Representation of urban geometry evolution through space-time cube

Abstract—**Evolution of neighbourhoods in cities are important for architects and urban planners. While data exists to document the evolution of the urban places, we lack methods to clearly visualize the evolution of a city or a neighbourhood in time. We propose a new representation of the city that integrates 3D urban data with time, inspired by the Space-Time Cube concept. Our representation allows the visualization and comparison of different versions of the city in a single interactive 3D space, based on a graph model of the data. In addition to displaying the 3D geometry, we also integrate a direct visualization of the type of changes between each version and provide several ways to interact with the visualization. We apply our visualization technique on real urban data and show that it allows quickly apprehending the evolution of a neighbourhood.**

Index Terms—**3D spatial and temporal urban data, space-time cube, evolution**

I. Introduction

Cities are complex and dynamic entities that are always in a state of change. As cities grow and face new challenges, their neighbourhoods adapt and transform to meet the changing needs of their residents. This evolution of the city can be contextualized through documents, photos, videos or other type of data, allowing to create a version of the city through time. To allow for a better understanding of this evolution, temporal 2D urban data can be visualized in 3D space to visualize the data through time. At the same time, 3D representations of cities are becoming more and more available and helping a better understanding the organisation of a district, a metropolis etc. These 3D representations can also be versioned to keep the history of a territory. Current proposals to visualize 3D temporal data are usually able to display the data at a given time but not its evolution over a period of time. How to represent the evolution of data in a time interval integrated in a 3D environment thus remains an open question.

We propose a representation that integrates both time and 3D urban data in a 3D interactive space. Time is integrated in the 3D space on the z-axis, place different versions of the data on top of each other, depending on their time of capture.

Our method aims at visualizing, in a 3D space, a graph representing the different versions of the city with their associated changes. The definition of this graph and the organisation of the versions can be found in Section III. We place these different versions in a 3D georeferenced space using our new representation, as detailed in Section IV. The position of each 3D element of the city is computed from its initial georeferenced position and the associated time. In addition, we integrate a visualization of the changes between each version, enhancing the understanding of the evolution (Section IV-B). Users can interact with this representation and refine its analysis by selecting the time range of the data on a double entry temporal slider or by selecting specific buildings to highlight, see Section IV-A. We have applied our method on a district of Lyon (France) which has received a number of modifications in the recent years (Section V). This application demonstrates the potentiality of our method to improve the analysis of the evolution of a neighbourhood through time.

II. State of the Art

2D urban data plays an important role in understanding a territory by showing, for example, how a road network is organized or the functions of a building in a district. Several techniques exist to be able to visualize the evolution of such data over time. One of them is the Space-Time Cube (STC), first introduced by Hägestrand [6], where the third axis is used to represent time in addition to the two spatial axis. This representation has typically widely be used with geographic data [5] or to represent trajectories [8, 11]. It is naturally best suited for 2D data, the STC then being a 3-dimensional object that can be projected on 2D via a variety of operations, including 3D rendering. Bach et al. [1] reviews the different ways a STC can be projected in 2D, e.g. by slicing the data or flattening it.

Using a STC with higher dimensional data, such as 3D data, remains a challenge since the obtained hypercube becomes 4D. Fouché et al. [4] proposed a way to visualize temporal 3D medical data by extracting 2D slices from the 3D data, thus falling back on the regular STC. This type of 3D slicing is not suitable for representing building morphology over time. We propose an approach inspired by the STC, but that allows visualizing the complete 3D urban data at each time step by using the z-axis to represent both the actual z-axis of the geospatial scene as well as time. Although visualizing a STC in 3D has been reported to be difficult to understand in a static setup, being able to freely interact and navigate within the scene can help to alleviate this issue [13]. Our method of representation is integrated in a 3D geospatial interactive environment, allowing the user to interact with the representation.

Another line of work uses temporal sliders to navigate through time (akin to a time-cutting in Bach et al. terminology [1]). After selecting the time with the slider, the user is then able to see the spatial data corresponding to that time. This approach has been used to visualize 3D urban data by Jaillot et al. [7], as pictured in Figure 1. They introduced a color code to help the user distinguish the changes between two time slices. However their system requires multiple user interactions, going back and fourth with the slider, for the user to clearly understand the evolution of the data. The time slider has further been improved by using a double entry slider, allowing choosing a time interval to visualize [2]. In this work, archival images from different eras are displayed in the 3D scene and the user can navigate through time by changing the time interval of the displayed data but can not directly see the evolution of the data. Our new representation allows to directly see the changes along the whole timeline in the 3D scene. We complement the STC with a temporal slider to further improve its interactivity.

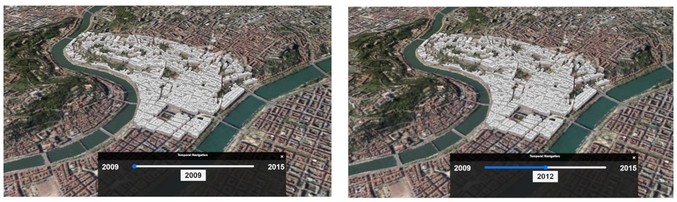


Fig. 1: The visualisation of 3D urban data with a time slider using the method from Jaillot et al [7]: data from 2009 (left) and from 2012 (right). It is difficult to see the differences between the two versions and distinguish constructed, destructed or modified places.

Stacking the different versions of the data over time would not be enough to understand its evolution without clearly depicting the changes from one version to another. A variety of methods have been developed to detect such changes given 3D urban data [7] or archival images [3, 10]. These tools provide a graph recording possible changes for each object of the scene, as well as the type of change (typically, construction, modification, destruction, or merge of geometric objects). However, there is no way to visualize these changes in a 3D scene. Our method incorporates the changes and their type in the Space-Time Cube, allowing to better understand the nature of the changes that have occured.

III. Data structure

In this section, we introduce the data that we seek to visualize. At a high level, our data consists in different versions of a 3D city model along with the list of changes between each version. A version refers to a state of data of the city at a particular instant or period of time (Samuel et al. [9]). These versions are composed of city objects which are virtual entities consisting of two main components: its geometry, and its unique identifier, which is referred to as a ID. Over time, the building IDs may change, but we are able to link them together using the comparison of the cadastre between versions. Each city object can be linked to a change between two versions (Figure 2), which can be of three kinds: construction, modification, destruction. These types of change are calculated using the difference between the geometry of the city objects between two dates (Jaillot et al. [7] and De Luca et al. [3]). We can therefore only trace the evolution of the data, which tries to be as faithful as possible to reality.

This data is stored as a 3D semantic model graph that integrates the different versions and the changes between them, stored as transactions. Figure 2 shows an example of such graph where the building has three versions (called State i) with transactions between them. For example, the transaction between State 1 and State 2 is a modification. We rely on the work from Vinasco-Alvarez [12] and use Resource Description Framework (RDF) knowledge graphs to structure the different versions of our data. This structure allows to link a transaction to a version of the data in the graph and to retrieve all versions of a given city object as well as its changes. This type of graph structure has already been used to show a version of the data at a given time t but our goal is to show the whole graph in a single 3D view.

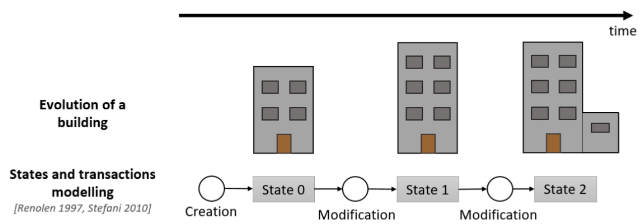


Fig. 2: Evolution of a building through three states and a graph model integrating transactions modelling (from [7]).

IV. Our representation

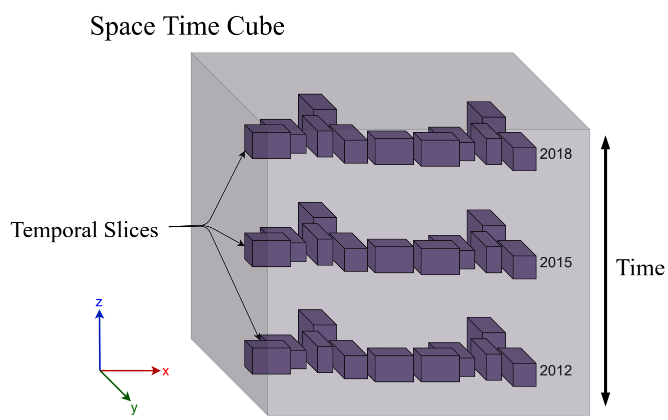
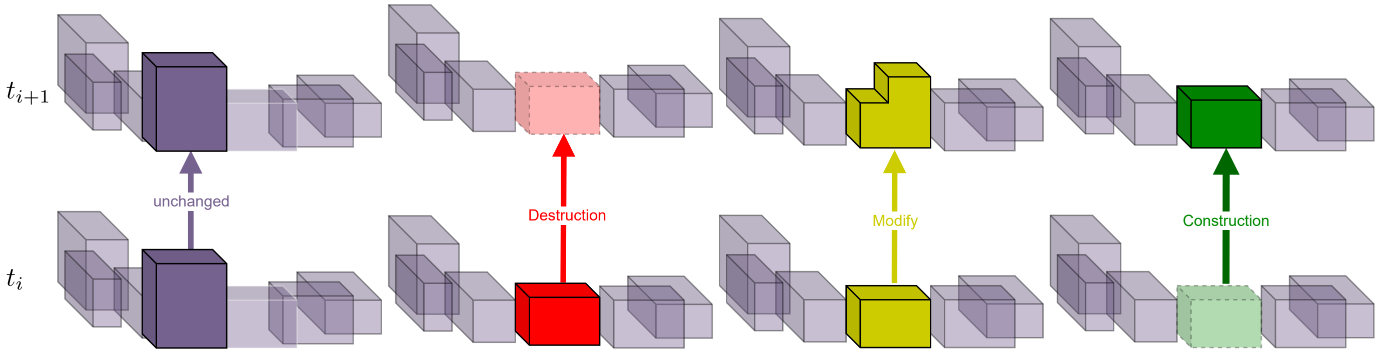


Fig. 3: 3D urban data integrated into a space-time cube representation, with time along the z-axis in 3D space. The different versions of the data are placed on top of each other. The time axis can be orientated toward the bottom or the top of the space.

The space-time cube (STC) is an effective 2D data representation tool for understanding the evolution of urban data. This method integrates data and time in a single view: the time is represented on the z-axis while the 2D space integrates the urban data.



(a) Unchanged transaction (b) Destruction transaction (c) Modification transaction (d) Construction transaction

Fig. 4: Concept schema of the four transactions integrated in space-time cube, between temporal levels t_i and t_{i+1}: (a) the unchanged state, (b) the destruction state (a geometry disappear), (c) the modification state (a building evolve) and (d) the construction state (a building appear).

In our approach, we couple the perception of time offered by the space-time cube with 3D urban data. Inspired by the principle of the STC, we place the layers of 3D data on top of each other along the z-axis (Figure 3). Each layer of the space-time cube will be called a *temporal level* and can be composed of different layers of the urban world like buildings, vegetation etc. In our case, this temporal level will essentially be a layer of buildings placed in the space.

A. Timeline integration

In the definition of the STC, the time moves from the bottom to the top of the space. We have kept this principle in a geospatial scene but with the possibility to choose the direction of the timeline (Figure 3). Data can thus be displayed from the oldest (the lowest height in space) to the most recent one or vice versa depending on how the user wishrs to analyze or interact with the temporal data. The time t can have different granularities (day, month, year or decades), depending on the available versioning of the dataset. In our examples, we will express t in years. To position a city object in the 3D space, we take its initial coordinates in the world $P_{world} = (x_0, y_0 z_0)$ and the time t_i corresponding to its version, and define its position in the STC as:

$$P_{STC} = T(t_i) \cdot P_{world}$$

where the transformation matrix T mainly depends on t_i. In our case, this transformation is a translation on the z-axis, T is thus defined as:

$$T = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \delta \times |t_i - t_0| \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where t_0 is the time of the version that will be displayed at ground level (the less or more recent version depending on the direction of the z-axis) and δ is the offset between two consecutive temporal level at time t_i and t_{i+1}. This spacing δ can depend on several parameters:

- The gap between consecutive levels t_i and t_{i+1}. The temporal granularity of the dataset that we want to display can be in days, years or even centuries, impacting the definition of δ.
- The maximum height of a building in a temporal level: δ should be big enough such that buildings do not intersect with the level above. This can particularly of importance in the presence of very tall buildings or if the data is set on uneven ground.

The positioning of the city object in the time level is therefore:

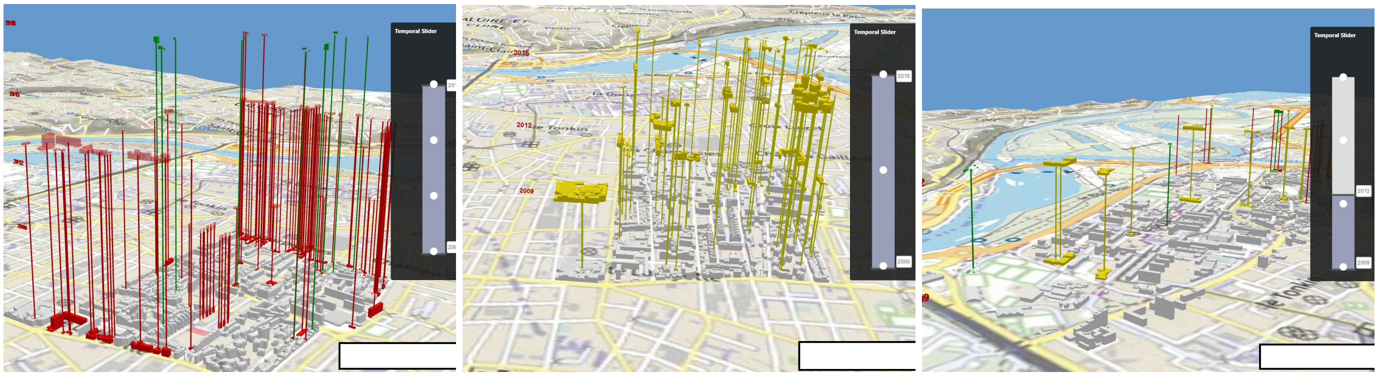
$$P_{STC} = \begin{pmatrix} x_0 \\ y_0 \\ z_0 + \delta \times |t_i - t_0| \end{pmatrix}$$

The temporal levels are thus positioned directly along the timeline, allowing to quickly observe over which period of time there has been a lot of changes in a neighborhood and link it to a historical event.

When there are many temporal levels in the space-time cube, it can be difficult to analyze them as a whole. To address this issue and allow urban planners to analyze the territory more precisely, we have added a double-entry time slider that controls which versions are to be displayed. This tool allows displaying the STC in its entirety or only certain temporal levels, as in Figure 5c, enabling focus on the selected time period. An example of the temporal slider in our implementation can be seen in Figure 5, at the right of the screen. The white dots represents versions of the city while the dark gray area represents the current time range. The time slider is a tool that complete the space-time cube. Users can adjust the time interval of the analysis, allowing for a more granular or macroscopic view of the data.

B. Integration of transactions

The STC alone is not enough to fully visualize the temporal evolution of the city, as it can be difficult to see where the geometry changes between temporal level. To put more



(a) ”destruction” and ”construction” transactions

(b) Only ”modification” transactions

(c) Display all transactions with specific temporal slider input on a different dataset

Fig. 5: Visualisation of our representation two districts of Lyon (Gratte-Ciel and La Doua in France). The user can select a specific type of transaction to display: (a) destructions and construction, (b) only modifications. (c) The Temporal slider allows to select the time range to be displayed, here only from 2009 to 2012.

emphasis on the changes between temporal levels, we integrate a visualization of the transactions between the versions.

Each type of transaction is linked to a unique color scheme. The transaction type affects the way the connected city objects (both at time t_i and t_{i+1}) will be displayed in the following way (summarized in Figure 4):

- **Unchanged:** it appears when there is no change between two versions (Figure 4a). The connected objects are set to a transparent (or semi-transparent) color, allowing to highlight the changes and avoiding to occlude lower levels.
- **Construction:** it appears when a new building is constructed between versions t_i and t_{i+1} (Figure 4b). The object appears in green transparent in the time level t_i in the 3D scene (before the building is effectively constructed), and in green fill (base color) at time t_{i+1} (when the building appears in the data).
- **Destruction:** it appears if a geometry disappears between t_i and t_{i+1} (Figure 4d), representing a destruction. The object appears in red in the time level t_i in the 3D scene with no transparency, and in red with transparency at time t_{i+1} (when the building does not exist anymore).
- **Modification:** it appears if a geometry between t_i and t_{i+1} has changed (adding/removing some polygons), thus when a building was modified. The object is pictured in yellow on the version t_i and t_{i+1} in the 3D scene (before and after the modification has occured).

This color scheme have been integrated in each temporal level of the STC to enhance the readability of the evolution of an urban district (See Figure 6).

In addition to the building color scheme, we have integrated a physical link between the versions (represented in Figure 4) to easily track the progression of a building or a neighborhood. The links start from the centroid of the city object in state t_i and go to the centroid of the building in the temporal level above (t_{i+1}). The link is colored with the same color scheme

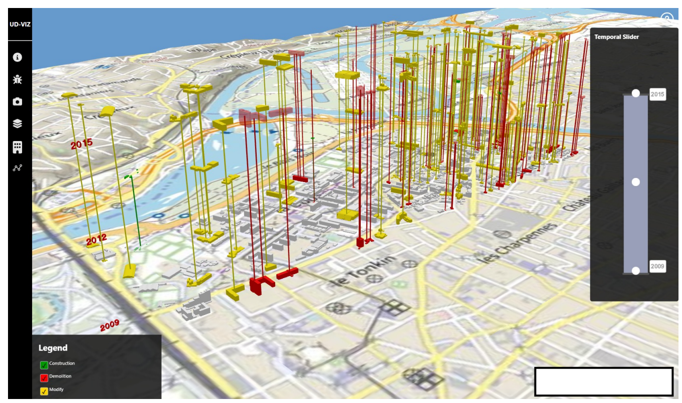


Fig. 6: An example of the STC integration with the use case of La Doua district (Lyon/France). All transactions types are displayed in the 3D view.

as the city objects, based on the corresponding transaction type.

Getting the position of an object that floats above the ground can be complicated for users. To correctly understand the geographic position of each modified objects, all transactions need to be grounded on the temporal level at time t_0. We display the state t_{i+1} of the transaction and push down the representation of the data at t_i, until reaching the next transaction that is not “unchanged“. For example, in Figure 5a, the link for the destructions that occured between 2012 and 2015 (t_1 and t_2 in this case) are displayed until reaching the ground level (t_0) since no other transactions occured in between. It allows not overloading the scene with intermediate versions that are similar to the version in t_0 while keeping a correct localization of the objects.

C. Space-time cube interactivity

Analyzing all the transactions that appears in a neighbourhood can be tedious. We thus added several types of data filtering in our representation.

The user can chose to display only certain types of transactions in the space-time cube. Examples of the resulting visualization are shown in Figure 5a and 5b where the user chose to focus solely on destructions or modifications. Focusing on destructions and constructions allows (as in Figure 5a), for example, to quickly notice in which period there have been major urbanisation works in a district.

We also give the possibility to the user to chose one building on which to focus by directly clicking on the building of interest in the 3D view. This hides all the transactions that are not linked to this object such that the user can focus solely on the history of this specific building, with more details about the exact timeline of the changes. The visualization of the transactions is modified in this case, since we also display the "unchanged" transactions in the base color (gray). An example is shown in Figure 7: the selected building has not been changed between 2009 and 2012, and then has been destroyed between 2012 and 2015. We thus display the transaction in gray between 2009 and 2012, and color it in red only between 2012 and 2015, thus giving more details about the exact time the destruction occurs.

This interactive approach thus allows users to zoom in on specific buildings, providing a more detailed analysis of their morphological evolution over time. The ability to toggle between a more global or localized view can be particularly useful for a variety of applications, from tracking urban development patterns to analyzing changes in environmental data over time.

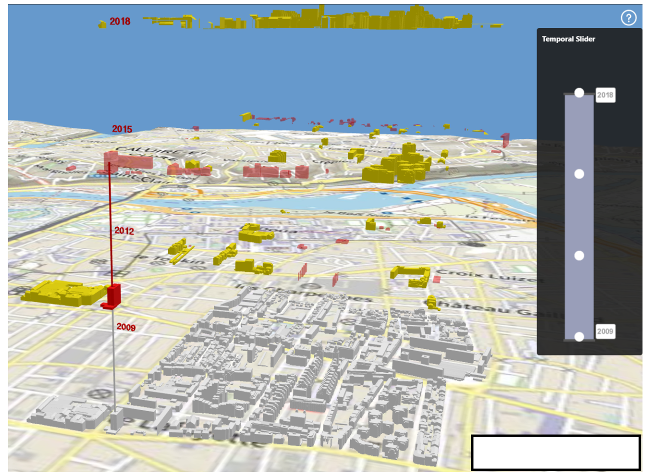


Fig. 7: An example of the STC integration with the use case of Gratte-ciel district (Lyon/France). One building has been selected and the capture show the full temporal transactions linked to that building. The building has remained unchanged from 2009 to 2012 (gray link), an destroyed in 2015 (red link).

V. Application on a real district

We implement our approach with the UD-Viz library[1]. This library is designed for immersive 3D data visualization, and offers a wide range of interactive tools such as the ability to zoom, rotate, and move freely within the geospatial scene. UD-Viz allows to integrate 3D data as 3D Tiles[2], a format specifically designed for 3D geospatial content. We have used the temporal 3DTiles extension [7] that allows to store the different versions of each city object and the related transactions in a single file.

In addition, a temporal graph of the district based on RDF has been linked to the 3D data model. From the identifier of a specific city object, this graph is used to query the list of identifiers of all the associated city objects through time, as well as the associated transaction types. These identifiers then serves to retrieve the proper geometry in the temporal 3D tiles. This geometry can finally be positioned according to its time and the physical links between the versions can be generated from one centroid to another.

We demonstrate the potentiality of our approach on two district of Lyon: Gratte-ciel and La Doua (France). These area have evolved a lot in recent years and the metropolis of Lyon provides open source versions of this area from 2009 to 2018.

The entire visualization of the history of La Doua district can be found in Figure 6. This first visualization already allows to see that the area undergos a large number of modifications and destructions. We have focused on destructions and construction (Fig. 5a) or modifications (Fig. 5b) on the district of Gratte-Ciel. These to type of use-case allows to refine the analysis:

- Between 2012 and 2015 (Figure 6) the neighborhood has received a lot of modification on the morphology of the buildings which can be linked either to urban projects or to a more accurate 3D data.
- Between 2012 and 2015 (Figure 5a) a large number of buildings were destroyed.
- Between 2009 and 2015 on the La Doua district (Figure 6) there is not a lot of construction

Finally, the use of the temporal slider (Fig. 5c) on the La Doua district allows to focus on the time period between 2009 and 2012 and better observe which buildings were destroyed during these years.

This use case shows how our representation helps to observe the changes in this neighbourhood, allowing to very quickly have an idea of the global evolution of the area. While we focus here on two neighbourhood, the code of our approach will be released in open-source upon publication and can be applied to any territory, at different spatial and time scale.

VI. Conclusion

The temporal evolution of 3D data plays an important role in the understanding of a territory. We present a new visualization approach, inspired by the Space-Time Cube, that allows showing the evolution of the data through time. By showing all versions of the data and their changes in a unique interactive 3D space, our representation highlights the changes in the urban geometric morphology and shows how a district has evolved over time. We integrated several ways

[1] https://github.com/VCityTeam/UD-Viz

[2] https://www.ogc.org/standard/3dtiles/

to control the visualization, by filtering types of transactions, selecting specific time range or focusing on specific buildings. Using these controls, users can gain a deeper understanding of how spatial and temporal data interact and evolve, ultimately leading to more informed decision-making and planning.

While our approach can provide a representation of the morphological evolution of the city, the transactions could be augmented with other contextual informations such as documents or pictures. The temporal slice could also be completed with other layers of data such as point cloud data, images or archival videos that can explain the changes. Our approach is particularly well suited for versions of the data that are regularly sampled in time. A question arises as to how to display the data in the space-time cube when versions have a different granularity in time (e.g. versions separated by days and years). Showing all the versions on a simple timeline might then not be enough, it would require the ability to zoom on specific portions of the timeline and to cluster versions that are too close from each other depending on the zoom level. Finally, another interesting improvement could be to enhance the graph mode RDF linked to the space-time cube with different possible scenarios of a territory. This would allow planners to visualize the different urbanisation projects that have taken place in an area. It could be possible to switch between scenarios and compare them in the space-time cube.

References

[1] Benjamin Bach et al. "A review of temporal data visualizations based on space-time cube operations". In: *Eurographics conference on visualization*. 2014.

[2] Jonas Bruschke, Cindy Kröber, and Florian Niebling. "Ein 4D-Browser für historische Fotografien-Forschungspotenziale für die Kunstgeschichte. Das Projekt HistStadt4D". In: (2022).

[3] Livio De Luca et al. "An iconography-based modeling approach for the spatio-temporal analysis of architectural heritage". In: *2010 Shape Modeling International Conference*. IEEE. 2010, pp. 78–89.

[4] Gwendal Fouché et al. "Immersive and interactive visualization of 3D spatio-temporal data using a space time hypercube: Application to cell division and morphogenesis analysis". In: *Frontiers in Bioinformatics* 3 (2023).

[5] Peter Gatalsky, Natalia Andrienko, and Gennady Andrienko. "Interactive analysis of event data using space-time cube". In: *Proceedings. Eighth International Conference on Information Visualisation, 2004. IV 2004.* IEEE. 2004.

[6] T Hagerstrand. "What about people in regional science?" In: *Papers of the Regional Science Association*. Vol. 24. 1. 1970, pp. 7–21.

[7] Vincent Jaillot, Sylvie Servigne, and Gilles Gesquière. "Delivering time-evolving 3D city models for web visualization". In: *International Journal of Geographical Information Science* (2020).

[8] Mei-Po Kwan and Jiyeong Lee. "Geovisualization of human activity patterns using 3D GIS: a time-geographic approach". In: *Spatially integrated social science* 27 (2004), pp. 721–744.

[9] John Samuel, Sylvie Servigne, and Gilles Gesquière. "Representation of concurrent points of view of urban changes for city models". In: *Journal of Geographical Systems* 22 (2020).

[10] Grant Schindler and Frank Dellaert. "4D Cities: Analyzing, Visualizing, and Interacting with Historical Urban Photo Collections". In: *Journal of Multimedia* (2012).

[11] Shih-Lung Shaw and Hongbo Yu. "A GIS-based time-geographic approach of studying individual activities and interactions in a hybrid physical–virtual space". In: *Journal of Transport Geography* 17.2 (2009), pp. 141–149.

[12] Diego Vinasco-Alvarez. "Leveraging Standards in Model-Centric Geospatial Knowledge Graph Creation". In: *The Semantic Web: ESWC 2022 Satellite Events: Hersonissos, Crete, Greece, May 29–June 2, 2022, Proceedings*. Springer, 2022, pp. 224–233.

[13] Jorge A Wagner Filho, Wolfgang Stuerzlinger, and Luciana Nedel. "Evaluating an immersive space-time cube geovisualization for intuitive trajectory data exploration". In: *IEEE transactions on visualization and computer graphics* 1 (2019), pp. 514–524.