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Modeling the Spatiotemporal Evolution of Brazil

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Abstract This article presents the modeling of a geographic database that includes temporal data on the evolution of territorial boundaries. Data on the changes that occurred in the Brazilian territory between the years of 1872 and 2015 are organized in order to implement the necessary structures for manipulation of temporal data. The purpose of this work is to achieve a single structure for analysis, comparison and visualization of spatiotemporal data. The result of the modeling is presented, along with an interaction in which it is possible to retrieve geographic data from a range of years.

Keywords: Temporal Data, Spatiotemporal Data, Geoprocessing, GIS, Brazilian Territory, Database Modeling

1 Introduction

Brazil is currently composed of 26 states plus a Federal District, and divided into 5,570 municipalities, according to IBGE[1]. Over the years, the Brazilian territory has changed numerous times, either by changes in the country's borders, or by modification of internal subdivisions, such as states (or provinces) and municipalities. These changes include dismemberment or union of municipalities, state divisions, and changes in subdivision names.

Municipalities can emerge from the territory of other municipalities, in a process that subdivides the territory and introduces a new federal unit. Likewise, municipal or state territories may be combined, or merged into one another. Such situations are described in an IBGE document[2], which also contains information on name changes, some of which are due to a reform of the Portuguese spelling in the early twentieth century.

According to [Dias *et al.*, 2005], spatiotemporal modeling is one of the biggest challenges of geoinformation. Such modeling must be capable of representing changes both in space and in time. Resulting schemas are based on two main features: the choice of space and time representation concepts, and the construction of appropriate computational representations.

There is a challenge in the modeling of this historical process in a spatial database. In fact, due to the modifications in the shape of subdivisions over time, spatiotemporal representation is required, so that the territorial configuration of the country can be retrieved at any point in time. This requires modeling temporal aspects of the data that are associated to geographic representations, and the definition of a set of integrity constraints that ensure that, for any reference date, there is a complete and correct territorial configuration.

The implementation of the ensuing database would enable historians and students to gain a better view of the evolution of Brazil's territorial division.

This work aims to present a spatiotemporal database schema that represents the changes that have happened in the Brazilian territory over the years, ensuring the integrity of the data. Since no complete spatiotemporal database management system exists today, the schema is implemented using a geographic database management system, namely PostGIS, with the creation of special attributes that allow selecting the set of valid territorial subdivisions at any given time. This allows analyzing and comparing the changes over the years, and for that purpose we present a visualization tool attached to the resulting database. Naturally, since many (most) other countries have undergone similar border dynamics, the modeling and implementation presented in this article using Brazil as a case study can be used to create other spatiotemporal territorial evolution processes.

This paper is an extended version of [Ramalho and Davis Jr., 2022], presented in the XXIII Brazilian Symposium on Geoinformatics (GEOINFO 2022).

2 Related Work

Concerning spatiotemporal databases, there is no consensus on how to represent temporal information. As discussed by Ferreira *et al.* [2015]; Santos *et al.* [2016], there are many proposals of conceptual models to represent spatiotemporal data in GIS, but most existing technologies are specific for certain application domains.

Gregory [2002] informs that many European countries and regions have created or were planning to create geographic systems in order to understand the changes of their administrative boundaries over time. The author examines different approaches to the creation of temporal GIS, the difficulties and the advantages of having spatiotemporal databases, then compares them with the solutions and methods used by the European countries to add a temporal dimension to their GIS

[1] https://www.ibge.gov.br/ - Instituto Brasileiro de Geografia e Estatística

[2] https://www.ibge.gov.br/geociencias/organizacao-do-territorio/estrutura-territorial/15771-evolucao-da-divisao-territorial-do-brasil.html

data model. The approaches used involve digitizing boundaries at key dates and creating a space-time composite structure, both similar to Langran's proposed models to spatiotemporal GIS [Langran, 1989], and date-stamping individual features, based on Vrana's approach [Vrana, 1989].

Plumejeaud *et al.* [2011] presents a data model that manages changes in territorial organization, regarding operations on territorial units, such as split, merge and reorganization, which cause changes in spatial limits. The model enables the comparison of units and their changes over time. It is based on the identity of geographical units and on their genealogy.

Alam *et al.* [2021] provide an overview of existing spatio-temporal data analytics systems in addition to tools, packages and GIS softwares for processing and analyzing spatial, spatio-temporal and trajectory data. Jitkajornwanich *et al.* [2020] also show research results on spatio-temporal databases. They also include modeling, query languages and operators.

In this work, we propose a spatiotemporal model to represent the evolution of the Brazilian territory, focusing on a conceptual and physical modeling of a geographic database, incorporating a time dimension, based on Temporal OMT-G [Meinerz, 2005].

3 Materials and Methods

3.1 Data

The previously mentioned document on the evolution of the state and municipal divisions of Brazil, produced by IBGE, describes the limits of the territories between 1872 and 1991. IBGE shows changes that occured during these years, including population numbers and different spellings of names, and provides static maps of the subdivisions at each Census year.

The data also contains information on the dismemberment of municipalities, including the source of the new subdivision and the names of each subdivision at the end of the process, presented as an alphanumeric table. **Figure 1** shows the difference in the division of the municipalities in the Brazilian territory between 1872 and 1991. It is possible to notice the changes of the national borders and the difference in the number of municipalities.

Data sources used for this work refer to each Census year between 1872 and 1991, with the addition of data on 2000, 2001, 2005, 2007, 2013 and 2015 subdivisions. From 2000 onwards, the data refers to editions of IBGE's official data on municipal subdivisions, which correspond to years in which some modification was introduced. The expansion to encompass the years beyond 1991 allows us to apply the proposed modeling and implementation to a more complete database. Therefore, we pursue the main goal of creating a more concise structure, even as the data volume increases.

3.2 Conceptual and Logical Modeling

Traditional data models have two dimensions: data instances and their attributes. Each attribute has only one value, and if this value is changed, the previous one is lost. With temporal models, there is one more dimension, the temporal one, in which every new value is added to the database without removing the previous ones [Edelweiss, 1998].

There are two distinct time representations in a DBMS: valid time, which indicates the moment a change occurred, and transaction time, which is the moment when the change event was recorded in the database. A temporal database includes data on these moments, representing temporal information. For this work, as discussed later, valid time is more relevant, as it is used to indicate when subdivision boundaries changed.

There are two main classes to model the territorial subdivisions: "State" and "Municipality". Each class includes territorial boundaries as its geographic representation, plus the division instance's name and the year in which it has been created. To implement this model, a DBMS that records the valid time is required. Thus, it is possible to access the data history, and the time can be associated with each value or instance.

Figure 2 and **Figure 3** show the OMT-G modeling [Borges *et al.*, 2001] for State and Municipality elements in a non-temporal geographic database. **Figure 2** considers the two classes being represented by polygons and the aggregation relationship between them, showing that the State is composed by Municipalities – a schema that is independent of time. In **Figure 3**, the geographic part was separated, thus obtaining a conventional (non-geographic) class for State and Municipality, linking each one to multiple geographic representations. Such alternative representations should then be used to represent evolution along time, using appropriate attributes that would indicate the period during which that subdivision remained valid.

These two schemas, however, do not allow comparisons between previous states, nor do they allow for representing changes in attributes, such as municipality or state name. The separation made in **Figure 3** simply enables the construction of a time series of geographic representations for State and Municipality.

To evolve from that limitation, we use elements of the Temporal OMT-G technique proposed by [Meinerz, 2005]. This technique extends the OMT-G model to include primitives for the representation of spatiotemporal properties of geographical data. In Temporal OMT-G, stereotypes are used to indicate the model of time used in the schema. The technique adopts, among others, the transaction time and the valid time. For this work, only the valid time was considered, which allows recording current, past and possibly future states of the classes, their representations and their attributes.

According to [Meinerz, 2005], valid time defines Value Primitives, that are used to define new properties for elements of the model, and Constraints. Value Primitives refer to the valid time's lifecycle, which requires the time value to be entered by the user. They also refer to the Temporal Interval, that represents the duration of time records. Constraints refer to the length of time the element has existed in the database and require that the element only contains static and/or valid time properties; and that the values exist in the database only during their lifetime. Temporal OMT-G allows modeling the temporality of relationships, so that the association between instances of the involved classes can vary along

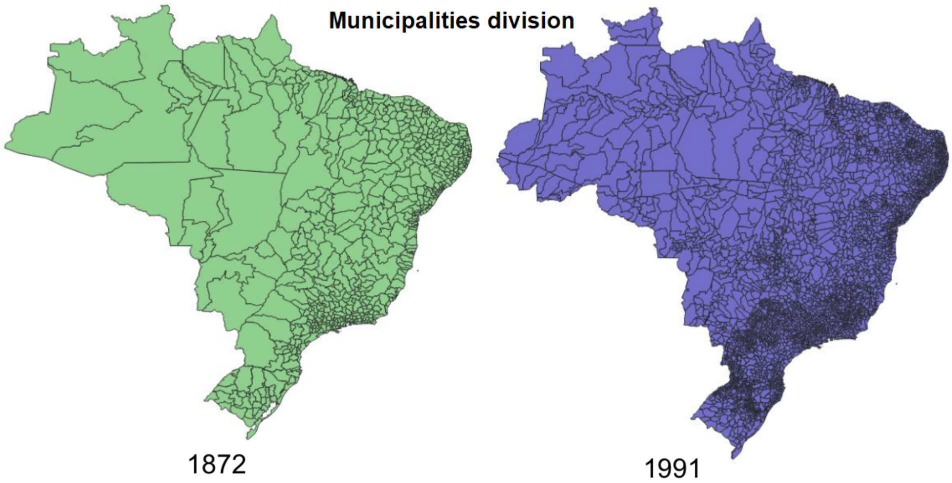

Figure 1. Brazilian territory in 1872 and 1991, divided into municipalities

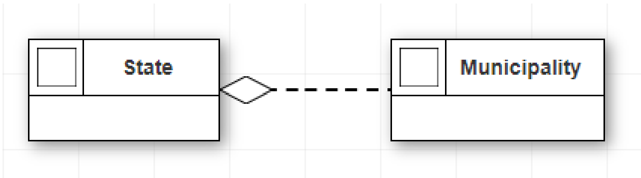

Figure 2. Modeling for a static geographic database

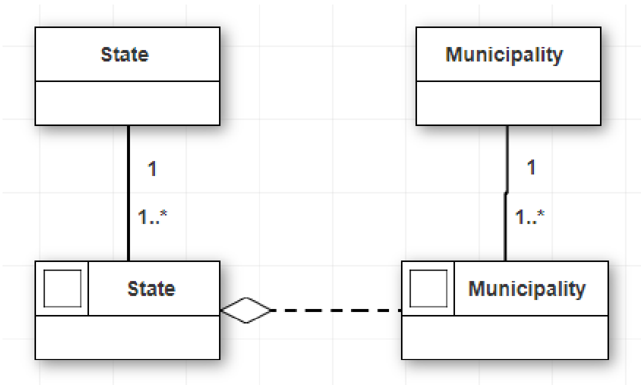

Figure 3. Modeling for a static geographic database (separate geography)

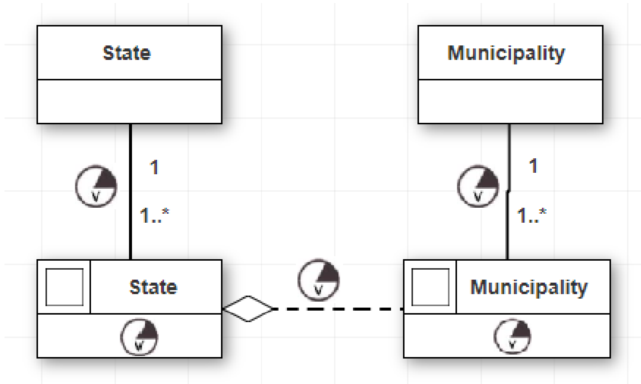

Figure 4. Conceptual modeling for a temporal geographic database

time.

Figure 4 shows the result obtained by applying the temporal aspects to the conceptual model. Since Temporal OMT-G does not require all attributes to vary in time, we decided to have both temporal and static attributes on the same object. The Valid Time was added to the State and Municipality attributes, in order to show that the attributes such as "Name" of the objects have the temporal property.

Between the conventional and spatial elements, temporal relationships with Valid Time were adopted. This makes it possible to maintain various instances of the relationship between objects over time. One example would be in the case of municipalities that move to another state.

The aggregation between the georeferenced elements is on Valid Time and shows that "State" can consist of many "Municipalities". The temporal aspect is also important in this case to show that, even if the geography (geometric shape) of "Municipality" changes and, for example, it is no longer contained within the same "State", its integrity is guaranteed.

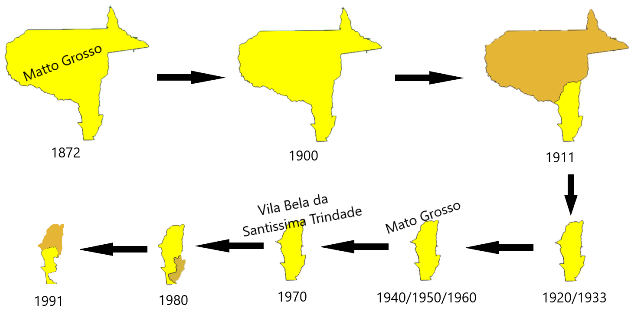

Figure 5. Municipality changes during the years. Same code, but different names and geometries

3.3 Physical Modeling

3.3.1 Tools

The software used in this work includes PostgreSQL[3] to manage the database and the PostGIS[4] extension, which allows the storage and analysis of geographic objects in databases.

To handle the data, scripts were developed in Python and SQL. QGIS[5] was used for the visualization, editing and analysis of georeferenced data, in addition to ArcGIS Online[6], which was also used to generate interactive visualizations and host the data.

3.3.2 Data Treatment

From the conceptual schema, it was necessary to restructure the data so that valid time could be used in the implementation.

Data provided by IBGE were separated into tables indicating the reference year for each object, and had the name of the municipality, municipality code and geometry as attributes. In order to implement the conceptual schema, while using temporal concepts, each table was extended to contain a start date and an end date to indicate the period through which the boundaries remained valid. Since each original table refers to the same year, these dates are the same for all objects.

The start and end dates are related to all aspects of the municipality. If the geometry or name changes, the expiration date also follows those changes, and a new temporal version has to be created.

Between the years of 1991 and 2000 there were changes in cartographic details between one dataset and the other, including changes of the spatial reference system, and the level of detail in borders. Before 1991 all the data had already been treated by IBGE. In the years after that, cartographic differences were observed. Each dataset's geometry was transformed to SIRGAS 2000, Brazil's current official geodetic coordinate system.

Figure 5 represents a municipality during the registered years. It has the same code, thus is treated as the same municipality across all the initial tables. But it also has geometry (between 1900 and 1911; 1970 and 1980; 1980 and 1991) and name (between 1933 and 1940; 1960 and 1970) changes.

In the next sections we discuss how these changes are incorporated into the temporal modeling.

3.3.3 Geometric Aspects

Each municipality has a polygon associated with it, which represents its territory. According to IBGE, the maps with the evolution of the municipalities were built from the Institute's data on municipal borders in 1991. Older versions of the municipal territories were built by incrementally modifying 1991 geometries, back to 1872, since the most common modification is the division of a municipality's territory in two, with the emancipation of a district or secondary urban nucleus. Thus, previous municipal subdivisions were in most cases assembled from the most recent year to the oldest, through the union of polygons. This process is intended to avoid topological inaccuracies between different years. However, IBGE warns, in the documentation of the process, that small issues persisted.

For this work, to put together a series of temporal versions of each municipality, it was necessary to compare the geometries in sequence along the tables. IBGE indicates that the codes of the municipalities are defined in such a way as to be unique; thus, when a municipality is extinct, its code cannot be assigned to another. Likewise, municipalities that have moved from one state to another receive new codes.

A sequence of temporal versions of municipalities can then be put together, based on the IBGE code. If a sequential pair of versions has the same name and the same geometry, they are merged, using the initial valid date of the first version and the final valid date of the second. This new, merged, version is then compared to the next temporal version. If there are differences, the process stops, and the version is added to a results table (see next section). The divergent version is then used as the start of a new sequence of temporal versions, up until 2015.

In order to check whether the geometries of two versions actually coincide, PostGIS topology functions were used. The ST_Equals function was first used, checking if the geometries are spatially equal. However, as there are certain inaccuracies in the geometric data, and between some years there are differences on the detailing of the polygon's borders, the results of the comparisons were unsatisfying.

To get around this situation, we compare the area of the difference between the two polygons with the area of one of them. Differences under a small threshold were disconsidered.

Table 1 shows some of the results of the comparisons of versions of municipalities between the years 1940 and 1950. It presents the name of the municipality in each year, its code and the result of the area difference.

Since, in the years after 1991, there are differences on the borders due to the projections, scales and cartographic level of detail, we treat those cases as new geometries, preserving both versions between the years in which this occurs. A study to correct such small differences between temporal instances is left for future work.

When the difference is zero, it means that geometries can be treated as being spatially equal. Differences like the one in "Mineiros" were considered to be irrelevant. The munici-

[3]https://www.postgresql.org/
[4]https://postgis.net/
[5]https://qgis.org/
[6]https://www.arcgis.com/

Table 1. Table with the calculated differences of the geometries of two municipalities

Name (1940)	Name (1950)	Code	Area Difference
Mineiros	Mineiros	5213103	1.761e-09
Porto de Pedras	Porto de Pedras	2707404	0
Santa Rita	Santa Rita	2513703	0.0294

palities that had these results are those where the projection was slightly different, but still the same. When the difference is not as close to zero, as in the municipality of "Santa Rita" shown in the table, it means that the municipality may or may not have undergone territorial changes. To make this distinction, experiments were carried out by varying a tolerance limit of the difference values.

The query below shows how the difference between the geometries of two years were calculated. The geometry type is "Multipolygon", therefore it was possible to use PostGIS functions ST_SymDifference and ST_Area. Tables 'a' and 'b' are tables of municipalities of consecutive years, i.e. 1940 and 1950 respectively. The total difference is represented by the area of the difference between the two geometries divided by the area of the first geometry, resulting in a percentual value for each entry.

```
SELECT a.code, a.name, b.name,
 ST_Area(ST_SymDifference(a.geom,b.geom))/
 ST_Area(a.geom) as area_difference
FROM table_a as a join table_b as b
ON a.code = b.code
ORDER BY area_difference;
```

The threshold was obtained by observing the results of the query and analyzing the municipality areas, with the help of the visual tool in QGIS, and identifying from which value there were significant differences between them, indicating changes in the territory. The result of the area of which polygon alone was also used to help get to a satisfying threshold.

Table 2 presents an example of part of the query's result for the years of 1940 and 1950, assuming that the name is the same. After an analysis, we observed that the borders of "Santa Rita" and the municipalities above it did not have visual changes, while "João Pessoa" and the municipalities below it had significative changes on them. Thus the threshold adopted for this example is approximately 3%, i.e. all the entries with differences less than this are considered to have had no geometry changes. Since differences on levels of detail between every analyzed year's borders were observed, this verification had to be made for each year change, and a new threshold was obtained each time.

The geometric difference between A and B is different from the geometric difference between B and A. Thus, to avoid erroneous results, the symmetric difference between the geometries was used (ST_SymDifference).

From the comparisons of geometries, it is possible to visualize how the municipalities are incrementally created. Parts of the territory may become emancipated, others can be annexed or incorporated to an existing municipality, or municipalities can be merged, losing their individual characteristics.

Table 2. Result of the query showing percentage differences between the areas (1940 and 1950)

code	name (1940/1950)	area_difference (%)
3099901	Distrito Federal	1.4
3302007	Itaguaí	2.3
2513703	Santa Rita	2.9
2507507	João Pessoa	3.3
2708006	Santana do Ipanema	6.4
4113205	Lapa	7.5
3149903	Perdões	7.6

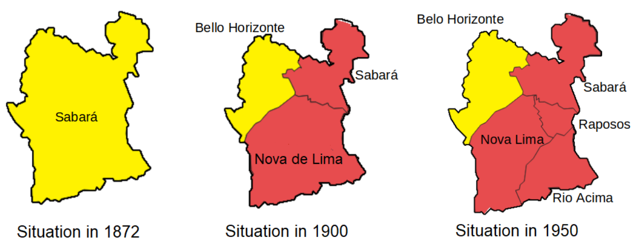

Figure 6. Example of a sequence of changes over the years

3.3.4 Temporal Aspects

Municipalities that resulted from the process described in the previous section were stored in a single table. The table's structure contains the municipality's code, name, geometry and the creation and expiration date. In this structure, the table no longer holds the physical version of an OMT-G planar subdivision, but a set of them. Each polygon has a creation and an expiration date. These attributes indicate the time period during which that version (geometry, name, code) was valid. Since the national territory has changed along history, new versions of the state borders are then obtained from the union of municipality polygons, grouping them according to the first digits of the municipality code. National borders can then be obtained in the same way.

Figure 6 shows a sequence of changes that occurred during three censuses in the region where Belo Horizonte is today. **Table 3** shows how these changes are encoded in the database table.

As can be observed in **Figure 6**, in 1872 there was only the municipality of Sabará. So the creation date reflects the situation in 1872. When analyzing the next year, 1900, it is observed that the municipality of Sabará was divided into three. As Sabará has a new geometry, an updated entry is created on the table, with a creation date of 1900. The expiration date is now 1991, since no other modifications have occurred in Sabará since this split.

From part of Sabará, a new municipality, Bello Horizonte, appeared in the 1900 data. Thus, we assume this to be its creation year. Between 1933 and 1940, the city's name changed to "Belo Horizonte", with the double letter removed by an

Table 3. Table with examples of changes that happened over time

Name	Creation Date	Expiration Date
Sabará	1872	1900
Sabará	1900	1991
Bello Horizonte	1900	1940
Belo Horizonte	1940	1991
Nova de Lima	1900	1911
Villa Nova de Lima	1911	1933
Nova Lima	1933	1950
Nova Lima	1950	1991
Raposos	1950	1991
Rio Acima	1950	1991

orthographic reform of the Portuguese language. No modifications to the territory were observed. The original version then has an expiration date of 1940, and the new version is considered to be created in 1940. The same types of modifications occurred in Nova de Lima. First, two name changes, one between 1900 and 1911, and the other between 1920 and 1933; and then a second division, between 1940 and 1950, creating Raposos and Rio Acima.

Notice that changes are perceived when the version corresponding to a new Census or a new digital mesh is different from the one preceding it. Thus, a change must have occurred in the years between the two observed. Establishing and recording the actual data of the change is left for future work, as this requires further data. The actual date for the establishment of Bello Horizonte is December 12, 1897, and the orthographic reform took place in 1938.

As there were no changes in the municipality of Sabará from 1900 onwards, the expiration date is updated to the maximum value, 1991. The same goes for the most recent entries of Belo Horizonte, Nova Lima, Raposos and Rio Acima. Expiration dates with a null value are used to indicate the current version of each record.

3.4 Final Physical Modeling

With the grouping of all data in a single structure, it is possible to have more than one entry for the same municipality. Therefore, the IBGE code can no longer be used as a primary key. The final version of the table then uses a composite key, comprising the code and the creation date.

`municipalities(code, name, geom, creation_date, expiration_date)`

4 Interaction

With the objective of comparing and visualizing, in a more concentrated way, the changes that occurred in the Brazilian territory, an interactive visualizer was developed using the ArcGIS application tools. **Figure 7** shows the initial screen of the developed interaction.

It has a timeline with the years between 1872 and 2015, in which it is possible to go through each available year and visualize the corresponding territorial configuration, zoom in and out on the map and click and check each municipality's name. It also has a *play* button that allows the user to observe the evolution of the territory as an animation.

The interaction can be found at:
`https://feramalho.github.io/Municipios/MunBR/V2/`

5 Conclusion and Future Works

The integration of geographic elements with temporal elements resulted in a concise structure that allows the maintenance of different versions of the territorial configurations, without unnecessary repetition. The insertion of creation and expiration dates facilitated the comparison and analysis of the municipalities over the years.

This structure allows the easy recovery of the history of each part of the territory, with the possibility of comparing them to other moments and directly analyzing the changes that have occurred. The implementation of the interaction was simplified because of the physical implementation, which takes into account the temporal aspects.

The final modeling and concepts can be used to facilitate analysis and representations that ensure data integrity, contemplating the spatial and temporal aspects of the data. All changes incorporated into a structure can benefit future research work involving the retrieval of different territorial situations, and also assist in studies on the Brazilian territory.

Since there are no structures today that present a concise representation of spatiotemporal data while allowing observation and tracking of its changes over time, this work, in addition to presenting an alternative for modeling territorial changes, also offers a starting point in modeling more generalized structures. The use of Temporal OMT-G including valid time was crucial to the development of the conceptual modeling, which was later transformed in the database's physical modeling.

To extend this work, we intend to improve the data to reflect the actual creation dates of the municipalities throughout the period between 1872 and 1991. These data are in part available as a spreadsheet in IBGE's original work. Depending on the existence of data prior to 1872, the authors also intend to extend the temporal range to the early days of Portuguese colonization of Brazil, since 1500. An evolution of the visualization tools and techniques is also planned, so that the historical data on the constitution of the Brazilian territory can be presented interactively to fundamental school students. Furthermore, all concepts, modeling and tools used for Brazilian data can be reapplied to other geographic regions or countries, so the educational role of the spatiotemporal management of territorial division data can be used in multiple situations.

Authors' Contributions

Both authors collaborated in the modeling and in the overall definition of the work. FOR executed the data integration and implementation. Both authors collaborated in writing this manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

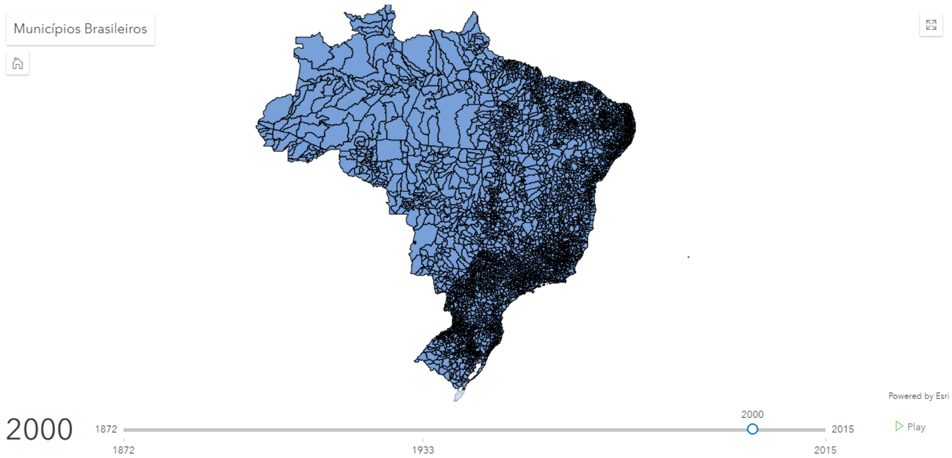

Figure 7. Screen of the interactive interface

Availability of data and materials

The datasets generated and analysed during the current study are available in `https://github.com/FeRamalho/municipios`.

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