Spatiotemporal Visualisation: A Survey and Outlook

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Abstract. Visualisation as a means of communication helps represent massive data sets, exchange knowledge and obtain better understanding of information. Spatiotemporal visualisation concerns changes of information in space and time. It has a natural advantage of revealing overall tendencies and movement patterns. Compared to traditional visual representations, it makes the notion of time accessible to non-expert users, and thus constitutes an important instrument in terms of decision-making that has been used in many application scenarios. As an interdisciplinary approach, substantial progress has been made in different domains, such as geographic information science, visualisation, or visual analytics, but there remains a lot of room for further advancements. In view of this, this paper presents a review of significant research in spatiotemporal visualisation, highlights a general workflow of data acquisition, information modelling and visualisation. Existing work from different domains are introduced, linked to the workflow, and possible integration strategies are given. Inspired by this summary, we also propose future work aiming at improving current spatiotemporal visualisation by integrating visualisation and interaction techniques more tightly.

Keywords: Spatiotemporal visualisation, spatiotemporal modelling, GIS.

1 Introduction

"To occur is to take *place*. In other words, to exist is to have being within both *space* and *time*. This entanglement of thing, space and time adds to the difficulty of analyzing these concepts" (Peuquet, 2002). This chapter looks at this entanglement from a viewpoint of how to visualise data that exists both within space and time, so-called spatiotemporal data.

A spatiotemporal model is defined as a data model used to efficiently organise and manage temporal geographic data sets that are associated with additional attributes and with spatial and temporal semantics (Zhang and Qin, 2004). In order to make use of such data sets, which are typically available in terms of sampled points, and to make them visually readable, spatiotemporal visualisation has been developed. This visualisation technique acts as a powerful tool to extract implicit knowledge and loosely related information. A significant advantage of spatiotemporal visualisation is that it provides a global view of activities or progress, from which evolutions and overall tendencies can be detected. Thus, it is widely used as an instrument for depicting processes, for demonstrating spatial and temporal analysis results, and for decision-making. The range of applications is diverse and includes dispersion of infectious diseases, flood

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management, land cover change, landscape simulation, land use simulation, or transportation simulation. The situation of today's environmental issues and the need for sustainable development increase the importance of spatiotemporal visualisation, which transforms dynamic modelling of multidimensional data into visual representations and consequently makes such data more accessible to experts as well as non-expert users.

The challenges of successfully applying spatiotemporal visualisation arise from various aspects. First, current data acquisition techniques have promised the acquisition of large spatiotemporal data sets, which could be used to reconstruct details and reflect changes. However, the size of such data sets demands considerable computing capacity for data management, and requires new algorithms and representations in order to extract new knowledge. Second, the form of data representation aims at providing sense of reality and immersion, as well as comprehensive knowledge. It evolves from traditional 2D map representations to 3D layered models, to ultimately four-dimensional spatiotemporal models. Such representations require a deep understanding of how information and knowledge can be extracted from raw data and how cognitive principles can be applied. Finally, models and methods originating from different disciplines are often complementary but not well combined. This is a common problem addressed by existing literature dealing with interdisciplinary work. For instance, in order to improve the readability of views and to enhance corresponding interactive operations, previous work included techniques from cartography, geographic information science, visualisation, and visual analytics (Kraak, 2006).

This paper looks at these challenges starting from the perspective of Geographic Information Systems (GIS), and reflects on how to fill the gap between GIS, urban simulation as well as other related topics. Literature and previous works are reviewed to summarise the topics on spatiotemporal information modelling and visualisation. Research in different domains from the perspective of visualisation and interactive operations is linked and potential future directions are proposed. However, we focus on urban spatiotemporal information and most of the visualisations we refer to are map-based, concerning urban information and originating from GIS applications.

2 Overview and Existing Work

As mentioned, spatiotemporal visualisation involves methodologies and techniques from different domains. From the perspective of GIS, it originated from GIS 2D maps and 3D layered representations, evolving towards 4D temporal GIS (3D GIS plus time). From the perspective of computer science, it has strong links to information models, computer graphics and visualisation, including elements from information visualisation and time-based visualisation. Moreover, it is used in urban simulation to illustrate changes over time.

2.1 Basic Concepts

The following sections provide a brief introduction in terms of these different backgrounds. First, we highlight specific characteristics to each domain and then highlight advantages and extract common points that exist despite the different usage both in terms of terminology as well as applications in each domain.

Computer Science. Spatiotemporal visualisation includes elements from computer science mainly from two areas: Visualisation and human computer interaction (HCI). More specifically, visualisation is applied to extract and transform complex raw data into an easily readable and understandable format. Depending on different data types and objectives, visualisation has developed into different branches, such as geo-visualisation referring to cartographic data, information visualisation referring to abstract data, or visual analysis referring to knowledge extraction. Various representations are designed to reflect information in terms of time series or multiple dimensions, while caring less about spatiotemporal relationships. In addition, HCI attempts to make data exploration more effective. For instance, today's rapid development of tangible interfaces is used to implement new means of navigation in large data sets, and current work also focusses on realising interaction with such data, e.g. by providing interactive selection and filtering operations. In addition, other areas such as data mining, or database management are involved.

Geographic Information System (GIS). A temporal GIS, is based on a 2D or 3D GIS that additionally stores temporal information, has the goal to answer questions such as where and when changes occur, what induced change patterns may be observed, and what may be the underlying causes of such changes. Langran and Chrisman (1988) explored the idea of temporal GIS to outline a framework for conceptual design and implementation of incorporating temporal information in GIS. They defined four representational models, which are space-time cubes; sequence snapshots; base state with amendments; and space-time composites, and resulted in four major temporal GIS models Zhang and Qin (2004). Many concrete applications are within this domain, since GIS has a strong foundation in geography and offers significant advantages for spatial analysis. In particular, companies and government organisations in many countries recently started and will continue to transform their databases towards 3D GIS and will move towards integration of temporal data, especially for decision-making.

Urban Simulation. Urban simulation models and the visualisation of their results are increasingly used to assess important urban aspects such as land use regulations or alternative transportation schemes. According to Waddell and Ulfarsson (2004), when designing an urban simulation system, different choices should be considered to reflect the real world as a fused, dynamic environment. The choices include the level of behavioral aggregation, the level of determinism, the temporal representation, and the resolution of space and time. Many concrete applications like crowd simulation include the analysis of change of an urban environment. In addition, temporal representations are designed to highlight long-term equilibriums. Spatiotemporal visualisation, which embeds temporal information, has a natural advantage to support these applications. It should also be noted that there are ongoing efforts of filling the gaps between behavioral urban simulation and visualisation, e.g. (Vanegas et al., 2009). With the advancement of such approaches, the inclusion of temporal characteristics will become an even more important topic.

These three fields can be subdivided into even more detailed domains, and all have a close relationship with spatiotemporal visualisation. Computer science contributes with very advanced visualisation techniques and interactive operations but deals less with geographic information. GIS, which evolved with a strong geographic background, now advertises itself to be a popular spatial analysis tool, but is still mainly used for data management and layer-based static visualisation. Urban simulation has the capability the realistically model temporal behaviour of urban state, but its results are often inadequately visualised. However, GIS and urban simulation already share common concepts in terms of urban information modelling. Thus, when we view these fields (and potentially others) together, the increasing importance of dynamic behaviour and the notion of time is clearly visible, and it is natural that their advantages should be combined.

2.2 Previous Reviews

Former reviews have been made from different perspectives. From the perspective of GIS, temporal GIS have become one of the main pillars of recent developments. Originally, Langran and Chrisman (1988) examined four representational models for spatiotemporality, which were (1) space-time cubes, (2) sequential snapshots, (3) base state with amendments and (4) space-time composites. The space-time cube (STC) is based on original definitions of the space-time-path and space-time-prisms (Hägerstrand, 1970), which nowadays are considered highly important methods of spatiotemporal visualisation. Kraak (1988) conducted a series of interactive operations on the space-time cube, and revised the progress of the advanced space-time cubes from the perspective of time geographic and revisualisation. Vasiliev (1997) proposed a framework for representing spatiotemporal information on static maps based on symbolisation in cartography. More recently, time series have been added to commercial geospatial software, such as in ArcMap (Goodall et al., 2004). Time series are used to show dynamic events, such as weather changes, water condition, and pollution desperation. From the perspective of the visual analyst, Andrienko et al. (2003) reviews visualisation methods by including the aspects of exploration technologies. Interactive operations are introduced for different data types and tasks.

In contrast to previous reviews, we summarise classical spatiotemporal visualisation techniques as well as related ones. The examples and illustrations in this chapter are not limited to a single research field. Thus, the main objective of the chapter is to provide an overview of basic ideas and recent trends in order to inspire future visualisation methods of comprehensive knowledge.

2.3 Workflow of Spatiotemporal Visualisation

Visualisation can be regarded as a translation from unstructured raw data to structured data representations. According to Spence (2007), "to visualise is to form a mental model or mental image of something." The relevant definitions of *model* in the Oxford Dictionary are given as "a thing used as an example to follow or imitate" and as "a simplified description, especially a mathematical one, of a system or a process, to assist calculations and predictions."

This paper introduces and adheres to a workflow that starts with data acquisition, performs information modelling, and concludes with actual visualisation techniques as shown in figure 1. First, section 3 deals with 4D data acquisition, which makes the automatic generation of spatiotemporal data efficient due to significant recent improvements.

After data acquisition, the original spatial datasets effect the subsequent processes in the workflow; thus section 4 has a closer look at information modelling. As shown in figure 1, this step in the workflow involves different tasks related to data storage, filtering, clustering, analysis; and results in a conceptual model that is based on abstract data types (ADTs). In practise, these tasks are not always performed sequentially, but rather iteratively. For instance, semantic information is required for data queries, pattern detection, as well as for spatial analysis. Or, the abstract data types used for storage are largely determined by the expected results of spatial analysis.

Section 5 deals with visualisation techniques, considering both data representation and interactive operations. Typical methods that involve time are summarised in terms of dimensionality, i.e. 1D (symbols), 2D (image series), 3D (space-time cube), 4D (real-time rendering of dynamic 3D scenes). Inspired by that, possible future possibilities for spatiotemporal visualisation and associated interactive operations are proposed in section 6.

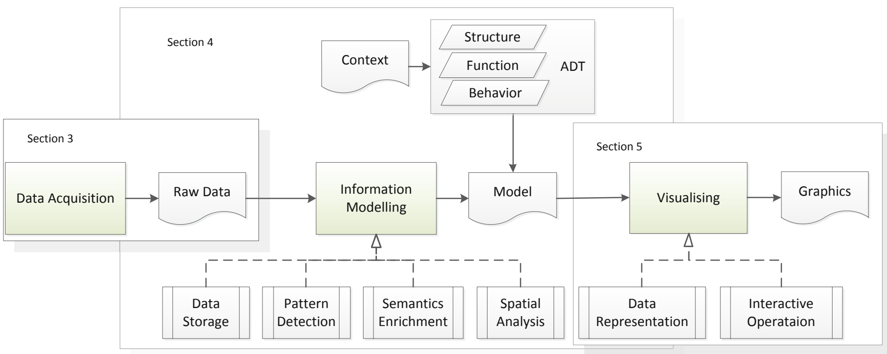


Fig. 1. Overall workflow to realise spatiotemporal visualisation

3 Spatiotemporal Data Acquisition

Spatial data acquisition has gone through revolutionary changes over the last fifty years. Evolving from labour-intensive and time-consuming points surveying, current technology involves high-precision and efficient satellite-based remote sensing techniques, as well as airborne and terrestrial methods supported by satellite-supported global positioning systems (GPS) (Longley et al., 2005). High-resolution and hyper-spectral imagery is now available at affordable cost, sometimes even for free, and includes data describing status and changes of natural phenomena and man-made artefacts, such as climate, water, land, vegetation, road and residential area development. Automatic methods to derive more detailed information or knowledge from image datasets have long attracted past and ongoing research efforts in photogrammetry, computer vision and geosciences. (Semi-)Automatic tools for 3D morphological reconstruction, such as terrain, vegetation, buildings, or infrastructure, have been implemented to support geospatial databases (Gruen, 2008). The following paragraphs provide a brief introduction of the most relevant data acquisition technologies and methods.

Global Navigation Satellite Systems (GNSS). were invented for military applications, but have in the meantime become available for civil applications. Current GNSS include the Global Positioning System (GPS) implemented by the United States, the GLObal NAvigation Satellite System (GLONASS) of Russia, the Compass Navigation System of China, and the Galileo Positioning System of European Union. The first two are providing global service while the latter two only provide regional service. As the most successful globally available system, the GPS is freely accessible by any user and has been the major choice for consumer usage in terms of positioning and navigation. In research and professional applications, the core functionality of GNSS is to survey 3D coordinates. The accuracy can yield 3 cm (horizontal) with the real-time or post differential processing supported by a terrestrial operating reference station. The availability of high-accuracy global positioning is highly relevant for many sensing and monitoring applications. With continuous data observation over a long period, dynamic visualisation in 3D of series of data can reveal the position and degree of changes of objects to be observed.

Remote Image Sensing (RS). is indispensable due to its capabilities of covering wide areas and for allowing continuous acquisition. The imagery can be acquired by satellite-based sensors or by aerial vehicles flying at different heights. Typically, there are two types of information that can be derived from remote sensing data: a) the geometry, which is derived mainly from high resolution images acquired by optical instruments, and b) the attributes, which can be extracted from hyper-spectral images. Recently, the launch of satellites with high spatial resolution sensors made it possible to extract both 2D and 3D geometric dimensions of geographic features.

Light Detection and Ranging (LiDAR). uses laser pulses to generate dense and accurate elevation maps of a target surface, which can be a terrain surface or building topology, or a combination thereof. The height or distance to a target surface is determined by the elapsed time between generation and return of each laser pulse. Combined with data from an inertial measuring unit and from GPS, the point clouds can be further correlated and processed resulting in a georeferenced dataset. When realised by a moving vehicle like an unmanned aerial vehicle (UAV), the density can be determined by flight speed, altitude and laser repetition rate. In order to fully employ the dense points clouds, classification and filtering algorithms are vital to the successful acquisition of precise surface features. Currently, there are open problems to accurately extract digital terrain elevation, especially in areas with vegetation cover or with abrupt changes such as in urban areas. In addition, the visualisation of LiDAR point clouds requires multi-scale preprocessing.

Volunteered Geographic Information. makes use of Web 2.0 technology, of crowd-sourcing techniques, and of the increasing popularity of portable computing devices: In contrast to traditional techniques, the users of maps and geographic information systems have become participants and producers of various geo-tagged information as well. Volunteered geographic information, or VGI, was coined as a new topic in geographic information science to research the integration, update and consistency considering professional datasets (Goodchild, 2007). In the meantime, the online community has produced huge amounts of imagery and videos at different locations and times, which bear more abundant information than that traditional geospatial database contains.

4 Information Modelling of Spatiotemporal Data

Generally, the workflow to realise data visualisation can be summarised in terms of four basic stages as follows (Ware, 2004):

1. Data collection and storage.
2. Data preprocessing designed to transform the data into understandable information.
3. Display hardware and rendering algorithms that produce one or multiple images on the screen.
4. Interpretation in the context of the human perceptual and cognitive system (the perceiver).

As a branch of visualisation in general, spatiotemporal visualisation fits into the above general pipeline. However, as one of the main challenges of spatiotemporal visualisation is not only making the raw data understandable, but also using it to depict dynamics, movements and activities, we suggest to further refine the overall process with additional steps as follows:

1. Data storage and query (Güting et al., 2000; Güting, 2008).
2. Data filtering and clustering, pattern detection (Nanni and Pedreschi, 2006; Palma et al., 2008).
3. Enriching data with semantics and knowledge (Baglioni et al., 2009).
4. Translation of data into object-oriented entities using a conceptual model (Brakatsoulas et al., 2004).
5. Spatial analysis according to actual concrete application tasks; formulation of moving patterns with mathematic models; and prediction of tendencies (Maguire et al., 2005).
6. Visualisation of the entities (Kraak, 2005; Eccles et al., 2008).

Except for the last step, which is treated in more detail in section 5, we consider these steps as the relevant steps for information modelling that precede the actual visualisation. In the following, we briefly introduce important elements that are part of the overall process.

Moving Objects Database. The database provides support for storing and querying time-dependent geometries and moving objects (Güting and Schneider, 2005). From the perspective of GIS, collected data can be divided into two categories: static and dynamic information. Static objects do not change within a given period of time; examples are roads, buildings, or land views. In contrast, dynamic data changes within a given time interval, either discretely or continuously; examples are urban expansion, spreading of infectious diseases, or people movements. Some dynamic phenomena are represented in terms of named moving objects, i.e., defined as specific objects that change position or extend continuously (Güting et al., 2000). Güting defined basic spatial data types as well as a corresponding query algebra. He emphasised the fact that the geometry may change continuously. Thus, in his research, the proposed database management system includes concepts for data models and data structures to represent moving objects (Güting, 2008) and to allow query and analysis of such objects.

Moving Patterns Detection. Since raw data sets can not be directly used for specific purposes, techniques are applied to detect patterns, trends, and relations for a given objective of investigation (Andrienko et al., 2003). In this context, the main goal is to filter and cluster the massive spatial data, and to allow for reasonable exploration of data sets. As shown in (Andrienko and Andrienko, 2011), clustering of trajectory data and transformation of the temporal structures for comparisons within and between clusters are proposed to improve the effectiveness of the space-time cube.

Semantic Enrichment. In order to transform the detected patterns into understandable knowledge, semantic analysis and enrichment is applied. A major class of the spatiotemporal data sets are records of human activities. They naturally contain social knowledge within a given context and can be described using semantics to allow for queries that can be well understood by normal users. An important concept is the identification of trajectories in space over time. Spaccapietra et al. (2008) provides a formal definition of trajectories in terms of stop and move states. The definitions serve as a standard approach to link numerical data with semantics and have been widely applied and extended in later visualisation methods. During analysis, the topology of geographic data (Shekhar and Chawla, 2003) and temporal relationships (like Allen relations) are considered and combined to detect and define patterns. Semantics based on ontologies (Baglioni et al., 2008) is added to enrich the data during all the above steps. A trajectory is then divided into a sequence of partial state, defined with function, behaviour and structure.

Conceptual Data Models. A conceptual model is built to formulate the moving information and to highlight the cause and effect in the dynamic phenomenon. Peuquet and Duan (1995) proposed a spatiotemporal GIS database framework. The *Event-based Spatiotemporal Data Model* (ESTDM) organises event changes in terms of an event list that comprises individual event entries. The representation of events in terms of a triple "when (time), what (attribute), and where (location)" contributed a substantially to the object-oriented representations of spatiotemporal data emerging later on. Based on these models, further researches mainly investigate the relationship between entities. In addition, and not limited to spatiotemporal data only, Bertin (1983) classified the related questions into three levels "elementary, intermediary and overall", which can be used to organise and analyse data at different scales.

Spatial Analysis. Many concrete applications incorporate spatial analysis methods that are applied to study entities using their spatial properties. Maguire et al. (2005) introduced the basic tools and techniques, and highlighted models that are available in GIS and modelling systems. In addition, they reviewed information models and applications in the context of urban simulation, such urban growth models, urban land-use and transportation models, and location planning applications. Due to the ubiquitous availability of GIS and the sinking costs of using it, the number of applications that employ data mapping techniques, powerful analysis methods, and user-friendly interfaces is growing.

Information modelling is a comprehensive process, and all involved processes deeply influence the data structures and the resulting visualisations. Through this step, the raw data sets are transformed into abstract data types (ADTs), which formulate the dynamic information. ADTs must be carefully designed so they can carry enough semantics and provide useful functionality. Typed entities, such as “people”, “places”, “events” and “time” are designed to describe moving objects. The first ADT for moving objects was proposed in (Erwig et al., 1999), in which data types and sets of operations are defined, and can be applied to perform uniform queries in various DBMS object algebras. For modelling the data, two main methods that had a strong influence on later research were proposed: event-based data models (Peuquet and Duan, 1995), and object-oriented data models (Worboys, 1992). ADTs play an important role as they determine how to link the objects with corresponding geometry that can be directly used for the next step: the actual visualisation techniques.

5 Visualisation Techniques for Spatiotemporal Data

The most widely applied method for representing interesting, geo-referenced phenomena are maps. Using maps, the geospatial characteristics, such as cluster patterns and associated rules, are generally more easily identified as opposed to data listed in a table. In order to efficiently communicate information encoded in a map to users, cartographers have set up many theories investigating linguistics and semiology to build a generic graphic language based on common understanding and perception. On analog maps, the symbols are usually decomposed into six visual variables besides of intrinsic location and geometry: shape, size, colour, orientation, hue, and texture. In digital maps, more variables can be introduced, such as appearance duration or flashing intervals to represent dynamic phenomena effectively (Slocum et al., 2009). Additional information visualisation techniques enhance the interactive ability of exploration; and visual analytics makes the patterns even more visible. The significant, rapid evolution of GIS, is enhancing traditional time-based visualisation with object-oriented visualisation methods. This section focuses on different forms of data representation, and summarises the most important methods, starting with static techniques and then moving towards dynamic and interactive methods.

Timestamps and Time Labels: Timestamps are series of events marked with date and time information and typically used in temporal GIS databases to include the dimension of time. Time labels are specific graphic variables and symbols used in maps indicating changes. The view is static. Minard’s famous graphic of Napoleon’s Russian campaign (figure 2) is often used to illustrate these types of representation, as it uses different variables in a temporal context: Line width indicates army size; horizontal and vertical position denote latitude and longitude, i.e., are used as location information; colour is applied to identify the direction of the march; and temperature is indicated in terms of a graph along the timeline.

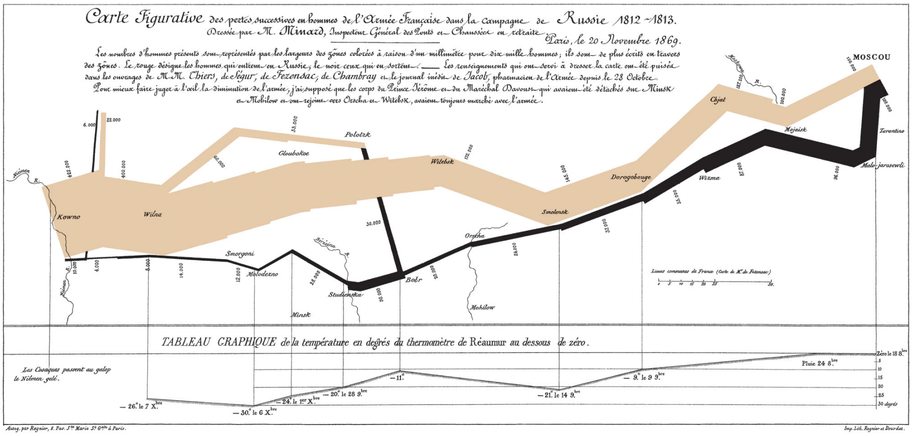


Fig. 2. Minard's graphic of Napoleon's Russian Campaign

Possible variables of graphic mapping have been summarised as shape, size, orientation, colour, texture, opacity, position and so on. Additional variables have been defined in the context of information visualisation, such as in (Spence, 2007). However, depending on the context, the specific symbols have to be carefully chosen, as they have to obey existing rules such as in cartography or urban planning.

Baselines. This technique uses arrows and lines, as well as charts and diagrams to indicate state changes, and frequently applies animation methods to represent the progress. It is widely used in 2D visualisations for both abstract and concrete information, such as for instance, a Gaussian distribution graphics to show demographic trends; an airline figure to show the entire flight plan (figure 3); or a vector field to show the movement directions (figure 4). While baselines can be used to provide an indication of time and dynamics, e.g. by using different arrow sizes for different speeds in a vector field, they cannot cover the absolute state of a model at a given point in time. Therefore baselines are not well suited for analysis of discrete events and relationships between events.

Image Series. As one class of dynamic representations, timelines are used as the basis for mapping events over time, and to dynamic information in terms of image series. When they are combined with a geographical map, they show the spatiotemporal patterns of those events (Hewagamage et al., 1999). Some basic timeline appearance types have been described by Kraak (2005), e.g., straight lines representing linear time like years; circular shapes to denote seasons in one year; spirals to indicate skewed time in geology. In map making, sequences of maps depict the changes of data in a region of interest. When a cursor moves along the timeline, maps change accordingly. The simplest animation type displays a small set of changing maps only, in terms of static pictures that change. An example is shown in figure 5, which gives a series of four remote sensing images indicating change over time. If the sets of changing images get larger, they can be shown in terms of animated video sequences. This technique can be applied in many cases for indicating continuous changes of the state of objects within a given

Fig. 3. Using a base line to indicate the flight path of a plane

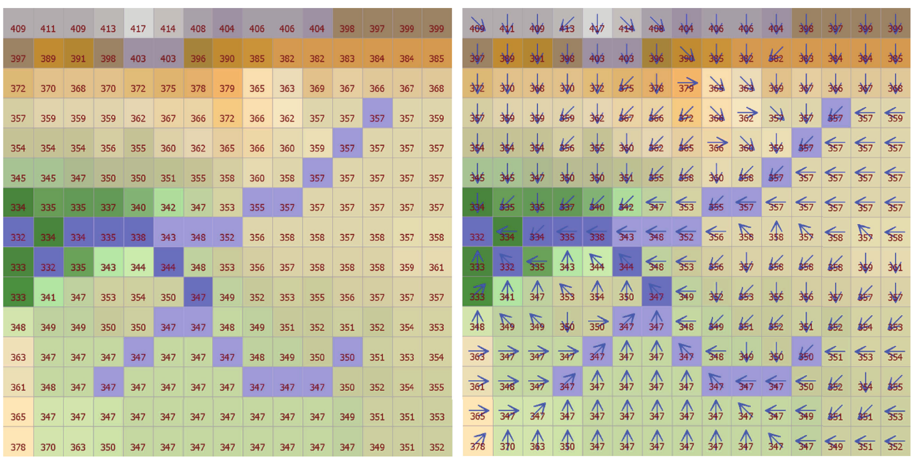


Fig. 4. Vector field used to indicate the direction of water flow

environment. For example, it is frequently used to visualise the output of mobility and transportation simulations, e.g., to depict activities and tendencies of movements over a period of time. A timeline animation can be enhanced with interactive operations, such as zoom in, zoom out, pan, or to focus on selected event types.

Space-Time Cube: In the early 70's, Hägerstrand (1970) developed a graphic view with time as an additional spatial dimension. He suggested a three-dimensional diagram, the so-called space-time cube (STC), to show life histories of people and how people interact in space and time. Two orthogonal horizontal axes were used to

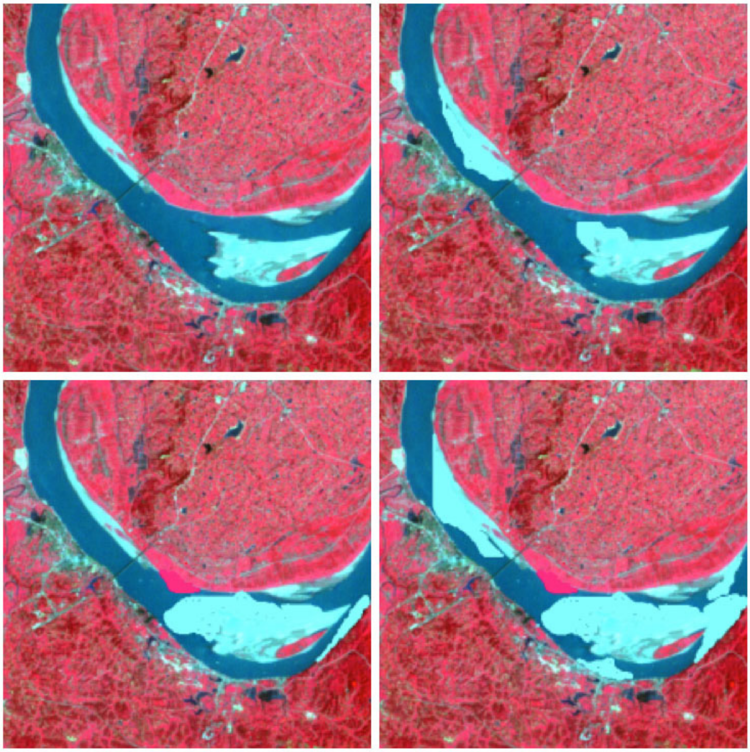


Fig. 5. Change detection: The multi-temporal Landsat TM change images of the famous Three Gorges

represent the x-y geographic coordinates, while the vertical axis represents the time dimension. Compared to the previously presented methods, the STC reveals real 3D characteristics. The main advantage of the STC is that the whole evolution of the scene can be shown within one image. In addition, more information can be overlaid onto the scene or individual events, thereby making interactive queries possible within a 3D environment. Thus, the STC has been extended with interactive techniques: In order to enhance the interactive manipulation and to reflect the detection of spatiotemporal clusters of events, based on the original space-time cube, Kraak (2005) presented an advanced version with operations of changing viewing perspective, temporal focusing, and dynamic linking of maps with corresponding symbols. Geotime (Eccles et al., 2008) as a mature commercial software supports many of these features. Today, many concrete applications using the STC have been realised (Kraak, 2006; ITC-2011, 2011). Three examples using space-time cube visualisation are shown in figure 6: the left image shows a visualisation of transportation simulation data; the top-right image shows trajectory data of people movements, and bottom-right shows the history of points of interest in a city. Gatalsky et al. (2004) compared baseline (2D) to space-time cube (3D) methods. They concluded that the space-time cube is comparably harder to understand for normal users, and interpretation errors can made. However, their evaluation showed that the users do benefit from space-time cube representations when analysing complex spatiotemporal patterns.

Real-Time Rendering of Dynamic 3D Scenes: One of the main limitations of the space-time cube is that usually movements along the vertical axis are lost (as this axis is used for time). This problem can be overcome to some extent by real-time animated 3D rendering techniques. For example, in urban simulation, timelines are used as an interface component to query instant changes. In contrast to the history timeline examples we mentioned above, for each frame, time is taken as one parameter input to simulate the current state of the model. In (Maguire et al., 2005), Batty and Goodchild introduce many concrete applications for urban simulation, including land use, transportation, or urban growth. In addition, Weber et al. (2009) presented a system that allows for interactive simulation of 4D cities, and lets the user change input parameters while the simulation runs. The system displays 3D models of an urban environment as the simulation evolves over time.

6 Potential Future Progress of Spatiotemporal Visualisation

In the report "space-time cube beyond time geography," Kraak (2006) reviewed different applications using space-time cube, and raised some open questions: Are there distinct strengths and weaknesses of the STC? Does the STC constitute a good alternative to other spatiotemporal visualisation techniques? Then, more specifically, can time and the third spatial dimension be used together along the same axis? When does a certain Space-Time-Path make sense?

In the following we discussion, we shall address some of these questions, but also focus on the superordinate, more general question, whether users of STC applications understand what they see. The discussion is based on a concrete custom application that uses STC (figure 6, bottom-right). The application is a guidance system for tourism to help finding places of interests and for querying historical events of such points. In order to evaluate the users' understanding of the application, the following concrete questions were given:

1. Can users tell the meaning of the axes without any pre-instruction?
2. Can users tell the meaning of the results generated from the basic operations?
3. How much information can users obtain from the view?
4. What other interactive operations do users suggest?

It showed that nearly all the participators could quickly understand the basic functioning and meaning of the STC visualisation, as well as the basic operations like zoom, rotate, pan, select. However, many users found it hard to perceive precise information. In particular, when the amount of data was increased (i.e., adding more points of interest), the dense point sets made it hard select and isolate individual events. Some users were intrigued by the "cool-looking" 3D scene but questioned the usefulness of the representation (as opposed to more conservative, map-based approaches).

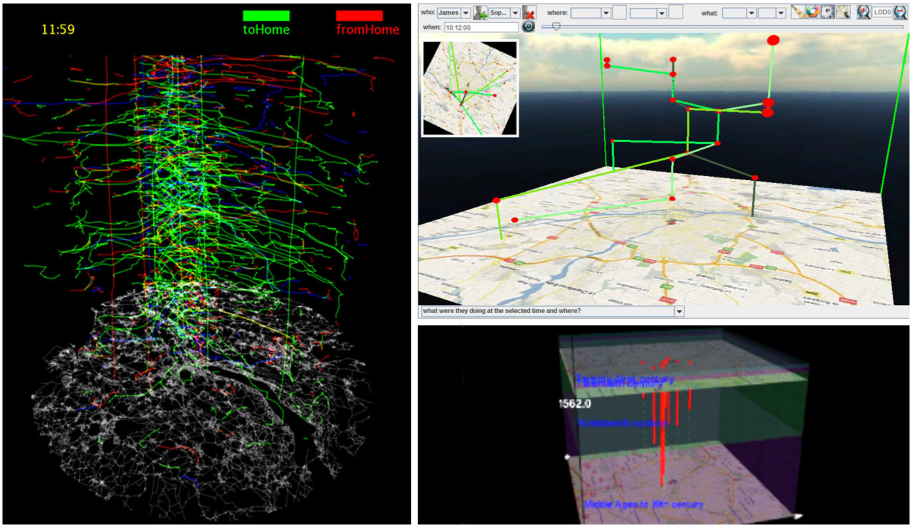


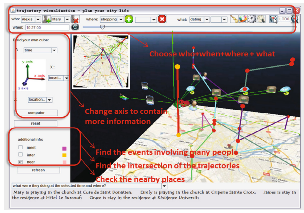
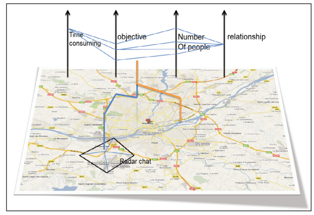
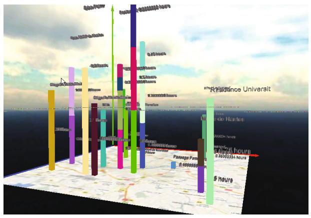
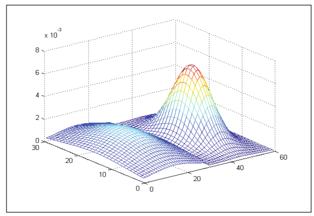
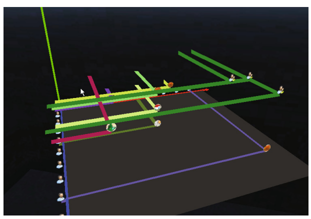
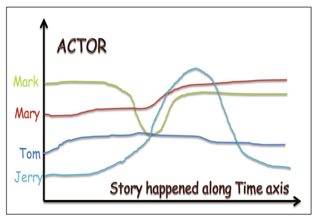
Fig. 6. Typical space-time cube applications: Spatiotemporal visualisation of transportation simulation data (left), visualisation of trajectories (top-right) and history visualisation of points of interest (bottom-right)

When it comes to question 4 (possible additional operations), the spectrum of answers was quite diverse, also reflecting different backgrounds of the users. Non-technical users suggested to use two parallel views, 3D STC, as well as 2D traditional views to obtain a more focused view of specific data. Technically oriented users' feedback could mainly be categorised into two classes of extra operations: a) providing means of subdividing the cube and of clipping the cube using planes, and b) emphasise on data aggregation in order to provide a cleaner and less complex view.

Integrated 2D and 3D Visualisation. When comparing the visualisation techniques introduced in section 5, one obvious categorisation is by dimension, i.e. 2D vs. 3D views. Traditionally, 2D techniques have been most established and accepted in the GIS domain, a clear shift towards 3D (and 4D) also in these domains is recognisable, and today, high-performance 3D is available on consumer computers. Therefore we may ask what the most effective synergies between the two types might be, and how they could be combined. In GIS applications combined 2D and 3D views are commonly found – a prominent example is the combination of Google maps, street view, and Google Earth. Transfer the two representations can happen in both ways, e.g. extrude operations can generate 3D views from 2D base data, or dedicated projection operations may recreate 2D views from 3D geometry.

Based on this, we suggest a number of techniques that complement 2D and 3D STC views, as given in table 1. The images in the second column of the table were created from our research that focussed on semantic visualisation of trajectory data using STCs. It aimed at finding new visualisation methods to map defined semantics and to overlay additional information within the limited cube space while keeping the view at an

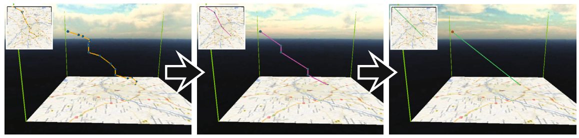
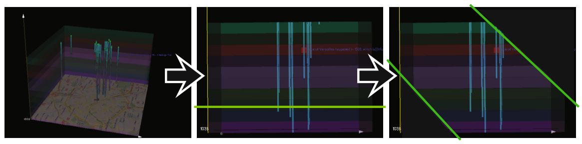
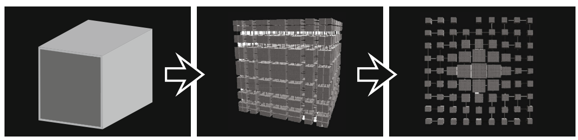
Table 1. Possible visualisation techniques that complement 3D and 2D views

Application	Space-Time Cube Visualisation	Information Visualisation
Multi-dimensional Data Visualisation		
Visualisation of Statistics Results		
Visualisation of Relationships Between Entities		

understandable level. The table presents three tasks that show the potential of integrating 2D and 3D visualisation:

1. Multi-dimensional data visualisation (first row). Here, we suggest the use of information visualisation techniques to make the interface more user friendly. Traditional interfaces use controls like combo-boxes to input query conditions (left image), which bloats the user interface and makes it confusing. Multi-dimensional visualisation techniques can be used to provide a cleaner view. In the right image, parallel coordinate are used to instead of combo-boxes, and a radar chart is used to evaluate the queried movements with multiple variables. An examples is found in (Forlines and Wittenburg, 2010): The 3D view is used to make an overall and direct understanding of the progress, while 2D view reflects details. In addition, animations and projections can be used to transform the 2D and 3D view between each other.
2. Visualisation of statistics results (second row). This visualisation has the goal of showing statistical data in real-time in order to make tendencies in a period of time understandable. The image on the left shows the result of a query, i.e. the number of visitors during a period of time. The image on the right enhances this view, and

Table 2. Possible operations that can be applied to space-time cube visualisation (images 2 and 3 in last row were recreated from Carpendale et al. (1996))

Operation	Description	Illustration
Interactive Aggregation	Interactive context-based data aggregation with user defined parameters. Query details from high to low sampling rate.	
Regular and Irregular Profiles	Query continuous spatiotemporal information. Intersect the STC with horizontal or arbitrary planes.	
3D Distortion	Subdivide cube, and use 3D distortion techniques to highlight and focus objects of interest.	

can provide additional degrees of freedom with peak values, area and gradients to denote different meanings. With this type of view, clusters can more easily be detected, as it has been shown in (Nanni and Pedreschi, 2006).

3. Visualisation of relationships between entities (last row). The example employes data mapping and aggregation of knowledge that includes geographic reference. It employs social network graphics, which have been widely used to reflect links between people. In spatiotemporal visualisation, one of the main objectives can be to find out the relationships and influences between people, activities and environment. With a time axis projection, the 3D view (left image) can be enhanced with a 2D network graphics (right image). Another example on visualising social elements was given in (Smith, 2009), where density maps demonstrated the mapping of social information like urban structure, employment structure with geographic reference, as well as data aggregation.

Interactive Operations. Today, 3D GIS platforms constitute an important communication platform for urban planners and decision makers. Successful commercial examples are ESRI ArcGIS or ERDAS VirtualGIS. Advanced spatial analysis operations such as time slice, oblique slice, or fence slice are designed to visualise features otherwise hidden. We believe that it is possible to transform and implement such operations into the context of space-time cube, so they can be used to query and highlight implicit spatiotemporal information, which in our view of point. We illustrate possible use cases in table 2, explained in more detail as follows:

1. Interactive aggregation (first row). As the size of data sets increases, massive amounts of points and lines make the view unreadable, and it becomes very hard to

carry out interactive selection of elements. We suggest two possible solutions; the first one filters data that is not related to the query, and the second that performs context-based aggregation. The latter provides varying level-of-detail according to different requirements (e.g. inspection versus selection). As in (Bertin, 1983), the three levels of information, "elementary, intermediary and overall" should be employed and generalised .

2. Regular and irregular profiles (second row). Indexing space-time data is a common querying operation, normally achieved by interacting with the timeline scrollbar. This corresponds to a "regular profile" (middle image), where a plane perpendicular to the time axis "cuts" through the STC. In contrast, an irregular profile lets the user define arbitrary planes or even surfaces to intersect with the STC (right image).
3. 3D shape distortion (last row). This operation suggests the separation of the whole space-time cube into smaller pieces with a dispersing transformation . Thus, each single sub-cube constitutes an independent spatiotemporal unit. User can easily interact with individual sub-cubes, focussing on information within a short period of time and within smaller area of interest. Additional operations would be navigation within a spatial structure of distorted cubes (Carpendale et al., 1996), or sorting operations among sub-cubes that could make relationships between them more explicit.

7 Summary and Conclusion

Spatiotemporal visualisation has been successfully applied in diverse domains. In this paper, we focussed on spatiotemporal visualisation related to urban models and data. We highlighted previous reviews, introduced a processing pipeline, that consists of data acquisition, information modelling, and the actual visualisation. For each of these steps we provided existing work, and established overall connections. Based on this, we proposed possible future progress, mainly dealing with closer integration of visualisation and interaction, and with enhancing the capabilities of interactive operations.

With wide-spread and increasingly available 3D and 4D urban data sets, spatiotemporal visualisation in the urban context also gains in importance. Our future work will focus on visualisation techniques for data stemming from urban simulations. Urban data, which includes both physical information from the environment as well as abstract information from social activities, constitutes an unique data set, and urban simulation attracts people from different domains to work together. Thus, many concrete applications can be proposed for urban simulation involving spatiotemporal issues. As the immediate step, we intend to realise the proposed future enhancements to spatiotemporal visualisations, so the resulting applications can contribute to better understanding dynamic phenomena that are ubiquitous in urban environments.

References

Andrienko, G., Andrienko, N.: Dynamic time transformations for visualizing multiple trajectories in interactive space-time cube. In: International Cartographic Conference, ICC 2011 (2011)

Andrienko, N., Andrienko, G., Gatalsky, P.: Exploratory spatio-temporal visualization: an analytical review. Journal of Visual Languages & Computing 14(6), 503–541 (2003) ISSN 1045-926X

Baglioni, M., Macedo, J., Renso, C., Wachowicz, M.: An Ontology-Based Approach for the Semantic Modelling and Reasoning on Trajectories. In: Song, I.-Y., Piattini, M., Chen, Y.-P.P., Hartmann, S., Grandi, F., Trujillo, J., Opdahl, A.L., Ferri, F., Grifoni, P., Caschera, M.C., Rolland, C., Woo, C., Salinesi, C., Zimányi, E., Claramunt, C., Frasincar, F., Houben, G.-J., Thiran, P. (eds.) ER Workshops 2008. LNCS, vol. 5232, pp. 344–353. Springer, Heidelberg (2008)

Baglioni, M., Fernandes de Macêdo, J.A., Renso, C., Trasarti, R., Wachowicz, M.: Towards semantic interpretation of movement behavior. In: Advances in GIScience, pp. 271–288 (2009)

Bertin, J.: Semiology of graphics. University of Wisconsin Press (1983) ISBN 0299090604

Brakatsoulas, S., Pfoser, D., Tryfona, N.: Modeling, storing and mining moving object databases. In: Proceedings of International Database Engineering and Applications Symposium, IDEAS 2004, pp. 68–77. IEEE (2004) ISBN 0769521681

Carpendale, M.S.T., Cowperthwaite, D.J., Fracchia, F.D.: Distortion viewing techniques for 3-dimensional data. In: Proceedings of IEEE Symposium on Information Visualization 1996, pp. 46–53 (1996)

Eccles, R., Kapler, T., Harper, R., Wright, W.: Stories in geotime. Information Visualization 7(1), 3–17 (2008) ISSN 1473-8716

Erwig, M., Güting, R.H., Schneider, M., Vazirgiannis, M.: Spatio-temporal data types: An approach to modeling and querying moving objects in databases. GeoInformatica 3(3), 269–296 (1999) ISSN 1384-6175

Forlines, C., Wittenburg, K.: Wakame: sense making of multi-dimensional spatial-temporal data. In: Proceedings of the International Conference on Advanced Visual Interfaces, pp. 33–40. ACM (2010)

Gatalsky, P., Andrienko, N., Andrienko, G.: Interactive analysis of event data using space-time cube. In: Proceedings of Eighth International Conference on Information Visualisation, IV 2004, pp. 145–152. IEEE (2004) ISBN 0769521770

Goodall, J.L., Maidment, D.R., Sorenson, J.: Representation of spatial and temporal data in ArcGIS. In: GIS and Water Resources III, AWRA, Nashville, TN (2004)

Goodchild, M.F.: Citizens as sensors: web 2.0 and the volunteering of geographic information. GeoFocus (Editorial) 2, 24–32 (2007)

Gruen, A.: Building extraction from aerial imagery. Remote Sensing of Impervious Surfaces (2008)

Güting, R.H.: Moving object languages. In: Encyclopedia of Geographic Information Systems, pp. 732–740. Springer, Heidelberg (2008)

Güting, R.H., Schneider, M.: Moving objects databases. Morgan Kaufmann Pub. (2005)

Güting, R.H., Böhlen, M.H., Erwig, M., Jensen, C.S., Lorentzos, N.A., Schneider, M., Vazirgiannis, M.: A foundation for representing and querying moving objects. ACM Transactions on Database Systems (TODS) 25(1), 42 (2000) ISSN 0362-5915

Hägerstrand, T.: What about people in regional science? Papers in Regional Science 24(1), 6–21 (1970) ISSN 1056-8190

Hewagamage, K.P., Hirakawa, M., Ichikawa, T.: Interactive visualization of spatiotemporal patterns using spirals on a geographical map. In: vl, p. 296 (1999) ISSN 1049-2615

ITC-2011. What has ITC done with Minard's map (2011), `http://www.itc.nl/personal/kraak/1812/minard-itc.htm` (accessed March 1, 2011)

Kraak, M.J.: The space-time cube revisited from a geovisualization perspective. In: Proceedings of the 21st International Cartographic Conference (1995/1988)

Kraak, M.J.: Timelines, temporal resolution, temporal zoom and time geography. In: Proceedings 22nd International Cartographic Conference, A Coruna Spain (2005)

Kraak, M.J.: Visualization viewpoints: beyond geovisualization. IEEE Computer Graphics and Applications 26(4), 6–9 (2006) ISSN 0272-1716

Langran, G., Chrisman, N.R.: A framework for temporal geographic information. Cartographica: The International Journal for Geographic Information and Geovisualization 25(3), 1–14 (1988) ISSN 0317-7173

Longley, P., Goodchild, M.F., Maguire, D.J., Rhind, D.W.: Geographical information systems: principles, techniques, management, and applications. John Wiley & Sons (2005)

Maguire, D.J., Batty, M., Goodchild, M.F.: GIS, spatial analysis, and modeling. Esri Press (2005)

Nanni, M., Pedreschi, D.: Time-focused clustering of trajectories of moving objects. Journal of Intelligent Information Systems 27(3), 267–289 (2006) ISSN 0925-9902

Palma, A.T., Bogorny, V., Kuijpers, B., Alvares, L.: A clustering-based approach for discovering interesting places in trajectories. In: Proceedings of the 2008 ACM Symposium on Applied Computing, pp. 863–868. ACM (2008)

Peuquet, D.J.: Representations of space and time. The Guilford Press (2002) ISBN 1572307730

Peuquet, D.J., Duan, N.: An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. International Journal of Geographical Information Science 9(1), 7–24 (1995) ISSN 1365-8816

Shekhar, S., Chawla, S.: Spatial databases: a tour. Prentice Hall (2003) ISBN 0130174807

Slocum, T.A., McMaster, R.B., Kessler, F.C., Howard, H.H.: Thematic cartography and geovisualization. Pearson Prentice Hall, Upper Saddle River (2009)

Smith, D.: Mapping, analysing and visualising fine scale urban form and socio-economic datasets. In: Workshop on Geographic Information in a Web-based World, Centre for Advanced Spatial Analysis, University College London (2009)

Spaccapietra, S., Parent, C., Damiani, M.L., De Macedo, J.A., Porto, F., Vangenot, C.: A conceptual view on trajectories. Data & Knowledge Engineering 65(1), 126–146 (2008) ISSN 0169-023X

Spence, R.: Information Visualization: Design for Interaction. Prentice-Hall (2007) ISBN 0132065509

Vanegas, C.A., Aliaga, D.G., Wonka, P., Müller, P., Waddell, P., Watson, B.: Modeling the appearance and behavior of urban spaces. In: Proceedings of Eurographics, State of the Art Report, vol. 1-18, Eurographics Association (2009)

Vasiliev, I.R.: Mapping time. Cartographica: The International Journal for Geographic Information and Geovisualization 34(2), 1–51 (1997) ISSN 0317-7173

Waddell, P., Ulfarsson, G.F.: Introduction to urban simulation: design and development of operational models. Handbook in Transport 5, 203–236 (2004)

Ware, C.: Information visualization: perception for design. Morgan Kaufmann (2004) ISBN 1558608192

Weber, B., Müller, P., Wonka, P., Gross, M.: Interactive geometric simulation of 4d cities. Comput. Graph. Forum 28(2), 481–492 (2009) doi:http://dx.doi.org/10.1111/j.1467-8659.2009.01387.x

Worboys, M.F.: A model for spatio-temporal information. In: Proceedings of the 5th International Symposium on Spatial Data Handling, vol. 2, pp. 602–611 (1992)

Zhang, C.C., Qin, K.: GIS spatial analysis theory and methodology. Wuhan University Press (2004)