of the elements in the scheme is not significant from the point of view of the information content of the MIO. The resulting T^o_{output} is added to the end T^1:

$$T^1_d = T^1 / T^0_i , \tag{4}$$

$$T^1_{output} = C^1_{fi}(T^1) = T^1_d \cup T^o_{output} = \left(\frac{T^1}{T^0_i}\right) \cup C^0_f(T^0_i), \tag{5}$$

The result of applying (1) the simple change operation to the MIO T^1 (2) will take the form:

$$T^1 = \{T^0_1, T^0_2, \dots, T^0_{k-1}, f(T^0_i)\} . \tag{6}$$

MIO of dimension 2is defined:

$$T^2 = \left\{T^1_1, T^1_2, \dots, T^1_j, \dots, T^1_k\right\} \tag{7}$$

To change MIO T^2 it is necessary to specify *j*-element that needs to be converted: $T^1_j = \{T^0_1, T^0_2, \dots, T^0_i, \dots, T^0_k\}$. Similarly to (3)-(4), primarily, element T^1 is removed from T^2:

$$T^2_d = T^2 / T^1_j, \tag{8}$$

Next, it is necessary to indicate i-element in T^1_j, then it is necessary to remove T^1_j from T^0_i containing the value that needs to be changed:

$$T^1_{jd} = T^1_j / T^0_i, \tag{9}$$

Now apply to it the operation of simply changing the MIO:

$$T^1_{j,outpu} = C^1_{fi}(T^1) = T^1_{dj} \cup T^0_{i,output} = (T^1_j / T^0_j) \cup C^0_f(T^0_i). \tag{10}$$

And then add $T^1_{j,output}$ to T^2_d:

$$T^2_{j,output} = C^1_{fij}(T^2) = T^2_d \cup T^1_{j,output} = (T^2 / T^1_j) \cup C^1_{fi}(T^1_i) \tag{11}$$

In scientific studies [13] and [14], methods for describing various spatial objects base on MIO are proposed. The application of these developments helps to show the change in the coordinate of an individual spatial object using the introduced operation of a simple change in the MIO.

Consider MIO of dimension 3 to describe the polygonal object S^3_{Π}. It is necessary to change the value of the Y coordinate for an individual nodal point for such an object. This will be the first nodal point of the first line bounding the polygon.

$$T^3_{\Pi} = \{T^2_{L1}, T^2_{L1}, \dots, T^2_{Lk}\}, \tag{12}$$

where k is the number of bounding polygons lines.

To change such MIO T_{Π}^{3} it is necessary to specify the item to be converted. Let this element T_{L1}^{2} be the MIO containing data on a separate line.

$$T_{L1}^{2} = \{T_{p1}^{1}, T_{p2}^{1}, \dots, T_{pk_1}^{1}\} \quad (13)$$

where k_1 is the number of points in the line.

The element T_{Π}^{3} is removed from T_{L1}^{1}:

$$T_{\Pi d}^{3} = T_{\Pi}^{3} / T_{L1}^{2}. \quad (14)$$

Then it is requisite to remove T_{p1}^{1} fromT_{L1}^{2}. The element T_{L1}^{2} is needed to transform:

$$T_{L1d}^{2} = T_{L1}^{2} / T_{p1}^{1}, \quad (15)$$

Let the data element T_{A2}^{0} included in the MIO:

$$T_{p1}^{1} = \{T_{A1}^{0}, T_{A2}^{0}, \dots, T_{Ak_2}^{0}\}, \quad (16)$$

where k_2 is the number of characteristics of the point, contains the Y-coordinate value for the first point.

The element T_{p1}^{1} is removed from T_{A2}^{0} and operation of simply changing the MIO applies the operation to it:

$$T_{P1d}^{1} = T_{P1}^{1} / T_{A2}^{0}, \quad (17)$$

$$T_{P1,output}^{1} = C_{f2}^{1}(T_{P1}^{1}) = T_{P1d}^{1} \cup T_{A2,output}^{0} = = \left(\frac{T_{P1}^{1}}{T_{A2}^{0}}\right) \cup C_{f}^{0}(T_{A2}^{0}) \quad (18)$$

Then add element $T_{P1,output}^{1}$ to T_{L1d}^{2}:

$$T_{L1,output}^{2} = C_{f21}^{2}(T^{2}) = T_{L1d}^{2} \cup T_{P1,output}^{1}, \quad (19)$$

$$T_{\Pi,output}^{3} = C_{f211}^{3}(T_{\Pi}^{3}) = T_{\Pi d}^{3} \cup T_{L1,output}^{2}, \quad (20)$$

Given the methods proposed in [15] for the following relation can show describing various spatial objects using the MIO, the main meaning of the simple change operation:

$$C_{fl}^{0}(T_{input}^{n-3}, T_{output}^{n-3}):$$

$$T_{input}^{n-3} \xrightarrow{\Pi_{S1l}(T_{output}^{n-3}) = f(\Pi_{S1l}(T_{input}^{n-3}))} T_{output}^{n-3} \quad (21)$$

The relation (21) means the change in the value of the attribute l of the scheme S_1 in the object T_{output}^{n-3} by the value of a certain functional transformation f from the value of the attribute l of the scheme S_1 in the object T_{input}^{n-3}.

In the general case, for an MIO T^n of dimension n, the simple change operation is determined recursively as follows:

$$\begin{cases} T_{output}^{n} = C_{f,S}^{n}(T^{n}) = \left(\frac{T^{n}}{T_{i_{n-1}}^{n-1}}\right) \cup C_{f,S}^{n-1}(T_{i_{n-1}}^{n-1}), \\ T_{output}^{0} = C_{f}^{0}(T^{0}) = f(T^{0}), \end{cases} \quad (22)$$

where $f: x \to y$ is transformation function, y is a scalar quantity, $y = f(x), S = \{i_0, \dots, i_{n-1}\}$ is the set of elements of the corresponding schemes $S_1, \dots, S_n$, is defined MIO of dimension 0, which needs to be changed.

The simple change operation (22) allows to update the value of the MIO data element, but to solve the problem of generalizing spatial information it is necessary to generalize some elements of the MIO data according to a certain rule. It is necessary to introduce the operation of structural generalization (generalized change), the meaning of which is to obtain from the MIO of dimension n a new MIO of dimension (n-1) and to generalize the elements of the tuples indicated by the omitted dimension by some rule. This operation is denoted G_{g}^{n-1} and is defined recursively, similar to the definition of a simple change operation (20). However, since in this case the convolution of the values of a tuple (vector) into a number is considered, then the operation of generalized change over $T^1 = \{T_1^0, T_2^0, \dots, T_i^0, \dots, T_k^0\}$. Result will be an MIO of dimension 0:

$$T_{output}^{0} = G_{f}^{0}(T^{1}) = f(T_1^0, T_2^0, \dots, T_i^0, \dots, T_k^0), \quad (23)$$

where $f: (x_1, \dots, x_k) \to y$ is transformation function, y is a scalar quantity, $y = f(x_1, \dots, x_k)$.

As a result of applying this operation to the MIO $T^2 = \{T_1^1, \dots, T_{k_1}^1\}$, where k_1 is the number T_i^1 of dimension 2 with a scheme $S^2 = S(T^2) = (S_1, S_2)$ an MIO of dimension 1 (vector) will be obtained, consisting of elements equal to the values of the function of each $T_i^1, i = \overline{1,k}$:

$$T_{output}^{1} = G_{f}^{1}(T^{2}) = \{f(T_i^1)\} * S_2, \quad (24)$$

where S_2 *is element of* scheme S^2.

It is essential for this operation that the dimension determined by the element of the scheme S_1 is reduced. This is permissible, since, as already noted, the order of the elements of the scheme is not important, and therefore the element of the scheme by which the generalization is made, can not specify.

The generation operation will be used to assemble the new MIO, since the results of the functional transformation $f(T_j^1)$ are constants.

In the general case, for an MIO T^n of dimension n, the generalized change operation is determined recursively similarly to the definition of a simple change operation (20) as follows:

$$\begin{cases} T_{output}^{n-1} = G_{f}^{n-1}(T^{n}) = \{G_{f}^{n-2}(T_i^{n-1})\} * S_n, \\ T_{output}^{0} = G_{f}^{0}(T^{1}) = f(T_1^0, \dots, T_{k_1}^0), i = \overline{1,k}, \end{cases} \quad (25)$$

where k_n is the number T_i^{n-1}, $f: (x_1, \dots, x_k) \to y$ is transformation function, y is a scalar quantity, $y = f(x_1, \dots, x_k)$.

Given the methods proposed in [4] for describing various spatial objects using MIO, the main meaning of the generalized change operation can be shown by the following relation:

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$$C^1_{S_1 l}\left(\{T^{n-3}_{input,i}\}, T^{n-3}_{output}\right): \qquad (26)$$

$$\{T^{n-3}_{input,i}\} \xrightarrow{\Pi_{S_1 l}\left(T^{n-3}_{input}\right)=f\left(\Pi_{S_1 l}(T^{n-3}_{output,1}),\Pi_{S_1 l}\left(T^{n-3}_{inpu\ ,m}\right)\right)} T^{n-3}_{output}$$

The relation (26) means the change in the value of the attribute l of the scheme S_1 in the object T^{n-3}_{output} by the value of a certain functional transformation f from the value of the attribute l of the scheme S_1 in the object $T^{n-3}_{input,i}$.

To illustrate the operation, consider the solution to the following problem. It is necessary to determine the volume of earthwork during the organization of the relief of the construction site in the context of municipalities.

The initial information for solving the problem is spatial information that describes various spatial objects in the territory under development in the form of polygonal, linear and point objects with attributive characteristics.

And as a result, it is necessary to obtain the coordinates of the objects of general planning with generalized attributive characteristics.

According to [16], the layer of polygonal objects representing general planning objects can be described T^4_Π as MIO of dimension 4. Such an MIO is a set of polygonal objects $\{T^3_p\}$. The each describes a separate object of general planning:

$$T^4_\Pi = \{T^3_p\} = T^3 * S_4, \qquad (27)$$

where S_4 is the set that determines the location of the master plan objects in the corresponding drawing layer.

The layer of point objects of general planning in accordance with the method for describing point objects can be described T^4_t as MIO of dimension 4. Such an MIO is a set of point objects $\{\widetilde{T^3_t}\}$. The each describes a separate object of general planning:

$$\{\widetilde{T^3_t}\}: \widetilde{T^4_t} = \{\widetilde{T^3_t}\} = \widetilde{T^3} * S_4\,, \qquad (28)$$

This MIO has a scheme:

$$S^4 = S(T^4) = (S_1, S_2, S_3, S_4) \qquad (29)$$

where set S_1 = {Nodal point numbers of the contour line} = $\{ID_t\}$ = {1, 2, 3, …}, set S_2 = {Line codes} = $\{ID_l\}$ = {513625601, 513625602, ...}, set S_3 = {Characteristic identifiers} = {X, Y, Z, Attribute Characteristics}, set S_4 = {Polygon codes} = $\{ID_P\}$ = {71266501, 71266502, ...}.

The combination of MIOs describing the point layer and the layer of polygonal objects of general planning on the construction territory is described by this relation:

$$\widetilde{T^4_t} \cup T^4_\Pi = T^4 \qquad (30)$$

The set of general planning objects of municipalities (for example, the housing area of the city) can be described in the form of MIO dimension 5:

$$T^5 = \{T^4\} = T^4 * S_5, \qquad (31)$$

where set S_5 = {Area codes} = $\{ID_R\}$ = {100, ...}.

The solution to the problem of obtaining generalized data on the placement of objects of general planning consists of several steps:

1. Using the generalized change operation (25) from a set of polygons, it is necessary to obtain a set of point features grouped by the administrative regions, the location of which is determined by averaging the coordinates of the nodal points of the polygons. For this, it is necessary to double-apply the operation of generalized change (25) to the MIO of dimension T^5. The dimensions in the original MIO will be reduced, containing the numbers of the nodal points of the contour line of the polygon and the numbers of lines that bound the polygon.

$$\begin{cases} T^4_{output} = G^4_f(T^5) = \{G^3_f(T^4_i)\} * S_5, \\ T^1_{output} = G^1_F(T^2) = \{f_1(T^0_{1,1}, \dots, T^0_{1,k_1})\} * S_2, \end{cases} \qquad (32)$$

where k_1 is the number of MIO T^0_1 containing spatial information, function $f_1 : (x_1,\dots, x_k) \rightarrow y$:

$$y = f_1(x_1, \dots, x_k) \frac{x_1 + \dots + x_k}{k}$$

$$\begin{cases} T^3_{output} = G^3_f(T^4) = \{G^2_f(T^3_i)\} * S_4, \\ T^1_{output} = G^1_F(T^2) = \{f_1(T^0_{2,1}, \dots, T^0_{2,k_2}), f_3(T^0_{3,1}, \dots, T^0_{3,k_3})\} * S_2 \end{cases} \qquad (33)$$

where k_2 is the number of MIO T^0_2 containing spatial information, k_3 is the number of MIO T^0_3 containing attributive information, function $f_3 : (x_1,\dots, x_k) \rightarrow y$:

$$y = f_3(x_1, \dots, x_{k_3}) = x_1 + x_2 + \dots + x_{k_3}$$

2. It is necessary to again apply the operation of generalized change (18) to obtain a set of points, described polygonal objects of general planning for each district, obtained at the previous stage. The resulting set of points contains the total attributive characteristics for each construction site. Thus, applying the generalized change operation (18) to T^3_{output}, the dimension that contains the codes of the general planning objects is reduced. It turns out a new MIO T^2_{output}, which describes a set of points containing attributive characteristics of spatially located objects of general planning according to their coordinates.

$$\begin{cases} T^2_{output} = G^2_f(T^3) = \{G^1_f(T^1_i)\} * S_3, \\ T^1_{output} = G^1_F(T^2) = \{f_1(T^0_{4,1}, \dots, T^0_{4,k_4}), f_3(T^0_{5,1}, \dots, T^0_{5,k_5})\} * S_2 \end{cases} \qquad (34)$$

where k_4 is the number of MIO T^0_3 containing spatial information, k_5 is the number of MIO T^0_4 containing attributive information

The description of the generalized change operation in the form (26) allows the processing of various data elements using various transformations. There are tasks in information systems for processing spatial information that involve the transfer and generalization of data between organizational levels for objects that describe the same phenomena of the real world.

The generalized change operation (26) is used to process only data elements describing a spatial object. This operation is not applicable to obtain generalized data on the objects of general planning, not at the level of a separate construction area, but at the level of the general plan of the city. To solve the problems of generalization of this kind, it is necessary to determine yet another operation to change the MIO, which will be called spatial generalization. Its main differences from the operation of generalized change (structural generalization) are the following factors. The result of applying the spatial generalization operation to a set of MIOs, each of which has dimension n, is a MIO of the same dimension. There is a transformation of the entire object, which is called geoprocessing. Denote this transformation as:

$$g = \{F_s, F_A\},\ g: \{T_i^3\} \underset{i}{\rightarrow} T^3, \qquad (35)$$

where F_s is spatial transformation function, F_A is set of functions data element transformation.

The difference of these transformations from the set of functions F from (26) is that the spatial transformation, due to its complexity, cannot be divided into transformations of individual data elements that store coordinate values. For example, there is a decrease in the detail of objects during the transition from the district level of management to the city level. The spatial generalization operation is determined by such a system of equations:

$$\begin{aligned} T_{output}^{n-1} &= G_g(T^n) = \{G_g(T_j^{n-1})\} * S_n, \\ T_{output}^{3} &= g(\{T_i^3\}), \end{aligned} \qquad (36)$$

where $j = \overline{1, k_n}$, k_n is the number of T_j^{n-1}, g is geoprocessing function.

As an example of such spatial generalization, consider the task of forming generalized indicators for general planning objects at the level of the city's territorial administration. Such a department has subordinate seven territorial district administrations.

Each territorial district administration is assigned a controlled territory, on which there are many objects of general planning. The source data is a set of information on administrative areas located in the area of responsibility of the territorial administration. Each construction site can be described as a polygonal object, which is described by the MIO $T_{k,i}^3$. As a result of the transformation, it is necessary to obtain a polygonal object that describes the general plan of the city and contains the characteristics of all district master plans. Let us designate the polygonal object for the general plan of the city as an MIO T_{TY}^3 of dimension 3:

$$T_{TY}^3 = g(\{T_{k,i}^3\}), \qquad (37)$$

where k is the number of municipal master plans, and g is geoprocessing function, which is determined, according to (35), as follows:

$$g = \{F_s, F_A\} \qquad (38)$$

Spatial transformation F_s is the operation of combining polygons (since the set of boundaries of administrative regions determines the polygon of the area of responsibility of the territorial administration), and the transformation $F_A = \{f_i\}$ consists of functions such that:

$$\begin{aligned} &f_i: (x_1, \ldots, x_k) \to y \\ &y = f_i(x_1, \ldots, x_{k_1}) = x_1 + x_2 + \ldots + x_{k_i} \end{aligned} \qquad (39)$$

where i is the number of classes of objects of general planning, k_i is the number of attributes of the number of objects of this class.

The result of the operation is a territorial control polygon. This is the master plan of the city, described by the MIO T_{TY}^3 and obtained by combining the polygons of the administrative regions that are part of this territorial administration, and containing objects of general planning.

Figure 1 shows the algorithm of the proposed method of generalizing spatial information into a single multidimensional data model based on multidimensional information objects.

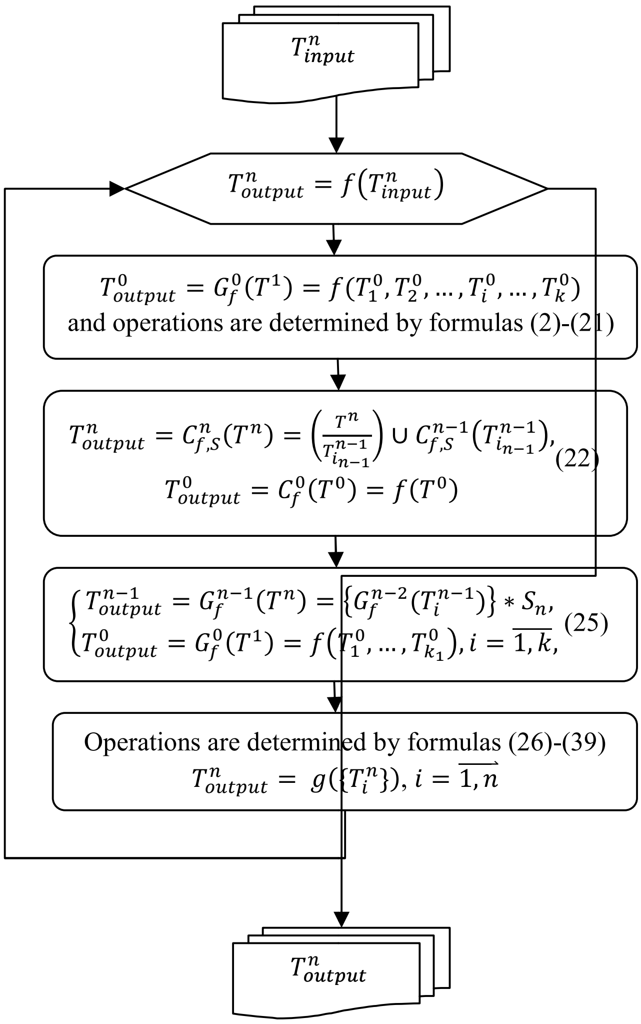

Fig.1. The algorithm of the method of generalizing spatial information into a single multidimensional data model

III. RESULT AND DISCUSSION

Graphical results of the application of the operation of a simple change of the MIO given by formulas (17)-(20) using the example of changing the value of the Z coordinate for the MIO of dimension 3 describing the polygonal object are shown on figures 2 and 3.

Figure 2 shows a graphical model of the MIO dimension 3 describing a polygonal object before applying the operation of a simple change of MIO.

Figure 3 shows a graphical model of the MIO dimension 3 describing a polygonal object after applying the operation $C_f^0\left(T_{A2}^0\right)$ of a simple change of MIO.

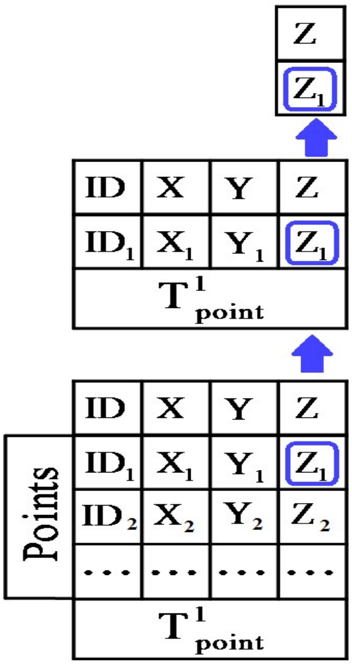

Fig.2.Graphical model of the MIO describing a polygonal object before applying the operation of a simple change

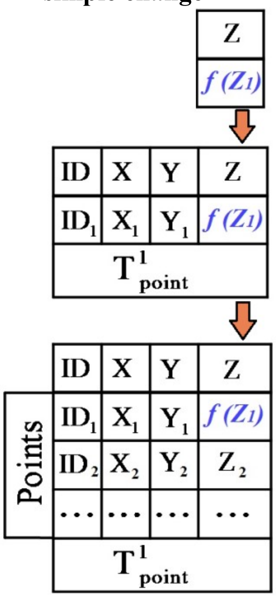

Fig.3. Graphical model of the MIO describing a polygonal object after applying the operation of a simple change

The scheme on figure 3 shows graphical result of applying the sequential use of the generalized change operation of MIO.

Figure 4 a) shows an example of visualization of a point layer of objects of general planning of placement on the design plan of a city housing area.

Figure 4 b) shows the new MIO will be obtained as a result of transformations by formulas (32)-(33).

Figure 4 c) shows a set of points for polygonal objects with attributive characteristics on general planning according to their coordinates.

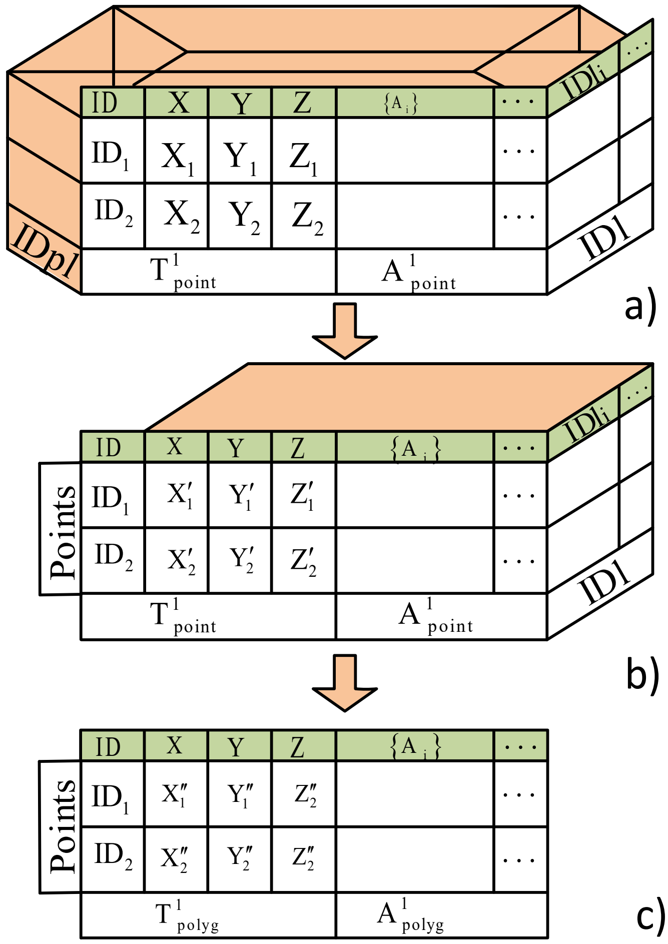

Fig.4. Graphical representations of the sequential use of the generalized change operation of MIO

IV. CONCLUSION

This study proposed method of generalizing spatial information into a single multidimensional data model technology based on multidimensional information objects. This advanced method is intended to describe various types of spatial information of general planning objects at a construction site and their generalization into a single multidimensional model of general plan data.

Scientific novelty is the use of multidimensional information objects to describe various parts of distributed spatial data and their generalization into a single model based on the newly introduced change operation.

Using this method allows for the integration into a single information space of heterogeneous spatial information at all organizational levels of the territory management while maintaining its integrity.

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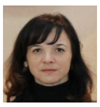

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