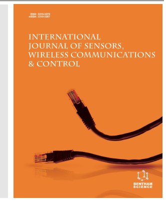
International Journal of Sensors, Wireless Communications and Control, 2021, 11, 498-504

RESEARCH ARTICLE



Formation of Hypercubes Based on Data Obtained from Systems of IoT Devices of Urban Resource Networks

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ARTICLE HISTORY

Received: March 31, 2020
Revised: June 09, 2020
Accepted: June 26, 2020

DOI:
10.2174/2210327910999201210145151

Abstract: ***Aim*:** The aim of this work is to construct a system of interrelated procedures that are used in the formation of data warehouses for information systems in smart cities.

***Objectives*:** Currently, the number of IoT devices integrated into the systems of information technology support of the processes taking place in supply networks of resources of Smart City, is constantly growing. While functioning, extensive sets of various types of information are generated. Using a single database, it is not possible to store data sets collected for multiple resource networks on a large city scale.

***Methods*:** This work is devoted to the research and improvement of processes of formation of data hypercubes, which are an informational model of functioning of urban resource networks on the basis of data coming from systems of IoT devices. Methods of information modeling and construction of data hypercubes were used in research, taking into account the high dynamics and rapidity of resource supply processes.

***Results*:** In this study, mainly the data hypercubes were constructed on the basis of the proposed improved methods that work based on messages received from real-functioning systems of IoT devices in urban resource networks. The use of this technology in the framework of information and technological support of the processes in urban resource networks provides an opportunity for detailed analysis of the current state of material resources of the city, and identifies trends in their changes and states by comparing data belonging to different time periods and different by origin collections.

***Conclusion*:** The basic characteristics of the data warehouse, which provides information about urban resource networks, are analyzed. The analysis and construction of data hypercubes prototypes on urban resource networks were carried out. Classification and parameterization of many categories and attributes were carried out to describe processes in urban resource networks, which allowed, using the OLAP information technology based on hypercubes, to develop information technology of complex multidimensional data analysis, obtained using IoT devices that characterize the flow of processes in the urban resource networks. The obtained results propose the procedures of formation of data hypercubes, containing information about the progress of urban resource networks, used in the development of real information systems that collect data using IoT devices. The information technology of process support in urban resource networks is developed for use in different types of resource networks in the presence of several providers.

Keywords: Hypercube, data warehouse, IoT device, resource network, smart city, dimension.

1. INTRODUCTION

With the rapid development of information technology, climate and environmental change, projects of smart city are created. The implementation of the projects gives the city administrations, institutions and organizations the opportunity to improve the procedures of providing service by means of urban resource and socio-communication networks. This approach requires the development of new models, methods and information technologies. One of the ways to solve the problem is the information technology of multidimensional data analysis in urban resource and socio-communication networks, which is formed on the basis of methodology of

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2210-3287/21 $65.00+.00

data hypercubes construction with the use of generated set of categories and attributes that are used to describe processes in resource and socio-communication networks.

2. RELATED INVESTIGATIONS

The tools of classic relational databases do not allow us to fully and comfortably submit and process messages over long periods. This has become one of the factors in the formation of data models of the "star" type. This has led to the emergence of a new class of data models based on the formalism of data hypercubes. Classic relational databases do not provide a convenient representation in cases where it is necessary to perform procedures for analysis and search for hidden patterns in large data sets.

It is proposed to use the technology of complex multidimensional data analysis (OLAP) to support decision-making for system analysis of the activities of general education institutions.

A work [1] shows the results of using complex multidimensional data analysis to conduct effective procedures of forming a unified university.

In a research work [2], the methodology of using multidimensional data analysis is presented in detail.

The authors, Huaxing Xing, Claudette Vaught, and Edgar Chambers [3], developed a simulation model to identify factors that contribute to product optimization and provide a deeper understanding of product indicators.

Janus Christian Jakobsen, Christian Gluud, and Jørn Wetterslev, Per Winkel [4] suggest using a multidimensional data analysis methodology to recover missing data, the absence of which could result in serious data loss. The authors note that data analysis with missing values requires careful planning and attention.

A smart city [5], according to Michael Scriney, Mark Roantree, requires the analysis of data sources from many providers in different formats. Data is obtained mainly from web streams, and its analysis can be done to improve the lives of citizens in areas such as transport, urban planning, environment and housing.

However, data incoming from these streams, for further processing with the use of OLAP technologies, is imported from data web streams and automatically generated in a cube format using StarGraph construction developed by authors.

The aim of this work is to construct a system of interrelated procedures that are used in the formation of data warehouses for information systems in smart cities.

3. MATERIALS AND METHOD

3.1. Characteristics of a Data Warehouse of Urban Resource Networks

Ensuring the effective functioning of urban resource networks generates the need to build interrelated procedures for the formation of data warehouses of information systems in smart cities.

Data warehouse [6] is a subject-oriented, integrated, permanent, chronological data set, which can be a comprehensive source for information technology "Intelligent data processing" (IDP) – IT_{IDP} and decision support systems (DSS) – IT_{DSS} [7]. The data warehouse for storing information entities, obtained using IoT devices regarding the operation of smart city resource networks, has the following features:

- Obtaining, normalizing, storing and presenting detailed and aggregated data from different types of sources integrated using IoT devices in the infrastructure of urban resource networks;
- Multidimensional representation of data collections accompanied by metadata with descriptions of the data structure and data warehouse structure for information technology support of processes in resource networks;
- Availability of software agents to implement procedures to import data from existing databases and data warehouses of organizations that supply resources and procedures for uploading them in universal formats;
- Availability of complex analytical processing procedures based on IT_{IDP} and IT_{DSS} with a purpose of obtaining new data and knowledge;
- Subject-oriented representation of data collections on current processes of smart city resource networks and IoT devices functioning.

The scheme of data aggregation into data warehouses for smart city resource networks is presented in Fig. (**1**).

Subject Orientation: Data in the data warehouse is organized according to the basic aspects of urban resource networks (resource, provider, IoT device, input, sensor, indicator, and so on). The correct organization of data storage in urban resource networks according to a domain-specific approach makes it possible to significantly simplify analytical processing procedures and increase the speed of search and analytical queries. Data is stored in specialized multidimensional DBMS based on n-dimensional cubes.

Integrity: Outputs about processes in smart city resource networks are extracted from the database of suppliers of resources, institutions, organizations, software-algorithmic complexes, IoT devices, mobile and web applications. The received data is validated, cleared and filtered, normalized and aggregated (primary processing and calculation of generalized and total indicators are performed) and uploaded to the appropriate storage.

Temporal data binding: Stored data about processes occurring in urban resource networks must have clear time tags that are bound to specific time periods. Data selected from operational databases is accumulated in the data warehouses as "historical collections" according to a specific period of

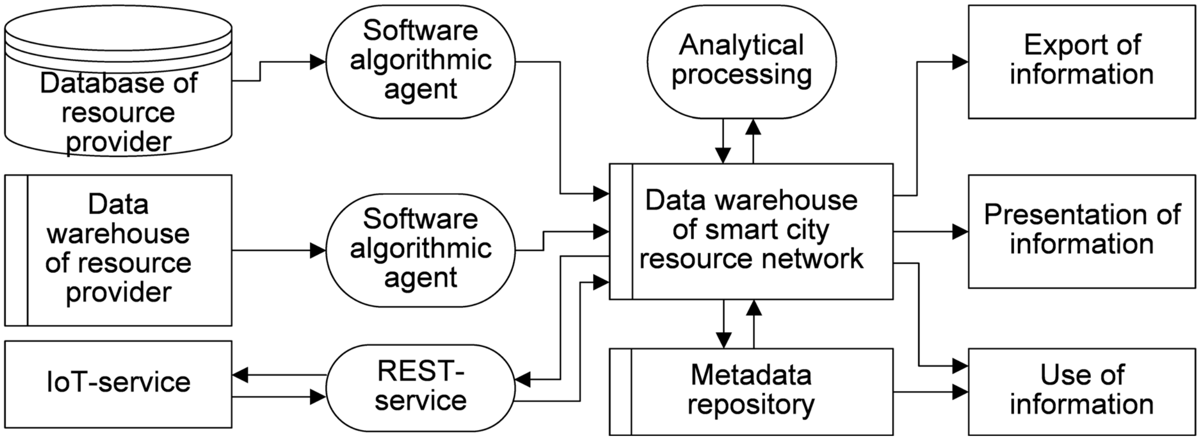

Fig. (1). Scheme of data aggregation into data warehouses for smart city resource networks.

time. Usually, data from urban resource networks is characterized by high dynamics and transience of processes, which allows us to analyze trends in the processes of their functioning.

Invariability: Once in a certain "historical collection" of repositories, data on urban resource networks cannot be changed and adjusted.

In a research work [8], an orgnanized description of the data warehouse of smart city resource network is presented as:

$$DW = \langle NR, DB, RF, rm, RM, func \rangle, \quad (1)$$

where NR is a set of resource networks;

DB is a set of relationships and their schemas and constraints that contain information from input databases (databases of institutions and organizations, including providers of resources, *etc*.);

RF is a scheme of a set of relations of facts rf ;

RM is a scheme of a set of relations of metadata rm ;

$func$ is a set of decision-making procedures.

The acquisition of new knowledge is to extract data from the collections of data warehouse through the implementation of functions $func$ based on the facts rf , taking into account the requirements according to the needs of the users. The relationships between sets rf and DB form hypercubes of data whose dimensions are a set of relations RF of data warehouses of urban resource networks. The peculiarities of the use of intellectual, analytical tools in the development process of data warehouse for smart city resource networks open up the possibility for more accurate disclosure and presentation of the features of data, gathered in the appropriate collections [9].

Based on the proposed formal descriptions and procedures, information technology has been formed.

3.2. Information Technology of Multidimensional Analysis of Data Obtained Using IoT Devices in Urban Resource Networks

One of the key components of process support in smart city resource networks is the organization of a data warehouse and information technology of multidimensional data analysis - OLAP (Operational Analytical Data Processing). The use of this technology in the framework of information and technological support of processes in urban resource networks provides an opportunity to conduct a detailed analysis of the current state of material resources of the city, as well as identify trends in their changes and states by comparing data belonging to different time periods and different collections by origin.

The processes of generalizing the detailed collections of data collected in resource networks are commonly used in smart city OLAP systems. This allows to obtain new knowledge on various aspects of the analysis, and interrelated information sets obtained with the use of IoT devices integrated into urban infrastructure [10-12]. Output datasets for analytical processing with the help of OLAP data on urban resource networks are the cost metrics for consumed resources, including water, gas, electricity and heat, and so on. The basis of OLAP information technology is a multidimensional data model whose basic entities are: hypercube of data rel , dimension D , attribute A , cell X , value $rel(D,A)$ [10]. An example of a hypercube of data for urban resource networks is shown in Fig. (**2**).

The hypercube of data, being an ordered set of cells, contains one or more dimensions. Each cell of a hypercube is defined by only one unique set of attribute values – dimensions. A cell can contain an actual value or can be considered empty containing 'Null'.

The set of attributes that form one of the faces of a hypercube is called a dimension. For urban resource networks, the important dimensions are time and geography. For time dimension, attributes are lists of years, quarters, months, days, hours, minutes, and seconds. For geographical dimension, attributes are a list of administrative and territorial objects: areas, districts, settlements, micro district,

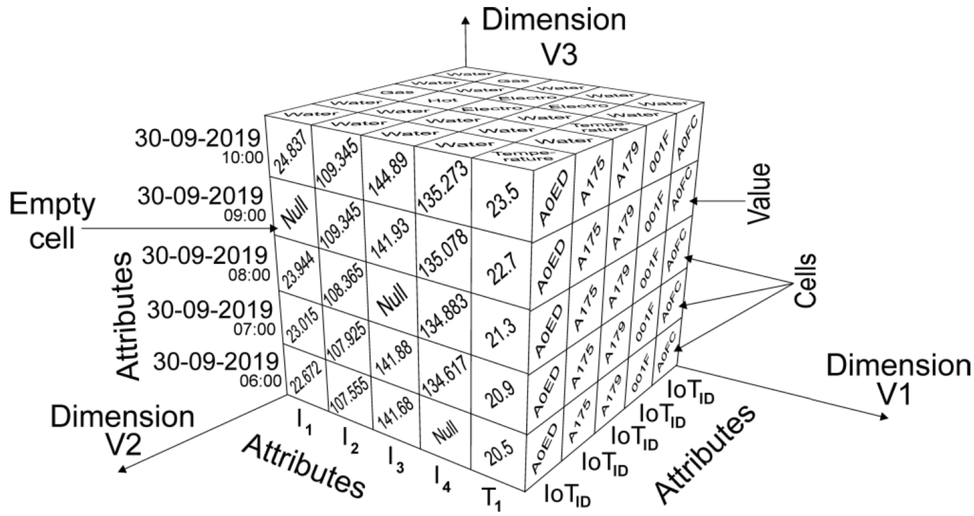

Fig. (2). Hypercube of data of the urban resource networks.

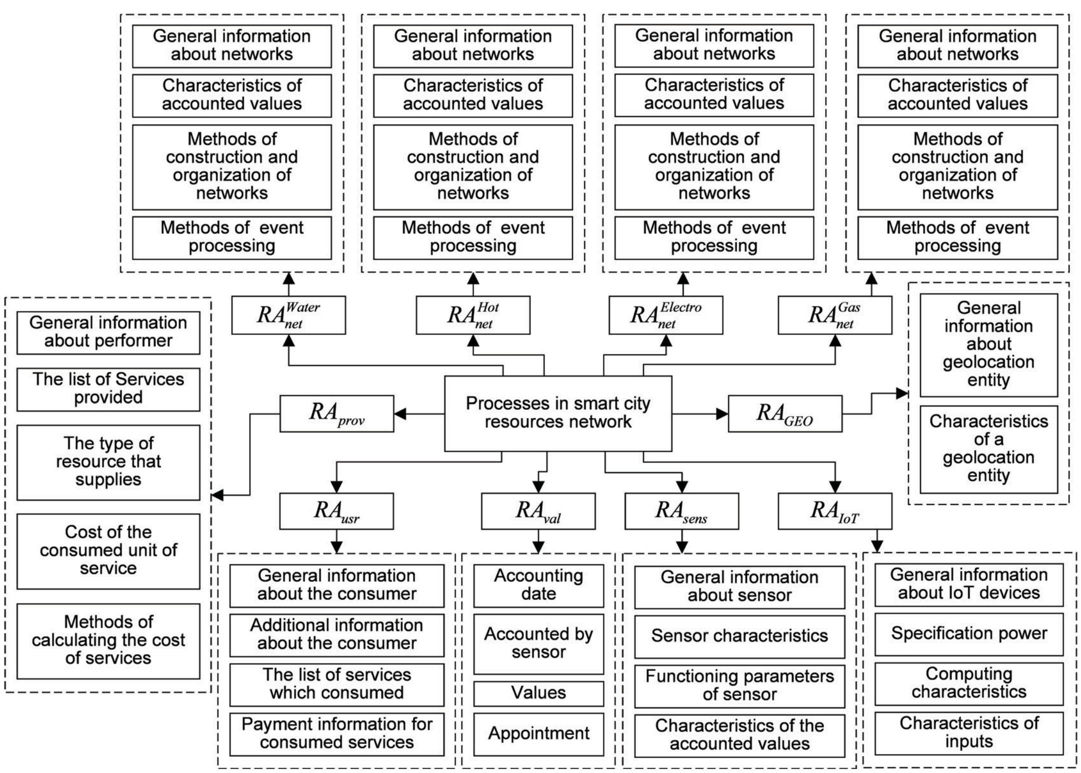

Fig. (3). Data hypercube attributes for information support of processes in urban resource networks.

streets, houses, apartments, *etc*. To access data in the hypercube, the user chooses one or more cells by specifying (fixing) the corresponding values of dimensions. The set of fixed values of dimensions is called the set of fixed attributes.

Multidimensional analysis of data, obtained using IoT devices, through processes in smart city resource networks involves the study and analysis of municipal resource network characteristics, including the selection of multiple attributes used to parameterize the relevant information model (Fig. **3**). The set of categories and attributes RA that are used to describe processes in smart city resource networks is classified as follows:

$$RA = \langle RA_{net} \cup RA_{GEO} \cup RA_{IoT} \cup RA_{sens} \cup RA_{val} \cup RA_{usr} \cup RA_{prov} \rangle. \quad (2)$$

where $RA_{net} = \{RA_{net}^{R}\}$, $R = \{Water, Hot, Electro, Gas\}$ are attributes of each individual urban resource network, including the water supply network $(Water)$, heat network (Hot), electricity $(Electro)$ and gas supply networks (Gas);

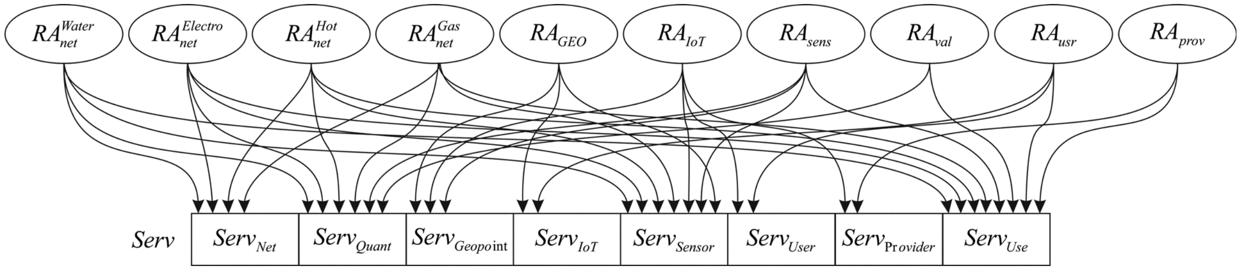

Fig. (4). Aggregation of process attributes of providing services by urban resource networks.

RA_{GEO} is a geolocation attribute category; RA_{IoT} is a category of attributes and properties of IoT devices; RA_{sens} is a category of attributes and properties of sensors, meters and flow meters integrated on a set RA_{net}; RA_{val} is a category of attributes of the description of accounted values of services provided by smart city resource networks from a set RA_{net}; RA_{usr} is a category of attributes of a description of individual consumers of services; RA_{prov} is a category of attributes of a description of performers utilities.

In many cases, attributes in different categories that are used to describe processes in urban resource networks are synonymous and have the same meaning. The full set of attributes can be divided into the following subcategories: Net is information on resource networks; $Quant$ is the characteristics of accounted values; Geopoint is a geolocation anchor point; IoT is the information about IoT devices; $Sensor$ is the information about the sensors; $User$ is the consumer information; $Provider$ is the information about service providers; Use is the information about service consumption.

The information model of the process of providing services by means of urban resource networks is presented as a set of information parameters (Fig. **4**).

Each of the attributes for a separate category:

$$Serv = \left(Serv_{Net}, Serv_{Quant}, Serv_{Geopoint}, Serv_{IoT}, Serv_{Sensor}, Serv_{User}, Serv_{Provider}, Serv_{Use}\right) \quad (3)$$

provides an appropriate characteristic of processes in resource networks, and together they characterize the processes of providing services by a set of urban resource networks.

The attributes selected for the purpose of describing processes were used to build a multidimensional information model of urban resource networks, represented as a hypercube of data:

$$S_{Prov}^{Res}\left(Dim^{Res}, Attr^{Res}\right) \quad (4)$$

where Dim^{Res} is a set of hypercube dimensions; S_{Prov}^{Res} is a service provided by a set of performers; $Prov^{Res} = \left\{Prov_k^{Res}\right\}$, $k = \overline{1,n}$ using a set of the urban resource networks $R_j, j = \overline{1,m}$, in particular, water, heat, electricity and gas; $Attr_{Dim_i^{Res}}^{Res} = \left\{Attr_{1_i}^{Res}, Attr_{2_i}^{Res}, \ldots, Attr_{n_i}^{Res}\right\}$, $i = 1, \ldots, m$ are multiple attributes specific to a dimension Dim_i^{Res}; $Attr^{Res} = Attr_1^{Res} \cup Attr_1^{Res} \cup \ldots \cup Attr_m^{Res}$ is a set of attributes specific to the hypercube; $Dim'^{Res} \subseteq Dim^{Res}$ is a set of fixed dimensions of the hypercube; $Attr'^{Res} \subseteq Attr^{Res}$ is a set of fixed attributes of the hypercube. Let us denote $S'^{Res}_{Prov}\left(Dim'^{Res}, Attr'^{Res}\right)$, that is used to represent a description of a subset of data hypercube $Prov^{Res}$, that corresponds to a set of fixed values to which a set of fixed dimensions must be specified $Dim'^{Res} \subseteq Dim^{Res}$ and fixed attributes values $Attr'^{Res} \subseteq Attr^{Res}$. The set of cells corresponding to the fixed attributes and dimensions will be indicated by $S'^{Res}\left(Dim'^{Res}, Attr'^{Res}\right) \middle| S_{Prov}'^{Res} \subseteq S_{Prov}^{Res}$. We will call the dimension key an attribute that uniquely specifies the tuple (string) of the hypercube dimension. The above mentioned and analyzed complexes of parameters for the description of processes in smart city resource networks allow us to form the following dimensions of a multidimensional data model:

Dim_1^{Res} is data about the input types of IoT devices, in particular $Attr_{Dim_1^{Res}}^{Res} = \left\{Attr_{i_1}^{Res}, i = \overline{1,3}\right\}$ is a set of dimension attributes Dim_1^{Res}, where $A_{1_1}^{Res}$ is a name of the input signal type, $A_{2_1}^{Res}$ is a letter designation, $A_{3_1}^{Res}$ is the assigning inputs. Dim_2^{Res} is the data about sensor types, in particular, $Attr_{Dim_2^{Res}}^{Res} = \left\{Attr_{i_2}^{Res}, i = \overline{1,8}\right\}$ is a set of dimension attributes Dim_2^{Res}, where $A_{1_2}^{Res}$ is a name of the counter type, $A_{2_2}^{Res}$ is a type of input to which the sensor can be connected, $A_{3_2}^{Res}$ is an indications divider, $A_{4_2}^{Res}$ is an indications multiplier, $A_{5_2}^{Res}$ is an offset of indications, $A_{6_2}^{Res}$ to calculate costs, $A_{7_2}^{Res}$ is the unit of measure of indicators, $A_{8_2}^{Res}$ is the resource for which it is used. Dim_3^{Res} is data regarding the types of IoT devices, in particular $Attr_{Dim_3^{Res}}^{Res} = \left\{Attr_{i_3}^{Res}, i = \overline{1,7}\right\}$ is a set of dimension attributes Dim_3^{Res}, where $A_{1_3}^{Res}$ is a name of the IoT device type, $A_{2_3}^{Res}$

is a set of inputs, $A_{3_3}^{\text{Res}}$ is a method of obtaining data, $A_{4_3}^{\text{Res}}$, to create a data spreadsheet, $A_{5_3}^{\text{Res}}$ is an operating directory for temporary and historical data, $A_{6_3}^{\text{Res}}$ is the beginning of the name of temporary and historical data files, $A_{7_3}^{\text{Res}}$ is a group number of online commands.

Dim_4^{Res} is a data on installed IoT devices, in particular $Attr_{Dim_4^{\text{Res}}}^{\text{Res}} = \left\{Attr_{i_4}^{\text{Res}}, i = \overline{1,16}\right\}$ is a set of dimension attributes Dim_4^{Res}, where $A_{1_4}^{\text{Res}}$ is a name of the installed IoT device, $A_{2_4}^{\text{Res}}$ is a type of installed IoT device from the set Dim_3^{Res}, $A_{3_4}^{\text{Res}}$ is a manufacturer's serial number, $A_{4_4}^{\text{Res}}$ is the purpose of the installed IoT device, such as for a group, individual, service, and so on, $A_{5_4}^{\text{Res}}$ is a settlement, $A_{6_4}^{\text{Res}}$ is a microdistrict, $A_{7_4}^{\text{Res}}$ is a street, $A_{8_4}^{\text{Res}}$ is an identifier of the anchor point GIS (geographic information system), $A_{9_4}^{\text{Res}}$ is the ID of the responsible person, $A_{10_4}^{\text{Res}}$ is a phone number of the responsible person, $A_{11_4}^{\text{Res}}$ is an altitude, $A_{12_4}^{\text{Res}}$ is a number of houses, $A_{13_4}^{\text{Res}}$ is a number of entrances, $A_{14_4}^{\text{Res}}$ is a number of apartments, $A_{15_4}^{\text{Res}}$ is a brand of installed battery, $A_{16_4}^{\text{Res}}$ is a date of battery installation.

Dim_5^{Res} is the data regarding sensors connected to installed IoT devices, in particular $Attr_{Dim_5^{\text{Res}}}^{\text{Res}} = \left\{Attr_{i_5}^{\text{Res}}, i = \overline{1,8}\right\}$ is a set of dimension attributes Dim_5^{Res}, where $A_{1_5}^{\text{Res}}$ is the name of the connected sensor, $A_{2_5}^{\text{Res}}$ is the sensor type from the set Dim_2^{Res}, $A_{3_5}^{\text{Res}}$ is the manufacturer's serial number, $A_{4_5}^{\text{Res}}$ is the purpose of the installed sensor, in particular nodal, house, driveway, site, apartment, individual, etc, $A_{5_5}^{\text{Res}}$ is the ID of the IoT device's input to which the sensor is connected, $A_{6_5}^{\text{Res}}$ is the ID of the resource network R_j in which the sensor is integrated, $A_{7_5}^{\text{Res}}$ is the ID of the top-level sensor, according to the hierarchical structure of the resource network, $A_{8_5}^{\text{Res}}$ is the role of the accounted value in relation to the resource network (resource generation, resource consumption, combined).

Dim_6^{Res} is the data about individual consumers of resource network services, in particular $Attr_{Dim_6^{\text{Res}}}^{\text{Res}} = \left\{Attr_{i_6}^{\text{Res}}, i = \overline{1,8}\right\}$ is a set of dimension attributes Dim_6^{Res}, where $A_{1_6}^{\text{Res}}$ is the surname, $A_{2_6}^{\text{Res}}$ is the name, $A_{3_6}^{\text{Res}}$ is the middle name, $A_{4_6}^{\text{Res}}$ is the settlement, $A_{5_6}^{\text{Res}}$ is the postal address, $A_{6_6}^{\text{Res}}$ is a form of ownership, $A_{7_6}^{\text{Res}}$ is the ID number, $A_{8_6}^{\text{Res}}$ is the phone number. Dim_7^{Res} is the data on accounting sensor indicators, in particular, $Attr_{Dim_7^{\text{Res}}}^{\text{Res}} = \left\{Attr_{i_7}^{\text{Res}}, i = \overline{1,4}\right\}$ is a set of dimension attributes Dim_7^{Res}, where $A_{1_7}^{\text{Res}}$ is the date and time of indicator accounting, $A_{2_7}^{\text{Res}}$ is the ID of a sensor of the accounted indicator from a set of dimensions Dim_6^{Res}, $A_{3_7}^{\text{Res}}$ is the ID of services executant from a set of executants $Prov^{\text{Res}}$, $A_{4_7}^{\text{Res}}$ is the ID of the resource network from a set R [11, 12].

The values given above of the dimensions (attributes) along each axis of the hypercube are hierarchically combined into one or more levels. This allows us to create hierarchical dimensions for further data analysis in order to explain them (Fig. **5**).

Aggregation of data in OLAP cubes of smart city resource networks is the process of obtaining new aggregates (values) corresponding to attributes of a certain level L based on the lower-level values $L-1$. These dimensions are the axes of hierarchical dimensions for resource networks $Prov_i^{\text{Res}}$, R_j and Dim_k^{Res}, containing the initial attributes of the lowest hierarchical level $(L=0)$ and can be supplemented by attributes of higher hierarchical levels of $L=1$ [13, 14].

To get the required subsets of resource cells $S_{\text{Prov}}^{\text{Res}}{}' \subseteq S_{\text{Prov}}^{\text{Res}}$ in order to cut off "unnecessary" values by sequentially fixing the attributes, we use the slice operation.

Thus, on the basis of research and improvement of the processes of data hypercubes formation, an information model of the functioning of urban resource networks [15] on the basis of data obtained from the systems of IoT devices

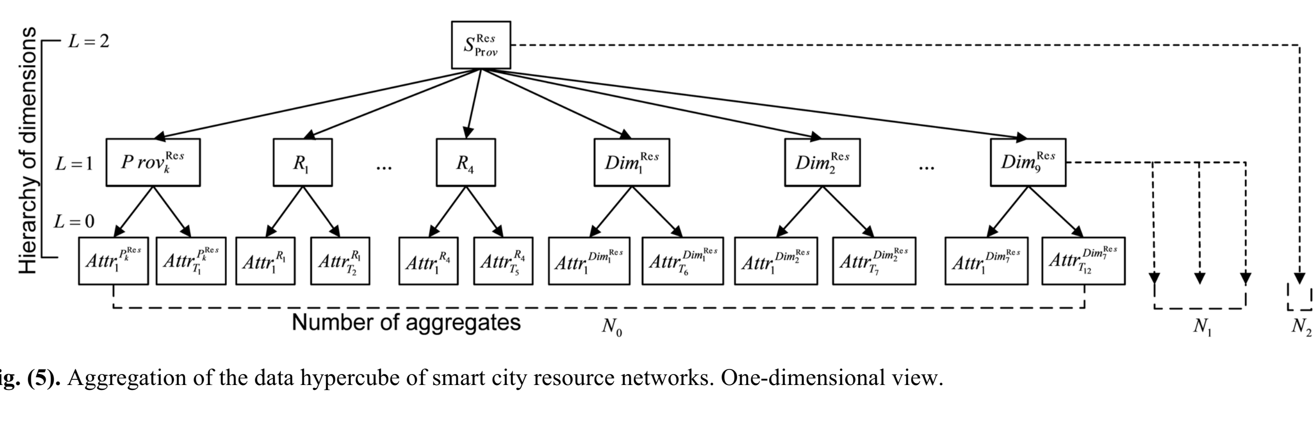

Fig. (5). Aggregation of the data hypercube of smart city resource networks. One-dimensional view.

has been designed. The practice of using the proposed information technology in the information and technological support of processes in urban resource networks facilitates regular monitoring of the current state of material resources of the city, as well as identifies changing trends in order to process events in urban resource networks with different types of resources.

CONCLUSION

The basic characteristics of the data warehouse, which provide information about urban resource networks, were identified and analyzed. The analysis and construction of data hypercubes prototypes on urban resource networks were carried out.

Classification and parameterization of many categories and attributes were carried out to describe processes in urban resource networks, which allowed, using the OLAP information technology based on hypercubes, to develop information technology of complex multidimensional data analysis, obtained using IoT devices that characterize the flow of processes in the urban resource networks.

The obtained results propose the procedures of formation of data hypercubes, containing information about the progress of processes in urban resource networks, used in the development of real information systems that collect data using IoT devices.

The information technology of process support in urban resource networks is developed for use in different types of resource networks in the presence of several providers.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIAL

Not applicable.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

The authors thank the reviewers for the relevant comments.

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