An Approach of Taxonomy of Multidimensional Cubes Representing Visually Multivariable Data

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Abstract. In data visualization, graphs representing multivariable data on multidimensional coordinates shaped cubes enable human to understand better the significance of data. There are various types of cubes for representing different datasets. The paper aims at classifying kinds of cubes to enable human to design cubes representing multivariable datasets. Mathematically, the functional relations among five groups of variables result in the way to structure cubes. The paper classifies cubes as three kinds by the characteristics of datasets, including non-space, 2D-space, and 3D-space multidimensional cubes. The non-space multidimensional cubes are applied for non-space multivariable datasets with variables of objects, attributes, and times. The 2D-space multidimensional cubes are applied for the datasets of movers or objects located on ground at time units. The 3D-space multidimensional cubes are applied for the datasets of flyers or objects positioned in elevated space at time units. The correlation in space and/or time shown on the cubes enables human to discover new valuable information.

Keywords: Multidimensional cube · Multivariable data · Multivariate data · Graph representing data · Data visualization

1 Introduction

A graph representing visually multivariable data is estimated as to be effective if it enables well to extract interesting information and/or discover new knowledge. Technically, the effectiveness of graph depends on the structure of the cube representing it. In other words, the structure of cube affects the effectiveness of graph representing a dataset. Mathematically, the structure of cube representing graph has to be appropriate for the characteristics of dataset [1]. Meanwhile, various types of multidimensional cubes (multivariate cubes, visualization cubes, and so on) have been

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proposed to represent visually multivariable datasets as graphs on planar screen. In a cube, each data variable is represented as an axis and each data value or data tuple is represented as a planar mark on screen [1–8].

The issue to be solved is how to structure an effective cube representing a multivariable dataset. The main idea is to classify the cubes representing multivariable data by the characteristics of dataset. Data variables of datasets are grouped into five variable groups including objects, attributes, time, 2D-space, and 3D-space, where each variable or variable group is independent or dependent on others, mathematically. The relations among variable groups are studied to constitute the types of structures of cubes. A taxonomy of multidimensional cubes enables designers to structure coordinates representing a dataset as an effective graph responding analytical questions. The combination of basic cubes composed of non-space cube, 3D-cube, and space-time cube results in three types of multidimensional cubes to represent multivariable datasets, including non-space multidimensional cube, 2D-space multidimensional cube, and 3D-space multidimensional cube.

This paper is structured as follows. The next section depicts the relations among entities by 3W-Triad, OTL-Triad, OATL-Quad, OATL-Pentad and classifies multidimensional cubes according to the groups of the relations. The third section depicts the structure of non-space multidimensional cube and its utilization for data analysis along with an illustration. The fourth section depicts the structure of 2D-space multidimensional cube and its utilization for data analysis along with two case studies. The fifth section depicts the structure of 3D-space multidimensional cube and its utilization for representing flight data. Finally, the sixth section is the conclusion of the paper.

2 Representing the Relations Among Entities

2.1 The 3W-Triad

While representing temporal dynamics in geographic information systems, Peuquet proposed the triad framework representing the relations of questions What, When, and Where [9]. In that, a vertex of the triad is known if the two remainders are given

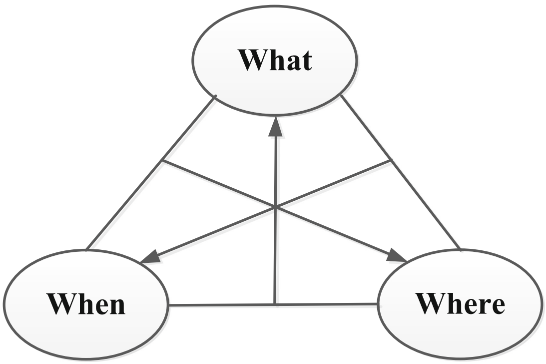

Fig. 1. The 3W-triad representing the relation What-When-Where.

(Fig. 1), i.e. When + Where → What; What + When → Where; What + Where → When. The 3D-triad relations are consistent with forming analytical questions at elementary level of spatio-temporal data analytics.

2.2 The OTL-Triad

While analyzing the movement of objects, Andrienko et al. considered that three sets of data suitable for studying movement are objects, times, and locations, among which the relation can be represented as a triad [10]. The relations in Objects-Times-Locations triad (OTL-Triad) represent the spatial and temporal characteristics of objects (Fig. 2). An object relating with time is considered as a temporal object of which the existent time is determined during observation. An object relating with a location is considered as a spatial object of which the spatial position is indicated during its existence. An object relating to a spatio-temporal position is considered as a spatio-temporal object of which spatio-temporal position is determined during its existence and within observational area. A moving object is a spatio-temporal object of which spatial position changes over time. Attributes of objects are not mentioned in OTL-triad.

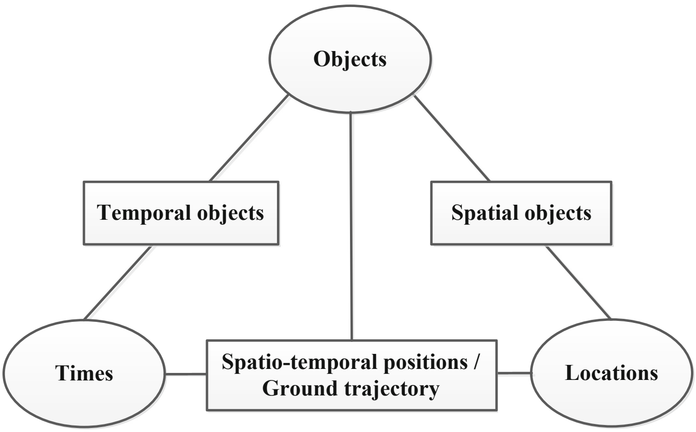

Fig. 2. The OTL-triad representing the relation Objects-Times-Locations.

2.3 The OATL-Quad

In geographic information systems, a dataset is structured by the following sets, objects, attributes, times, and 2D-space. In that, *objects* is the set of bounded and homogenous entities [11], *attributes* are the sets of inherent characteristics of objects, *times* is the set of time units which are instants or time intervals [12], and *2D-space* is the set of objects shaped points, lines, polygons on ground [9, 12]. In the OATL-quad (Fig. 3), the relation between objects and times or between objects and 2D-space defines temporal objects or spatial objects, respectively, the relations between attributes and objects are inherent relations, an attribute is-of objects and an object is-of attributes. As inherent characteristics of objects, attributes together with objects in OATL-quad refer to times or 2D-space. Objects referring simultaneously to times and 2D-space are spatio-temporal objects or moving objects (movers).

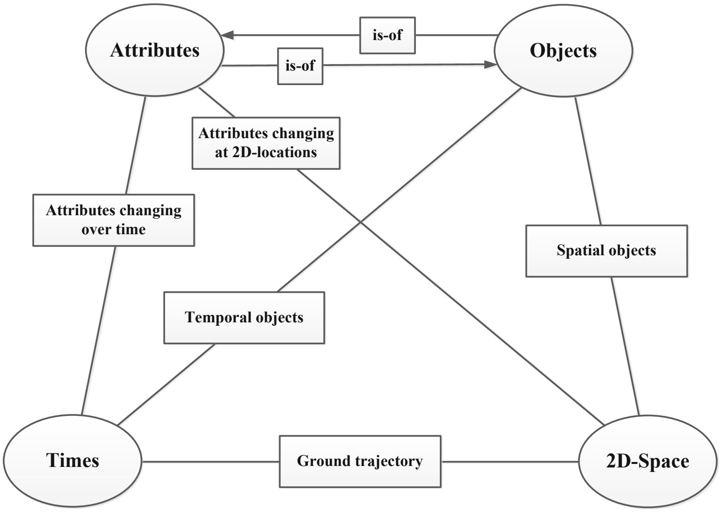

Fig. 3. The OATL-quad representing the relation of Objects-Attributes-Times-2D-Space.

2.4 The OATL-Pentad

OATL-pentad is developed from OATL-quad, where 3D-space is the set of locations positioned in elevated space. The relations among variables in dataset are depicted as OATL-pentad (Fig. 4). In that, *attributes* and *objects* are the variables depending on the reference variables of *times*, *2D-space* or *3D-space*. The dependence of *attributes*, *objects*, and the combination of *objects* and *attributes* on reference variables results in the cases of relations as follows.

– *Referring to time:* The relation of 6 represents the dependence of attributes on time. The relation set of 1, 2, 6 represents the dependence of the combination of objects and their attributes on time.
– *Referring to 2D-space:* The relation of 10 represents the positions of objects on ground. The relation of 5 represents the variation of attributes at ground locations. The relation set of 1, 2, 6, 10 represents different objects at ground and time positions, called spatio-temporal objects, of which the attributes change over time. The relation set of 2, 8, 10 represents the movement of objects on ground, where the ground position of each object changes over time and the relation of 8 traces their ground trajectories. The relation set of 1, 2, 6, 8, 10 represents the ground position and attributes of objects changing over time. The relation set of 5, 6, 8 represents attributes changing at 2D-locations and over time.

– *Referring to 3D-space:* The relation of 7 or the relation set of 7, 4, 10 represents the spatial positions of objects in elevated space, where the relation of 4 indicates the projections of objects on ground. The relation set of 2, 3, 7 or 2, 3, 7, 4, 8 represents the flight of objects in elevated space, where the relation of 3 traces trajectories, the relation of 4 traces the projections of trajectories on ground. The relation set of 2, 3, 7, 1, 6 or 2, 3, 7, 4, 8, 1, 6 represents the change of spatial positions of objects and the variation of their attributes over time, where the relation of 3 traces trajectories in elevated space, the relations of 3 and 4 trace the projections of trajectories on ground, the relations of 4 and 8 trace spatio-temporal trajectories referring to ground.

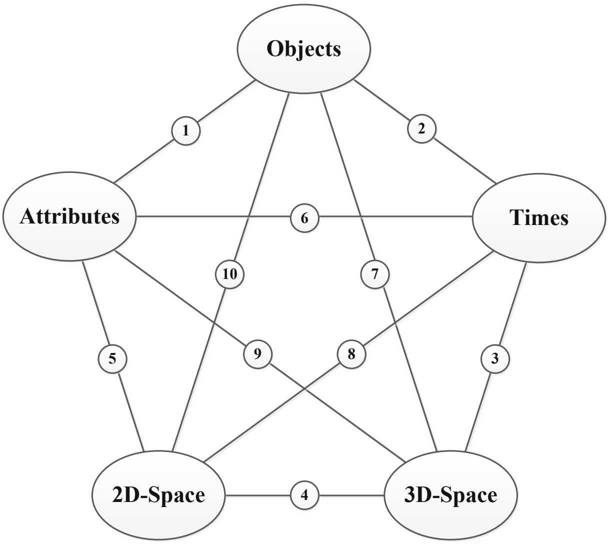

Fig. 4. The OATL-pentad representing the relations of Objects, Attributes, Times, 2D-space, 3D-space in a dataset.

2.5 The Types of Multidimensional Cubes

The functional relations of variables in the studied set of multivariable data shown in OATL-Pentad indicate three reference variables, times, 2D-space, 3D-space and three dependent variables, objects, attributes, and the combination of objects and attributes. The relations are represented in coordinates structured as cubes displayed on planar screen. The cubes are divided into three types according to three reference variables, non-space multidimensional cube, 2D-space multidimensional cube, 3D-space multidimensional cube.

– *Non-space multidimensional cubes:* The non-space multidimensional cubes are designed to represent the dependence of attributes on time by the relation of 6, the dependence of the combination of objects and their attributes on time by the relation set of 1, 2, 6.

- *2D-space multidimensional cubes:* The 2D-space multidimensional cubes without time are designed as traditional maps to indicate the locations of objects on ground by the relation 10, or as topographic maps to represent attributes changing at ground locations by the relation of 5, e.g. the map of landform, the map of temperature. The 2D-space multidimensional cubes with time are designed as multidimensional maps to represent the variation of attributes over time at some different ground positions by the relation set of 1, 2, 6, 10. The 2D-space multidimensional cubes with time are designed as space-time cube to represent objects moving on ground by the relation set of 2, 8, 10. The 2D-space multidimensional cubes with time are designed to represent objects moving on ground and their attributes changing over time by the relation set of 1, 2, 6, 8, 10.
- *3D-space multidimensional cubes:* The 3D-space multidimensional cubes are designed to represent the positions of objects in elevated space by the relation of 7 or the relation set of 7, 4, 10. The 3D-space multidimensional cubes are designed to represent the flight of objects by the relation set of 2, 3, 7, and the flyers together with their attributes changing over time by the relation set of 1, 2, 6, 3, 7, 4, 8.

3 The Non-space Multidimensional Cube

3.1 Structure of Non-space Multidimensional Cube

Non-space multidimensional cube is modified from parallel coordinates by rotating the axis representing the shared-reference variable by 90° to the direction perpendicular to the plane of parallel coordinates (Fig. 5a). For a non-space multidimensional cube, an axis is utilized to represent time which is the shared-reference variable, where time units associating with different attributes are synchronized. The other parallel axes are

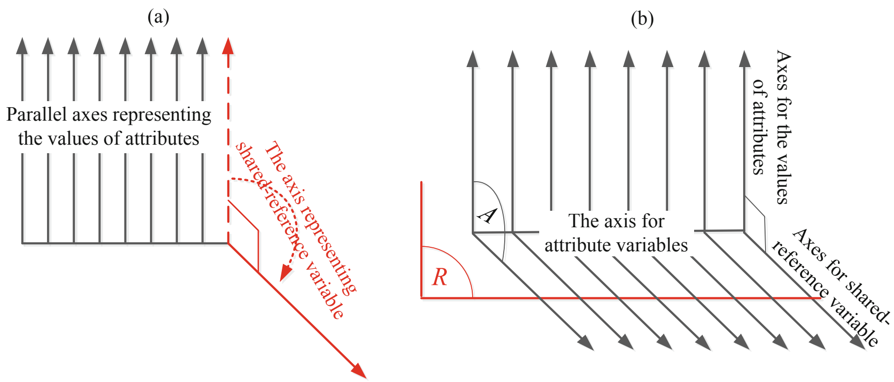

Fig. 5. (a) Non-space multidimensional cube is modified from parallel coordinates by rotating the axis for shared-reference variable; (b) Structure of non-space multidimensional cube with *A* is attribute plane and *R* is relation plane.

utilized to represent attributes or objects referring to time units on time axis. The plane *A* constituted by a time axis and an attribute axis is defined as an attribute plane to represent the values of an attribute or the existence of an object associating with time units (times). The relation plane *R* perpendicular to and moved along time axis shows the correlation between attributes over time (Fig. 5b).

3.2 Non-space Multidimensional Cube for Visual Analytics

For analyzing visually data, human can perceive information and significance of data by viewing graphs on attribute and relation planes of non-space multidimensional cube to answer local, global, and relative questions. Interacting to *A* and *R* planes and viewing the marks on it, human can answer:

- *Local questions:* Local questions are answered by viewing marks on *A* planes. On an *A* plane of a non-space multidimensional cube representing attributes, each mark refers to a value of the attribute of *A* and a time. On an *A* plane of a non-space multidimensional cube representing objects, each mark refers to the title of the object of *A* and a time during the existence of the object.
- *Global questions:* Global questions are answered by viewing marks on *A* planes. Human can perceive the characteristics of an attribute of *A* and answer global questions while viewing the variation of the attribute over time on this *A* plane.
- *Relative questions:* Relative questions are answered by interacting to *R* plane and viewing the marks on it. Moving the *R* plane along the time axis and viewing the marks on it, human can perceive and discover the correlation between attributes.

3.3 Case Study 1: The Non-space Multidimensional Cube Representing Epidemic Data in a Province

The dataset about the hand-foot-mouth epidemic in Binhduong province, Vietnam, during 2012–2014 is constituted by data variables referring time as the number of patients, the average rainfall, the average humidity, and the average temperature (Fig. 6) [2, 3]. Because the dataset does not include spatial data, we represented it on non-space multidimensional cube, where the time units referred by different data variables are synchronized to share the time axis of the cube with all data variables. The non-space multidimensional cube representing dataset of the hand-foot-mouth epidemic enables to answer analytical questions. Especially, moving the relation plane R along the time axis, human may discover the correlation between the number of patients and rainfall and humidity; but there is no correlation between the number of patients and average temperature.

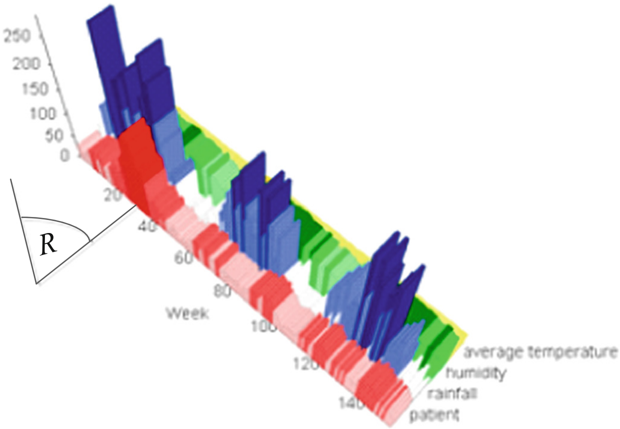

Fig. 6. Non-space multidimensional cube represents the hand-foot-mouth epidemic in Binhduong province, Vietnam, where the marks on relation plane *R* show the possible correlation between the number of patients and rainfall and humidity [2, 3].

4 The 2D-Space Multidimensional Cube

4.1 Structure of 2D-Space Multidimensional Cube

Generally, a 2D-space multidimensional cube is constituted by combining a non-space multidimensional cube with a space-time cube, where the time axis is shared with the cubes. A 2D-space multidimensional cube is used as a 3D-map to represent objects or attributes referring ground locations, as a multidimensional map to represent dataset of attributes referring ground locations and time, as a cube representing objects moving on ground.

For representing the variation of an attribute at locations on ground, the 2D-space multidimensional cube is structured as a 3D-map with 3 orthogonal axes, where two axes indicate locations on ground as a map, another indicates the values of the attribute. According to geographic information science, Thiesen polygon and Delauney triangle enable to represent the variation of attribute at locations on ground [13, 14]. The 2D-space multidimensional cube is suitable for representing terrain, the distribution of temperature or humidity on ground, etc.

For representing the variation of attributes over time at locations on ground, a 2D-space multidimensional cube is structured as a multidimensional map by combining a space-time cube with one or more non-space multidimensional cubes (Fig. 7). The space-time cube is utilized as a map to indicate locations on ground and its time axis is shared with attributes represented at the locations. The attributes at different locations are represented as time-reference variables on different non-space multidimensional cubes. After synchronizing time units on the time axes of non-space multidimensional cubes with time unit on the time axis of space-time cube, the non-space multidimensional cubes are combined with the space-time cube at suitable locations on ground map to form a 2D-space multidimensional cube.

For representing objects moving on ground, a space-time cube is utilized to indicate the ground positions of the objects changing over time [15, 16]. For representing movers along with their attributes, a 2D-space multidimensional cube is utilized to indicate spatio-temporal positions of the objects and the variation of the attributes over time. In studying the movement, attributes changing at locations can transfer to changing over time because locations of objects change over time. The 2D-space multidimensional cube representing movers along with their attributes is formed by combining a non-space multidimensional cube with a space-time cube, where the non-space multidimensional cube shares the time axis with the space-time cube.

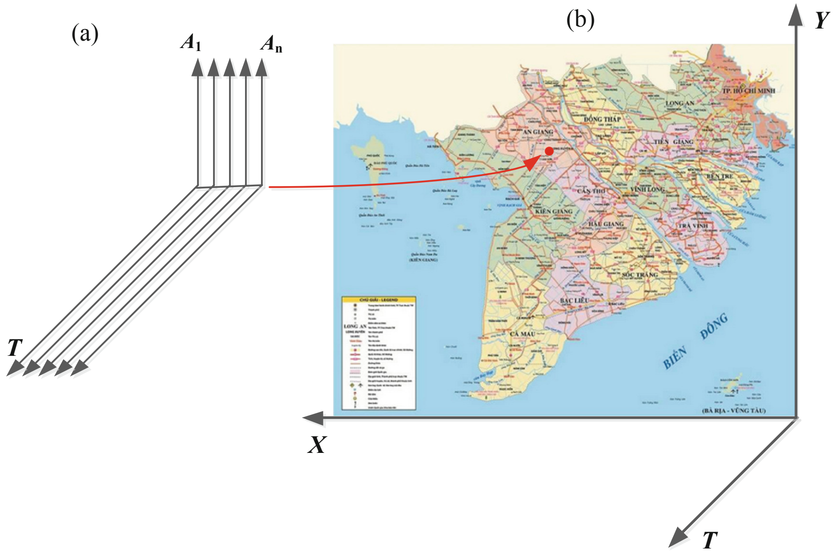

Fig. 7. The 2D-space multidimensional cube, designed as a multidimensional map, is the combination of a space-time cube (Fig. b) with one or more non-space multidimensional cubes (Fig. a) at different spatial positions indicated on the map. (Map source: https://www.google.com.vn/search?source=hp&ei=nuH4XPXpBJyQwgP7yLzQBw&q=b%E1%BA%A3n+%C4%91%E1%BB%93+vi%E1%BB%87t+nam&oq=b%E1%BA%A3n+%C4%91%E1%BB%93+&gs_l=psy-ab.1.0.0l10.1616.6227..9236…4.0..0.79.622.11……0….1..gws-wiz…..0..0i131j0i10.YPYjVWaCMaY)

4.2 The 2D-Space Multidimensional Cubes for Visual Analytics

For analyzing data represented visually on a 2D-space multidimensional cube, human can perceive the information and significance of data by viewing graphs and marks on the cube or on planes parallel or perpendicular to the plane of map.

– *Local questions:* For a cube structured as a 3D-map, the values of an attribute is inferred from the values recorded at indicated spatial positions by approaches of Thiesen or Delauney. For a cube structured as a multidimensional map, the value of an attribute at a spatio-temporal position is indicated on the attribute plane of this attribute of the non-space multidimensional cube at the corresponding spatial position. For a cube representing moving objects, the spatio-temporal position of an object is indicated on the space-time cube and the value of an attribute of an object at a time unit is indicated on the non-space multidimensional cube making up 2D-space multidimensional cube.

Fig. 8. The 3D-map of flood water level is represented visually by integrating the retinal variable of color [17].

– *Global questions:* For a cube structured as a 3D-map, the variation of an attribute at locations within a given spatial zone is perceived by the visual features of graph integrated by retinal variables (Fig. 8). For a cube structured as a multidimensional map, the variation of an attribute over time at a spatial position is studied on the plane of the attribute at the spatial position. For a cube representing moving objects, the ground and spatio-temporal trajectories are perceived on the space-time cube making up the 2D-space multidimensional cube, the variation of an attribute of the moving object over time is perceived on the non-space multidimensional cube making up the 2D-space multidimensional cube.
– *Relative questions:* The 2D-space multidimensional cube structured as a multidimensional map enables to discover the spatial and temporal correlations, the exchange the temporal for spatial correlation and vice versa. The 2D-space multidimensional cube representing moving objects enables to design spatio-temporal trajectories as well as to estimate the attribute correlation of different objects moving together within the same zone.

4.3 Case Study 2: The 2D-Space Multidimensional Cube Representing Epidemic Data at Several Locations

The dataset of the happening of dengue fever epidemic in Angiang, Soctrang, Tiengiang provinces, Vietnam, during 2009–2012 is constituted by data variables referring to time and spatial positions of the provinces [5]. The dataset is divided into three data subsets, each of which is located at a province. Three non-space multidimensional cubes are designed to represent the variables of the number of patients, rainfall, humidity, and average temperature changing over time, where each cube represents the subset of a province. These three cubes are combined with the space-time cube at the locations of corresponding provinces and share the time axis with the space-time cube (Fig. 9a).

It is easy to answer local and global questions by viewing the marks representing data on attribute planes of data variables at provinces. Technically, the relation plane parallel to the map plane indicates the topology relation of the durations of the epidemic happenings at different provinces. The time topology of happenings in Angiang and Soctrang enables human to infer the possible spatial correlation between Angiang and Soctrang. The discovery need to be considered whether there is an epidemical vector from Angiang to Soctrang because Angiang is upstream from Soctrang on Mekong riverside and the epidemic in Angiang happens at the end of the epidemic in Soctrang (Fig. 9b).

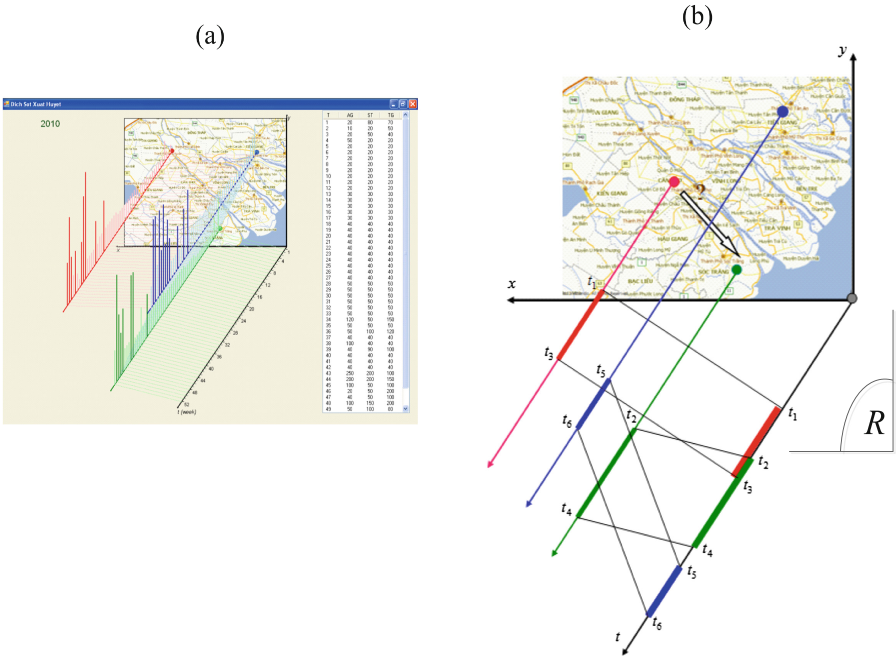

Fig. 9. (a) The 2D-space multidimensional cube represents the dengue fever epidemic in Angiang, Soctrang, Tiengiang provinces, Vietnam, during 2009–2012: (b) The time topology of the epidemic happenings in the provinces shows the possible spatial correlation between the epidemic happenings in Angiang and in Soctrang [5] (Map source: http://www.vietbando.com/maps/?t=0&st=0&l=9&kv=10.0378237,105.853271).

4.4 Case Study 3: The 2D-Space Multidimensional Cube Representing Moving Objects

The dataset of Napoleon's campaign in 1812 to Moscow comprises the data variables of the locations and the times of battles, the number of soldiers going to and coming out each battle, air temperature on retreating. The Napoleon's army is mathematically modeled as a moving object of which the attribute is the number of soldiers. The dataset is composed of the variables of space, time, and the number of soldier dependent on time. In addition, air temperature may be considered as an attribute dependent on time.

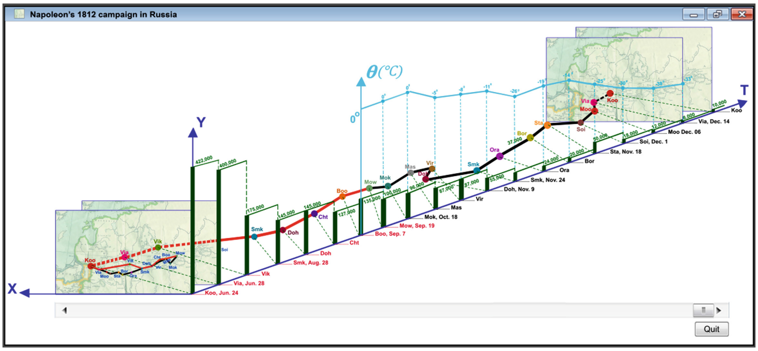

Fig. 10. Napoleon's march to Moscow in 1812 [7]

A 2D-space multidimensional cube may be utilized to represent the dataset (Fig. 10). In that, the space-time cube represents the march of Napoleon's army and the non-space multidimensional cube represents the number of soldiers changing over time. The space-time cube represents the march of the army as a space-time line of which the projection on map represents the line of march on ground. The non-space multidimensional cube represents the number of soldiers of the army coming in and coming out a battle. The space-time cube is combined with the non-space multidimensional cube to form the 2D-space multidimensional cube representing the Napoleon's campaign in 1812. The representation shows the loss of troops at each battle and the possible correlation between air temperature with the loss of soldier on retreating.

5 The 3D-Space Multidimensional Cube

5.1 Structure of 3D-Space Multidimensional Cube

A 3D-space multidimensional cube representing objects in elevated space is constituted by combining a 3D-cube and a non-space multidimensional cube. A 3D-space multidimensional cube for representing flyers is constituted by combining a 3D-cube, a space-time cube, and a non-space multidimensional cube (Fig. 11). In that, the 3D-cube shares ground map with the space-time cube, the non-space multidimensional cube shares the time axis with the space-time cube.

5.2 The 3D-Space Multidimensional Cube for Visual Analytics

– *Local questions:* A 3D-space multidimensional cube representing the data of objects in elevated space enables human to perceive the attributes of the objects at different positions in elevated space. A 3D-space multidimensional cube representing the flight data of flyers enables human to perceive the elevated positions as well as the projections on ground and attributes of the flyers at different time positions. Human views marks on cubes making up 3D-space multidimensional cube to answer local questions.
– *Global questions:* A 3D-space multidimensional cube representing the data of objects in elevated space enables human to perceive the heights of objects as buildings or towers by viewing on the planes parallel to ground map. A 3D-space multidimensional cube representing the flight data of flyers enables human to perceive the state of the flight as well as attributes of an flyer during studied time. Human views on 3D-cube to cognize the trajectories of flyers in elevated space and its projections on ground, views on space-time cube to cognize its spatio-temporal trajectories, and views on non-space multidimensional cube to cognize the variations of attributes over time.

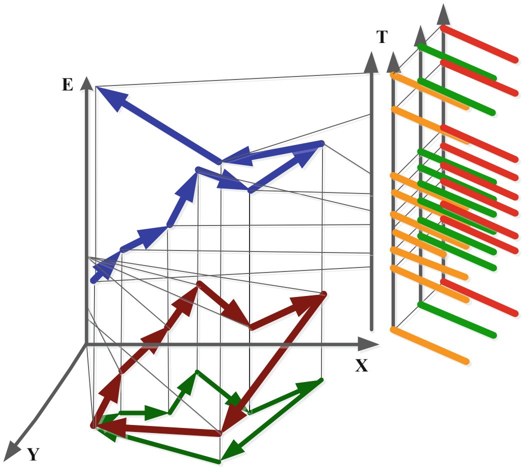

Fig. 11. The 3D-space multidimensional cube for representing flyers

6 Conclusion

The paper analyzed the relations among groups of variables making up a dataset to classify multidimensional cubes as non-space multidimensional cube, 2D-space multidimensional cube, 3D-space multidimensional cube. The non-space multidimensional cube represents dataset of the relations between objects, attributes, and time. The 2D-space multidimensional cube is designed to represent dataset of happening changing over time at some locations, and represent dataset of mover of which ground position and attributes change over time. The 3D-space multidimensional cube is designed to represent objects located in elevated space and flyers having attributes and positions in elevated space changing over time.

The paper summarized the case studies from previous studies to illustrate the effectiveness of types of multidimensional cubes. The non-space multidimensional cube representing the dataset of hand-foot-mouth epidemic in Binhduong province, Vietnam, shows the correlation between the number of patients and rainfall, humidity. The 2D-space multidimensional cube representing the dataset of dengue fever epidemic in Angiang, Soctrang, Tiengiang provinces, Vietnam, shows the spatial correlation between the happenings in Angiang and Soctrang, where the spatial correlation between Angiang and Soctrang provinces is inferred from the temporal correlation between two happenings of epidemic in two provinces.

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