

An Annotated Bibliography on Spatio-temporal Modelling Trends

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Abstract

This article presents a brief overview and an annotated bibliography on the spatio-temporal modelling approaches and spatio-temporal data models that have been proposed since the late 1980s. While some models are theoretical, others are grounded upon specific case studies that have dealt with the evolution of spatial objects over time applied to scenarios such as land use, wildfire growth, road networks reconfiguration, or the analysis of objects in movement (moving objects). A taxonomy of 14 spatio-temporal modelling trends is described, the annotated bibliography is classified accordingly. Furthermore, three sections closely related to spatio-temporal modelling issues are also included: (i) ontological modelling foundations, (ii) temporal modelling, and (iii) time geography. These sections show the origins and part of the fundamentals of spatio-temporal modelling in GIS. The purpose of this bibliography, which consists of 319 references, is to compile a comprehensive set of references that can be of help to students and researchers, as well as to practitioners, interested in spatio-temporal modelling issues. This article is supported by an extended, dynamic, online bibliography which contains over 1450 references available at <http://spaceandtime.wsiabato.info>.

Introduction

During the last three decades, several spatio-temporal models have been proposed [1-3]. They can be classified by considering the theoretical approach on which each model is based or the focus of interaction (e.g., processes; events; actions; movement; and dynamic objects). Several classifications have so far been suggested for spatio-temporal models. Yuan and Stewart Hornsby [4] suggest a comparison of approaches based on the origin of change and propose six categories: (i) time-stamped; (ii) changed-based; (iii) event-based; (iv) movement-based; (v) activity-based, and (vi) process-based. Another possibility relies on the distinction between the object-based and the field-based modelling approaches, where proposals can be classified according to their underlying (i) vector [5] and (ii) raster [6,7] data structures; considering (iii) hybrid approaches [8-11]; or (iv) models that are flexible enough to support either raster or vector data structures [12]. The SNAP/SPAN ontology introduced by Grenon and Smith [13] provides a sound conceptual background highlighting the objects vs. fields dichotomy, as well as the concepts of snapshot, change and process. Worboys [14] presented the “*brief history of time*” to define a general overview of the evolution of time in GIS, presenting four main stages in the development of spatio-temporal information systems: *Static GIS*, *Temporal snapshots*, *Object change*, and *Events and actions*. Although the continuous development of spatio-temporal modelling field would make necessary to add a fifth stage to Worboys classification: *intelligent agent systems*. Additionally, El-Geresy et al. [15] propose five categories by considering conceptual modelling aspects: (i) location-based; (ii) object or feature-based; (iii) event-based; (iv) functional or behavioural; and (v) causal approaches. Bothwell and Yuan [16] assert that six descriptors are required to adequately describe object spatio-temporal dynamics: location; attribute (theme); extent; mutation (attribute); movement (location); and evolution (topological relationships).

Showing a broader context, Yuan and Stewart Hornsby [4] define five basic concepts for research on geographic dynamics that “*address the mechanism by which geographic drivers interact with objects, people, phenomena, and places as well as the outcomes of the interactions. Geographic drivers refer to spatiotemporal activities, events, and processes, and change and movement are the outcomes of such interactions*”. Consequently, geographic dynamics representation

Publication History:

Received: September 12, 2016

Accepted: August 05, 2017

Published: August 07, 2017

Keywords:

Spatio-temporal models, Temporal GIS, Moving Objects, Survey, Bibliography

and modelling approaches can be classified considering the three drivers (i.e., activities, processes, and events) and the two observable outcomes (i.e., change and movement). Table 1 summarizes these conceptual elements based on the focus of analysis, the modelling approach, and the outcomes.

At large, all spatio-temporal modelling trends are intended to describe the dynamic nature of geographic phenomena by considering one or more of the following six modelling dimensions: changes, processes, events, actions, movement (activity), and dynamic objects. Based on a comprehensive classification of the performed bibliographic review (see Section 2) and by considering the six modelling dimensions and the fundamentals on which each modelling proposal remains, for this annotated bibliography we have identified 18 modelling trends for dynamic geographic phenomena. Our classification can be reduced to 14 trends considering the pioneering proposals as a single approach, i.e., location-based¹ (Table 2). Thus, this bibliography is classified according to the 14 modelling trends as shown in Figure 1. Siabato *et al.* [17] presents a complete analysis of the proposed classification.

This annotated bibliography focuses on the identification of spatio-temporal modelling trends and the modelling proposals published during about the last three decades. The contribution of this work falls into the given modelling trends classification and the chronological categorization of the modelling proposals while highlighting the most relevant approaches. The foundations on which spatio-temporal modelling has been grounded are also highlighted. Since some proposals are related to different modelling dimensions, we have

¹Other authors call this approach version-based [19] or changed-based [4].

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Citation: Siabato W (2017) An Annotated Bibliography on Spatio-temporal Modelling Trends. Int J Earth Environ Sci 2: 135. doi: <https://doi.org/10.15344/2456-351X/2017/135>

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Element	Definition
Activity	Action performed by individuals (e.g., objects or humans) in space and time. “ <i>The consequence of activities by an individual may generate movement of the individual or cause changes to the individual’s characteristics</i> ”. Activities occur at a specific time.
Event*	An event represents an incident, “ <i>an occurrence of something with significance that drives noteworthy changes at locations over time. The decision on ‘significance’ and ‘noteworthy’ is situational and problem-dependent</i> ”. Events denote happening. Events are occurrents, i.e., they happen and are then gone (e.g., rainfalls, landslides).
Process*	“A gradual transformation that transcends geographic properties, forms, and patterns over time. The determination of ‘gradualness’ is scale-dependent”, either temporal or spatial. <i>Processes mark transformation of stages or phases in space and time. While events refer to happenings, processes emphasize a ‘becoming’ (e.g., initiation, transition, development, and evolution). A rainfall in a city, for example, is an event, but how a rainstorm develops and produces rain over space and time is a process. Activities, events, and processes are all scale-dependent, and their differentiation may be situationally determined. “What is an event in one situation can be a process or an action in another.”</i>
Change	“ <i>Substitution of properties in an object, at a location, or conditions in an environment. Changes can occur to population counts, identities, thematic attributes, and spatial or temporal characteristics.</i> ”
Movement	“ <i>Shift in location of a geographic object over time. The object must maintain the same identity during a movement.</i> ”

Table 1: Drivers and observables of geographic dynamics representation [4].

* Disagreements exist amongst researchers regarding the distinction between processes and events, see section 4.4 below for further discussion.

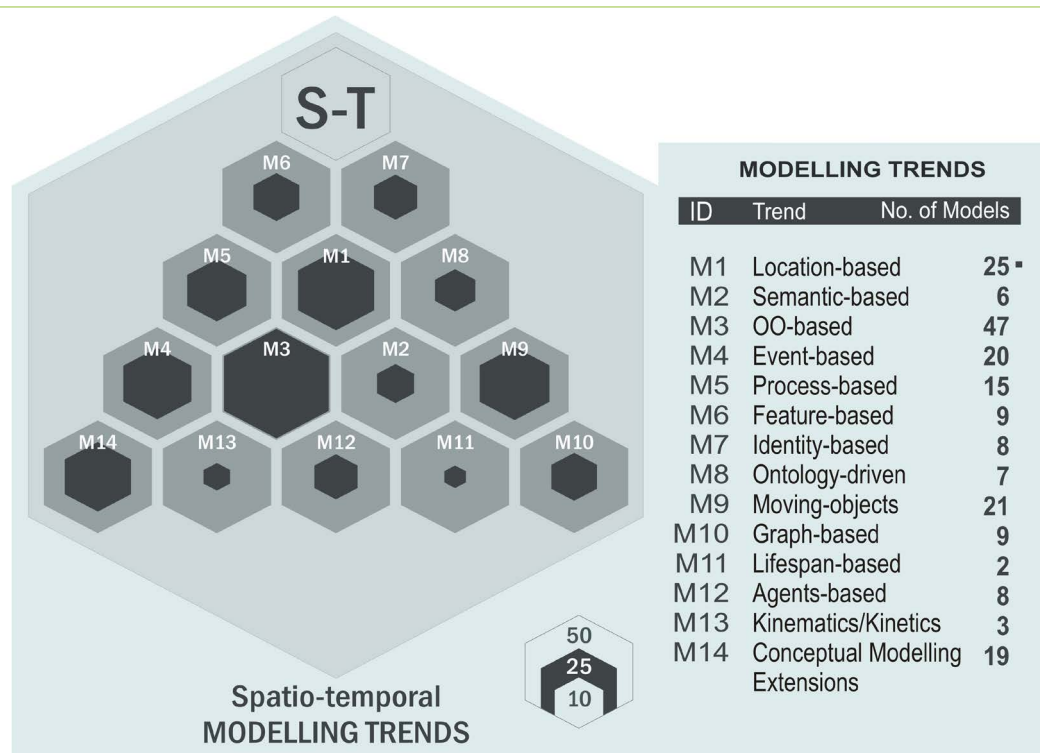


Figure 1: Classification of spatio-temporal modelling trends and number of models per approach [17].

Location-based modelling approaches

Snapshot method
Base state amendment vectors
Space-time composite model
Time stamping
Domain-based model

Table 2: Sub-classification of the location-based spatio-temporal modelling trend

classified them in the dominant approach as well as in the various approaches to which each model is related (multi-approach modelling).

This article complements several bibliographies and reviews that have been published as for the temporal, spatial, and spatio-temporal research fields (Table 3). This work relies on *TimeBibliography* [18,20], a comprehensive, dynamic online bibliography on temporal geographic information systems (T-GIS) and related topics. However, while the *TimeBibliography* is a general-purpose resource for T-GIS, this annotated bibliography is exclusively focused on the classification and description of *spatio-temporal modelling trends*.

Surveys	Role of time in information processing	Temporal databases	Temporal database modelling and implementation	Spatio-temporal databases	Spatio-temporal data models	Spatial data modelling, structures, and operators	Real-time databases	Temporal, spatial and spatio-temporal data mining	Temporal interpolation	Schema evolution and versioning	Temporal/spatio-temporal query languages	Conceptual modelling of time	Glossaries on temporal database concepts
Bolour et al. 1982a,b	✓	✓											
Roddick and Patrick 1992	✓												
Theodoulidis and Loucopoulos 1991	✓											✓	
McKenzie 1986		✓											
Stam and Snodgrass 1988		✓											
Snodgrass 1990		✓											
Soo 1991		✓											
Kline 1993		✓											
Tsotras and Kumar 1996		✓											
Snodgrass 1996		✓											
Wu et al. 1998		✓											
Barrera and Al-Taha 1990		✓	✓								✓		
Snodgrass 1992			✓								✓	✓	
Tansel et al. 1993		✓	✓										
Snodgrass 1995		✓	✓								✓	✓	
Böhlen 1995			✓										
Langran 1989		✓			✓								
Al-Taha et al. 1993, 1994		✓		✓									
Abraham and Roddick 1999				✓	✓								
Sellis 1999				✓									
Yuan 1996					✓								
Renolen 1997					✓								
Pavlopoulos 1998					✓								
Ratcliffe and McCullagh 1998		✓		✓	✓								
Peuquet 2001					✓								
Pelekis et al. 2004					✓								
Yuan and Stewart Hornsby 2008					✓	✓							
Yuan 2008					✓						✓		
Siabato et al. 2014					✓	✓						✓	
An et al. 2015					✓								
Demšar et al. 2015					✓								
Siabato et al. 2017					✓			✓					
Siabato et al. In print				✓	✓							✓	
Peuquet 1984						✓							
Güting 1994						✓							
Ríos Viqueira et al. 2005						✓							
Clarke and Irmischer 2017						✓		✓					
Ozsoyoglu and Snodgrass 1995		✓					✓						
Ulusoy 1995							✓						
Roddick and Spiliopoulou 1999								✓					
Roddick et al. 2001								✓					
Roddick 1992										✓			
Roddick 1995										✓			
Rahm and Bernstein 2006										✓			
Zhang and Hunter 2000									✓				
Chomicki 1994											✓		
Jensen et al. 1992													✓
Dyreson et al. 1994													✓
Jensen et al. 1998													✓
Bettini et al. 1998													✓

Table 3: Bibliographies, annotated bibliographies, and surveys related to temporal and spatio-temporal aspects.

In the remainder of the article, Section 2 describes the harvested bibliographic sources. Section 3 presents a brief introduction to the spatio-temporal modelling research area while Section 4 lists the core annotated bibliography. The lists presented in this section compose the central part of this article. Then, Section 5 lists some additional fundamental references related to spatio-temporal modelling in GIS. Finally, in Section 6, we present a discussion, and some remarks and recommendations.

Description of Bibliographic Sources

So as to define the bibliography presented in this article, we have harvested the bibliographic sources described in Table 5. Over 1,450 references have been compiled and published in a dynamic, online bibliography called *TimeBliography* (/tʌɪmˈblɪɒɡrəfi/) [18,20]. “*TimeBliography* is an online resource created to provide students and researchers with a dynamic bibliography whose focus is oriented towards temporal aspects of GIS and other [analytical]cross-related topics.” Apart from support the annotated bibliography presented herein, this online resource intends to cover the absence of an up-to-date bibliography related to T-GIS as a whole as well as to complement previous surveys and bibliographic compilations (Table 3). *TimeBliography* is categorized in 36 topics according to the different research subjects that have made multiple contributions to T-GIS. These categories, described in Table 4, were defined by considering several research agendas [21] and academic programmes [22] that have influenced the GIScience development and consequently spatio-temporal modelling. For this annotated bibliography, we have mainly considered the second category: *Spatio-temporal Modelling*. Table 4 shows in bold the additional sections related to this bibliography.

In a preliminary analysis, several conclusions can be extracted from the *TimeBliography* (Figure 2). For instance, by doing a simple graphical, trend analysis the application reveals that the most prolific period as for the spatio-temporal modelling area has been from 1998 to 2005. Nonetheless, it must be highlighted that interest in this topic is growing nowadays, mainly motivated by the huge spread of technologies and devices able to track moving objects, e.g., smartphones, GPS receivers, smartwatches, amongst others. Mobile sensors are currently a universal, pervasive technology on which several research efforts have been focused. Reflecting such interest, in 2011, we started to collect references concerning the handling of time for modelling spatial phenomena. Part of the results of this surveyed work is this annotated bibliography; a continuous updated version is available online at <http://spaceandtime.wsiabato.info>. Figure 2 to Figure 7 provide an infographic of the main bibliographic characteristics and resources compiled in the *TimeBliography*. Siabato et al. [18] offers a complete description of this academic resource.

Spatio-temporal Modelling in Brief²

The importance of time for analysing geographic phenomena has been considered since Hägerstrand's studies [23-25]. A review of the earliest bibliography related to space and time, [26], shows that, while researchers in fields such as databases and information systems had not ignored spatio-temporal issues, the work they performed simply showed bare sketches of temporal geographic information systems (T-GIS)not even considering a basic spatio-temporal model [27]. Most research was focused on spatial and temporal databases independently. Later, these independent branches of research converged and became the basis for spatio-temporal database models that supported the earlier steps of T-GIS [12]. Figure 2 shows some relevant milestones in the evolution of T-GIS.

Source	URL
ISI Web of Knowledge	http://isiknowledge.com
IEEE Xplore Digital Library	http://ieeexplore.ieee.org
ACM Digital Library	http://dl.acm.org
SpringerLink	http://www.springerlink.com
Scopus	http://www.scopus.com
Scirus	http://www.scirus.com
ScienceDirect	http://www.sciencedirect.com
CiteSeerX	http://citeseer.ist.psu.edu
Pion Publications Ltd.	http://www.pion.co.uk
The DBLP Computer Science	http://www.informatik.uni-trier.de/~ley/db
WorldCat	http://firstsearch.oclc.org
Ingenta	http://www.ingentaconnect.com
Engineering Village	http://www.engineeringvillage2.org
The AutoCarto Archives	http://mapcontext.com/autocarto/proceedings
International Archives of the ISPRS	http://www.isprs.org/publications/archives.aspx
EBSCO Host	http://search.ebscohost.com
Google Scholar	http://scholar.google.es/

Table 5: Main scientific databases searched for the setup of the *TimeBliography*

During the 1980s, several proposals were defined to incorporate temporal data in relational databases by applying time stamps to tables [28,29], tuples [30,31], and cells [32]. These database models fully inspired the development of early T-GIS proposals: tables were replicated as time-stamped layers, e.g., the snapshot model [12]; tuples (rows) as time-stamped attributes (columns), e.g., the space-time composite model [33]; and cells as spatio-temporal objects, e.g., the spatio-temporal object model [34].

Most of initial spatio-temporal attempts either lacked a conceptual framework to track changes in dynamic phenomena or were defined in the context of non-spatial applications. Langran and Chrisman [33] filled this gap creating such a conceptual framework putting into the context of GIS the studies of time conducted so far, defined the initial requirements and structure of a temporal GIS, and proposed the first spatio-temporal conceptual model in which time and space were integrated.

Early modelling approaches, namely snapshotand time-stamped, focused on changes of the geometric and attribute components on fixed geographic areas, for instance, on cadastral plots, the so-called LIS (Land Information System). Later, time-stamped and location-based models also considered continuous updates in attributes (space + theme) modelling evolving areas as a single set. In the meantime, the object-oriented approach arose as a convenient way to model and control objects and their properties independently, i.e., as individual features. Based on the object-oriented paradigm and the Object Modelling Technique (OMT) [35], early object-oriented models (see Section 4.3) considered changes that objects undergo and the relations that such changes imply.

These approaches reached their limits quickly when researchers realized that the events that generated such changes and the processes involved were not being considered. Thus, around the middle of the 1990s, the event-based approach [5,6] arose as a means of integrating space and time, considering richer modelling elements and a semantics that could reproduce accurately the dynamic nature of geographic phenomena and the drivers that trigger changes.

²This section is based on the analysis performed [17]. Please visit <http://dx.doi.org/10.1145/3141772>

Category / Subject	Description
Section I: Core	
Temporal GIS	Novel research domain at large at the intersection of temporal systems and GIS and whose objective is to explicitly extend current GIS to dynamic real-world phenomena.
Spatio-temporal Modelling	Development of conceptual and logical models oriented to the representation of spatio-temporal information.
Temporal Modelling	Conceptual and logical approaches for the modelling and representation of time.
Spatio-temporal Analysis	Development of integrated analytical spatio-temporal frameworks for the analysis of spatio-temporal information.
Query Languages	Query languages applied to the manipulation of spatial and temporal properties, and relationships in space and time, and implemented by spatio-temporal and standard query languages.
Case Studies	Successful T-GIS stories that solve spatio-temporal problems in different domains, e.g., transport, naval, census, and environment.
Time Geography	Principles and foundations of Time Geography as defined by Hägerstrand and followers. Developing of the space-time cube.
Temporal Databases	Domain of research in the database domain oriented to the development of conceptual and logical temporal, spatio-temporal, and moving object databases.
Surveys and Reviews	Bibliographic compilations, annotated bibliographies, surveys, and reviews relating to temporal aspects in spatial, temporal, and spatio-temporal modelling and other spatial/temporal subjects.
Reports and Studies	Several research agendas, foundational documents, and report studies related to the origins of T-GIS and GIScience are declared and/or defined.
Section II: Secondary	
Moving Objects and LBS	Development of frameworks for the representation and manipulation of moving objects, services and applications derived from them.
Data Mining and Analysis	Data mining and analysis methods related to mining in spatio-temporal databases and for spatio-temporal knowledge discovering.
Databases & Spatial Databases	References related to the origins, development, and evolution of databases and spatial databases.
Spatial Data Modelling	Spatial data models and spatial data representation methods.
Spatial Data Structures	Spatial data structures, storage data models for spatial data, data structures in information systems, encoding in spatial databases.
Spatial Reasoning	Qualitative spatial reasoning. Qualitative abstractions of spatial aspects of common-sense knowledge that can be able to model dynamic geographic phenomena.
AI and Logic	Works coming from the Artificial Intelligence and Logic research fields which have contributed to model temporal aspects in information systems and spatial information systems.
Semantics and NLP	Semantic and linguistic aspects of geography in space, processing of temporal expressions through Natural Language Processing techniques, algorithms for processing of language, and general computational techniques to handle language in computer systems.
IR, GIR, and TIR	This section is quite related to the previous, but it is focused on Information Retrieval (IR), Geographic Information Retrieval (GIR), and Temporal Information Retrieval (TIR).
Annotating Time	Works dealing with Natural Language Processing applied to the identification and tagging of temporal expressions considering the semantic meaning and semantic relationships.
Ontologies	List of ontologies and ontology-based methodologies applied to spatial/temporal domains. Ontological foundations of temporal GIS.
Visualization	Graphical representations of geographic information regarding their properties and relationships in space and/or time considering both dynamic and static aspects.
Topology	Spatial and temporal topological relationships and properties.
Section III: Others	
Interoperability	Interoperability of geoservices. Semantic and temporal interoperability. Types of interoperability.
SDI and Geoservices	Trends on Spatial Data Infrastructures (SDI) as to design and implementation. Development and implementation of geoservices.
GIS and GIScience	General background concepts of Geographic Information Systems and Science: theory and definitions, implementation, and development.
GI and data	Foundational topics regarding the perception, definition, and modelling of geographic information in digital systems. Evolution of cartography from ancient to contemporary methods. Background concepts such as Naive Geography, and other topics that have shaped geographic information and data.
Software	Software packages and libraries for databases, SDI, GIS, and T-GIS. Articles in which software prototypes and implementations are described are also included.
Calendars	Definition and formalization of calendars. Tools for comparing and convert dates from a calendar system to another.
3D/4D	Three-dimensional modelling and spatio-temporal analysis in 3D environments.
Section IV: Standardization	
Institutions	Online references and websites of the institutions that have made sort of contributions to T-GIS and cross-related topics, especially databases and GIS.
Standardization	Contributions to the development of methodologies for the implementation of (potential) standards.
W3C, ISO, OGC	These categories group several standards related to mark-up languages and/or the above-mentioned subjects. The listed standards are classified according to the three most relevant standardization institutions.

Table 4: Description of categories in the TimeBibliography.

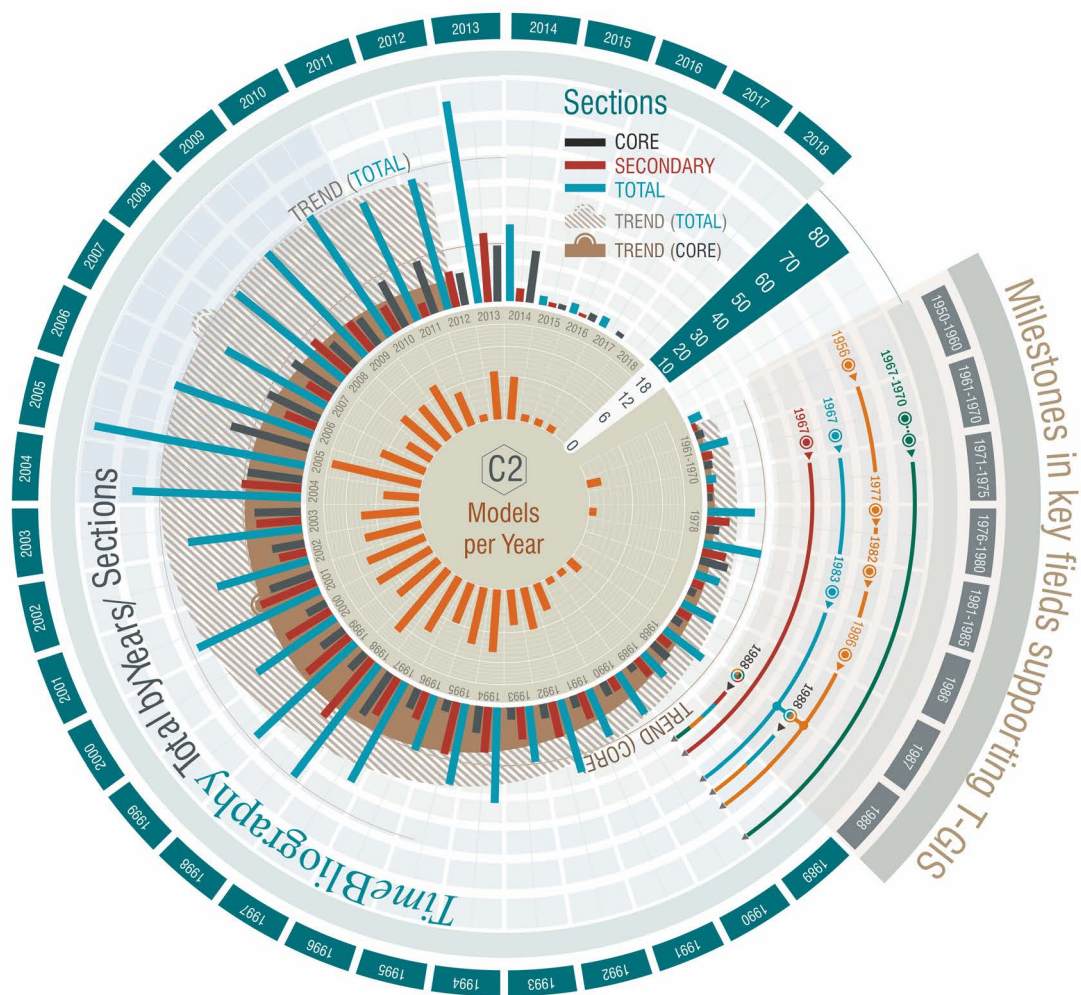


Figure 2: Representation of references by Sections and modelling trends per year in the *TimeBibliography*.

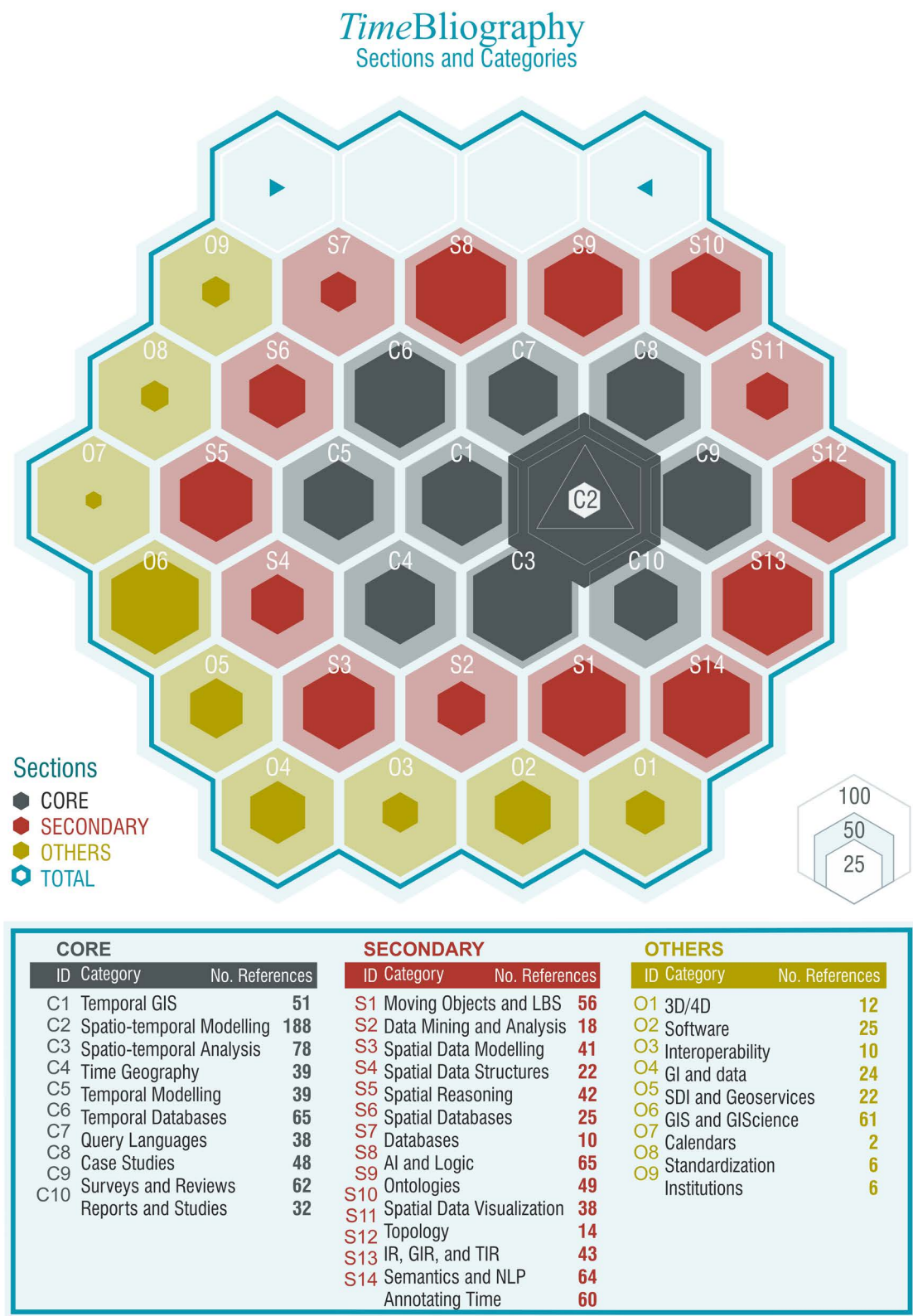


Figure 3: Infographic of categories and sections in the *TimeBliography*.

TimeBliography
Type of Publications

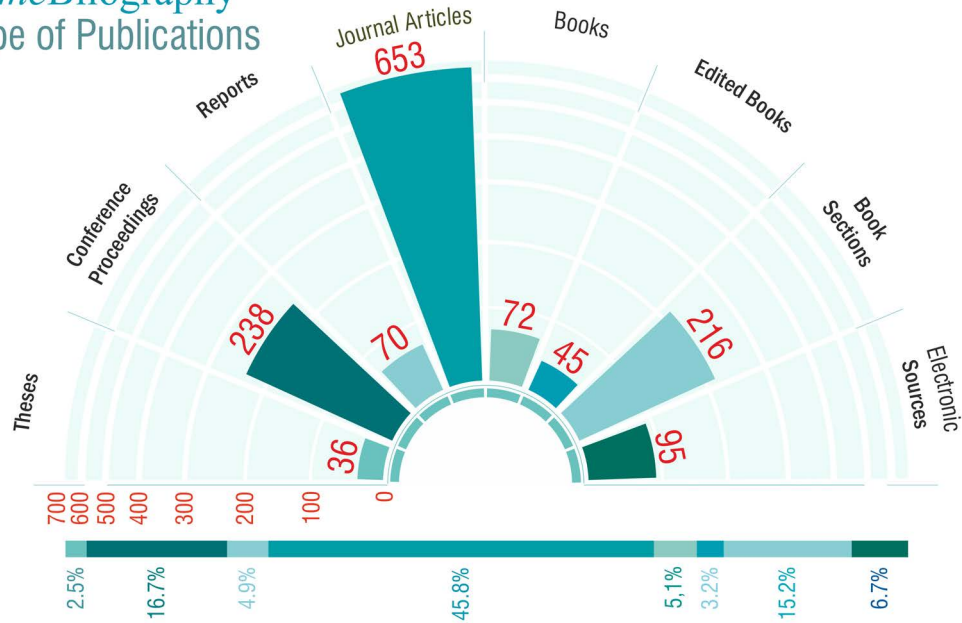


Figure 4: Infographic of type of publications registered in *TimeBliography*.

TimeBliography
Major Publishers

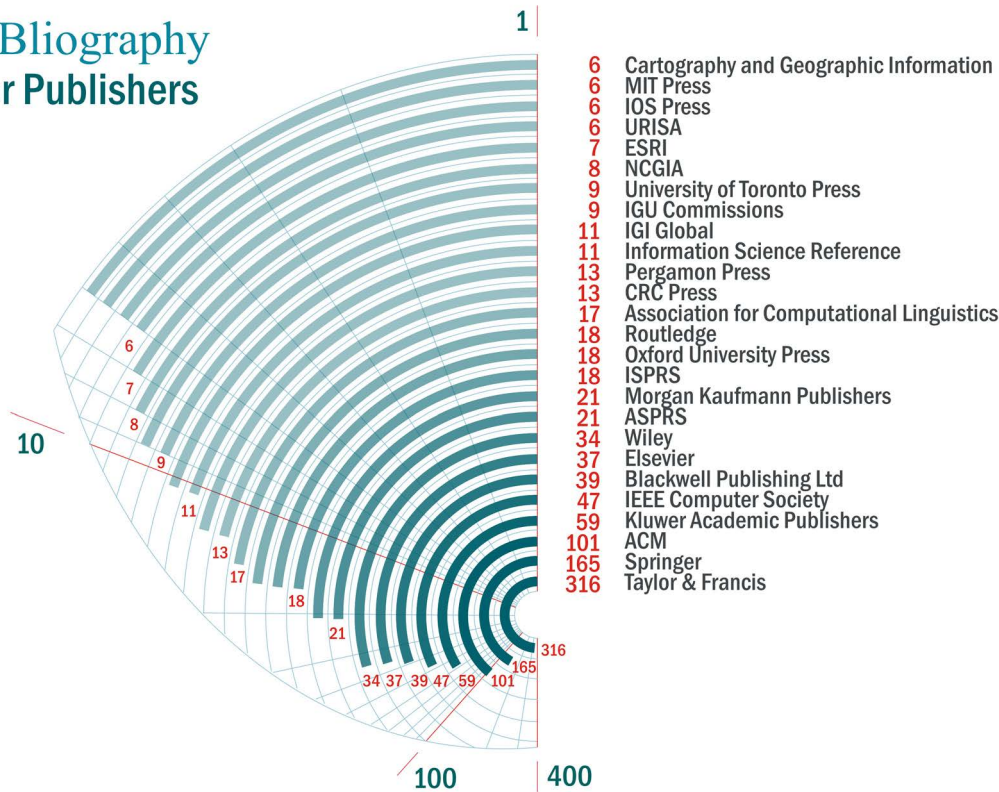


Figure 5: Infographic of major publishers inserted in the *TimeBliography*'s database

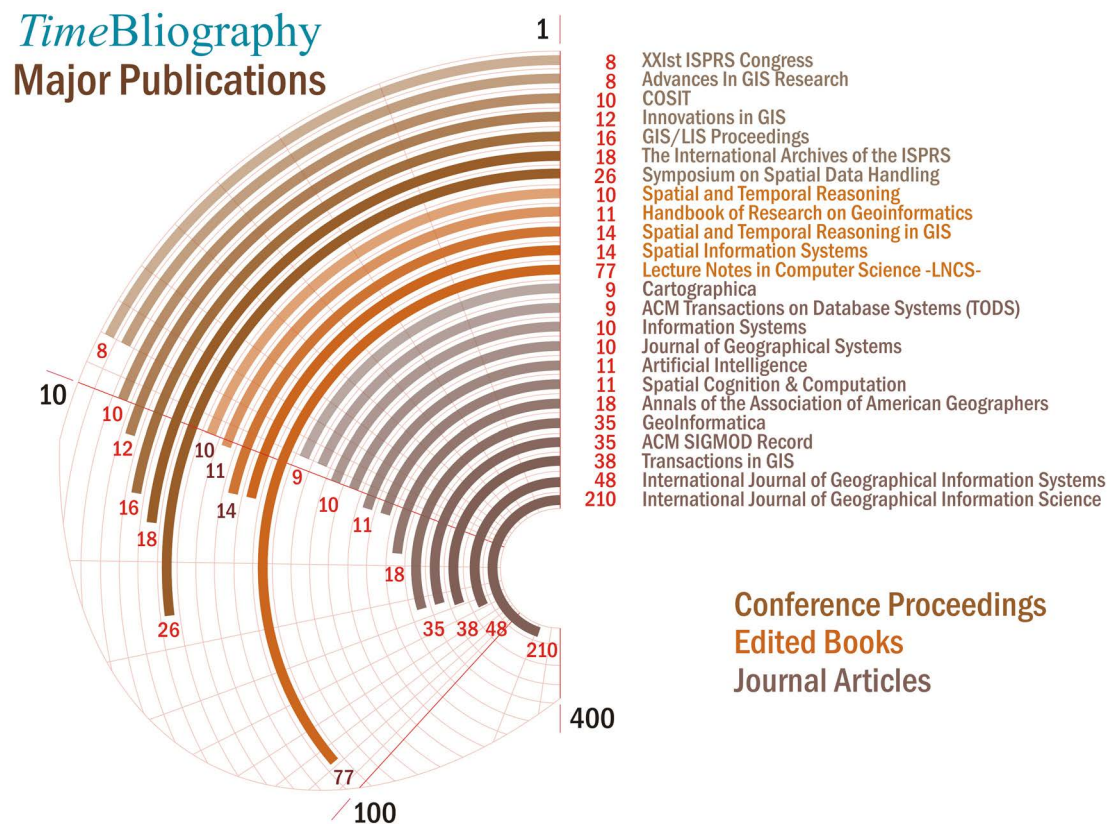


Figure 6: Infographic of major journals, conference proceedings, and edited books.

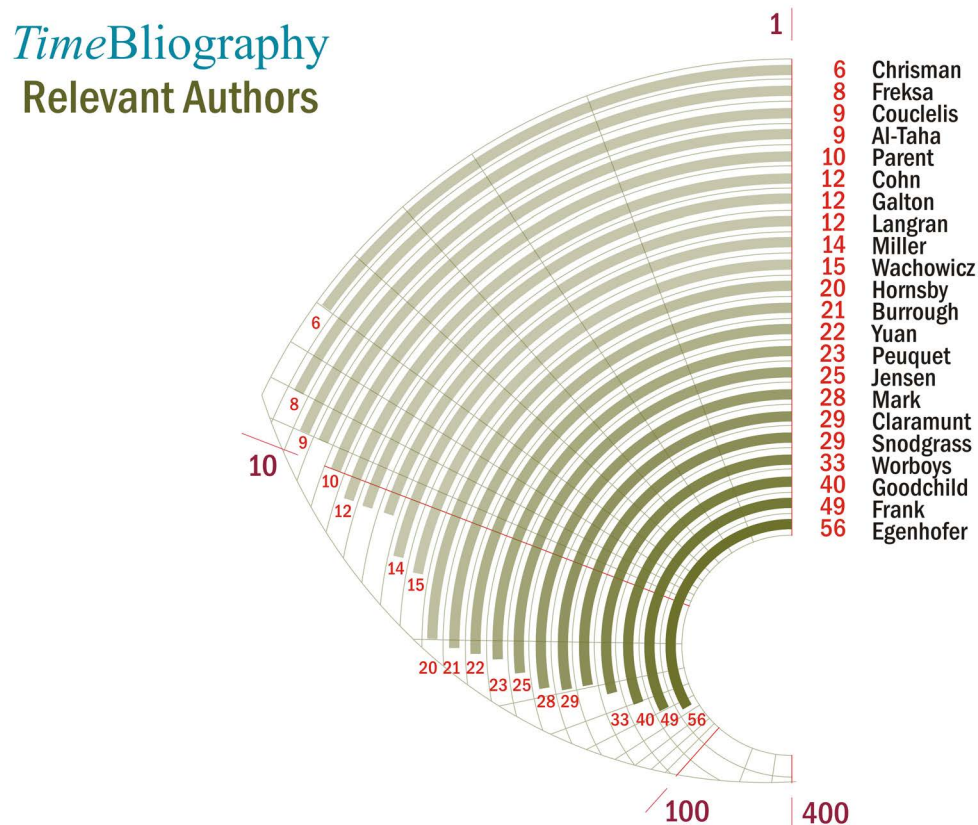


Figure 7: Infographic of the authors most referenced in the *TimeBliography*.

The late 1980s and first half of the 1990s have been the most relevant period for research in T-GIS. During this period, the spatio-temporal problem arose and T-GIS was established as a formal research area in the GIS field. As the consolidation of GIScience progressed [36], T-GIS started to be defined as a relevant and independent topic in research agendas [37,38]. More recent agendas still define spatio-temporal issues as long-term research topics [39,40]. Different modelling proposals ranging from time-stamped models to the object-oriented and event-driven approaches were defined and became established (see Section 4 for further details).

While spatio-temporal models evolved, GIS research progressively moved from asking basic questions such as “*what changed?*” or “*where does it change?*” to more fundamental ones such as “*why changed?*” or to “*how does it change?*”. Such questions provided the path to define new modelling approaches as shown in the models listed in this bibliography. This way, the spatio-temporal modelling trends listed in this bibliography have evolved per the dynamic dimensions modelled (e.g., object vs. action) and the focus of analysis, i.e., what/why is changing/evolving (in) space over time. As shown, initial trends rapidly evolved from a time-stamping [41] and a location-based [33] modelling to an object-oriented perspective [42], and subsequently to event/process-based [6,43] and domain/semantic-based [44] modelling trends. More recent perspectives and modelling proposals, [45-50], are still based on the same foundations: drivers and observables (Table 1). It must be highlighted that the definition of modelling approaches based on agents [51,47] and kinematic/kinetic [52,53] trends is a recent and innovative tendency. As shown in Figure 1, these are the two last trends identified.

Although significant results have been obtained (see Section 5.1, Ontological modelling foundations), much work has still to be done before achieving (i) a general spatio-temporal model and (ii) the basic functionalities for a general-purpose T-GIS [40]. On the other hand, so far GIS software does not reflect the progress that the GIScience community has achieved in the integration of time and space within GIS software, e.g., temporal data query languages and spatio-temporal analysis capabilities are not completely available. Such integration is often the exception and lacks standardization. There is no consensus amongst researchers and developers regarding the integration of solid foundations and temporal components into GIS; there is no standard as it exists for the spatial dimension in which concepts and software packages are built upon robust theoretical and modelling principles [54,55], as well as upon a set of standards such as those normalized by ISO and the Open Geospatial Consortium (OGC) regarding geoservices, and spatial data modelling and representation [56].

On the implementation side, most temporal GIS and temporal database technologies developed so far are rather limited or have remained in the research phase, e.g., the T-GIS prototype TEMPEST [57] or some of the prototypes and applications supported by the TimeCenter [58]. It is only recently, after several years of theoretical approaches and domain-specific case studies and proposals, that commercial companies and *free and open source software organizations* (FOSS) have started to offer general-purpose temporal components, modules, and tools. For instance, (i) the temporal capabilities offered in ArcGIS [59]; (ii) the temporal manager of QGIS [60]; (iii) the space-time GIS design based on Hägerstrand’s classical time geography [61,62]; (iv) the Oracle 11g Flashback Data Archive [63]; (v) the Allen’s algebra operators supported by PostgreSQL/PostGIS [64]; (vi) the abstract data types defined in the SECONDO platform [65,66]; (vii) the spatio-temporal functionality that Hermes [67,68] provides

to Oracle 10g and PostgreSQL/PostGIS; or (viii) the visualization, analytical, and reporting tools offered in GeoTime [68,69]. These software packages and libraries offer, amongst other functionalities, simple but reliable capabilities for (i) spatio-temporal analysis (e.g., hot spot analysis with space and time, a GIS-based analytical time-geographic framework); (ii) querying periods and instants using Period *Data Type*; (iii) database managing for historical data (e.g., storage and retrieval); (iv) constructing and querying databases with dynamic objects that change location, shape and size; and (v) dynamic visualization of features (e.g., time-slider and temporal filtering). This last capability complements and improves the typical approaches for the animation of temporal and historical data [71-73] in the sense that it provides analytic information and not merely animated scenes.

A complete analysis and thorough review of the evolution of spatio-temporal modelling trends is available in [17].

Annotated bibliography

From the full bibliographic collection (1450+ references), this annotated bibliography lists 319 references sorted in 17 lists: 12 correspond to spatio-temporal modelling trends; 1 shows proposals for conceptual modelling processes; and the remaining 4 lists highlight key cross-related topics: (i) the ontological foundations, (ii) temporal modelling; (iii) time geography; and (iii) other key references in spatio-temporal modelling and reasoning. Each list is sorted in ascending chronological order by considering publication date. First collection, composed of 180 references, contains most of the modelling proposals published in peer-reviewed journals and conferences as of December 2014. Second collection includes 19 references related to conceptual modelling extensions developed to integrate time and space in representational modelling approaches. Third collection, described in Section 5, shows 110 key references considering relevant works that have contributed to the development of spatio-temporal modelling, mainly focused on temporal modelling and time geography. This collection includes 13 references that present spatio-temporal modelling concepts non-classified in the main lists. Since a modelling proposal can relate more than one modelling trend, e.g., events/processes, several models (references) have been included/duplicated in the different sections of this bibliography, hence arbitrary misclassifications are avoided. Finally, we present an additional list of 10 articles that we consider as the must-reads for anyone that would like to be introduced to the spatio-temporal modelling of geographic phenomena.

Location-based models

As mention above, earlier T-GIS modelling proposals were fully inspired in the temporal database research field. The 22 modelling proposals listed in this section are based on three main modelling foundations: (i) time-stamped layers (tables); (ii) time-stamped attributes (rows/columns); and (iii) time-stamping cells (attributes). As shown in Table 2, location-based model is a generalization of 27 modelling trends.

Snapshot

1. Sinton, D. F. 1978, <<The inherent structure of information as a constraint to analysis: Mapped thematic data as a case study>> in: First International Advanced Study Symposium on topological data structures for Geographic Information Systems, G. Dutton (Ed.) Cambridge-MA-USA:Harvard University Laboratory for Computer Graphics and Spatial Analysis, pp.1-17, Dedham-MA-USA, 1978.

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Three-domain model

Yuan's *Three-Domain Model* [74-76] represents semantic, spatial, and temporal objects and provides links between them to describe geographic processes and phenomena. The three-domain representation, developed in the context of wildfire studies, is defined as a "normalization of the snapshot, space-time composite, and spatio-temporal object models"[76]. In this sense, this proposal inherits the characteristics of the location-based approach, although it goes one step further regarding the utility that spatio-temporal systems can bring to users through GIS in considering queries about attributes, location, spatial properties and relationships, as well as time and temporal properties and relationships. Yuan proposes a set of the minimum spatio-temporal queries that any spatio-temporal system should answer (simple and range queries). The three-domain model is proposed as a modelling approach to answering such queries; it focuses on the functionality of the model in actual systems through the implementation of the three-domain framework. The advantage of this vector-based model is its ability to handle changes in the three modelling components; this characteristic represents a significant improvement over existing models that handle either the time or, as in most cases, the location. The three-domain model considers time as a temporal object instead of an attribute.

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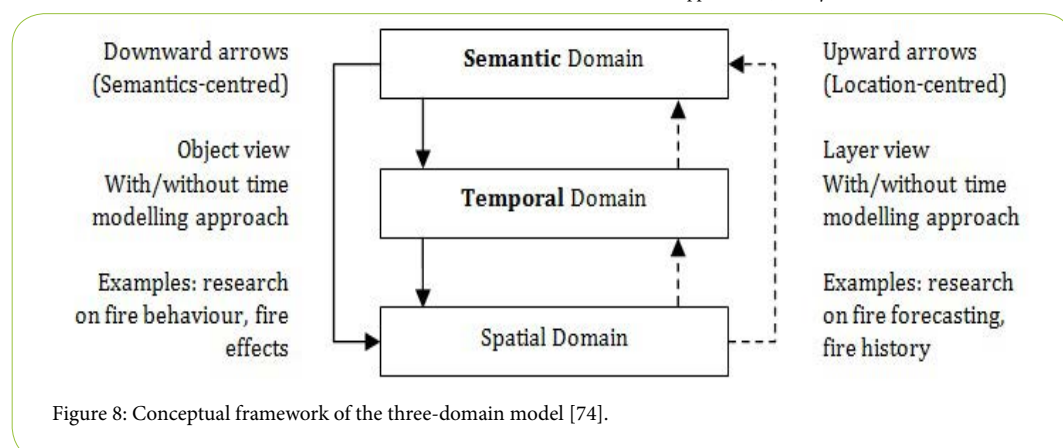


Figure 8: Conceptual framework of the three-domain model [74].

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Semantic-based models

Semantic changes include *variations in attributes* over time and a *static spatial distribution* of a geographic phenomenon. Spatial changes may be either static, looking at variations of a geographic phenomenon in a snapshot (same location), or transitional, comparing states of an event at different locations through entity snapshots (movement). In brief, changes are either mutations of an entity spatially fixed, or the movement of a non-changed entity from one location to another. Time is modelled as an independent domain instead of being a location's attribute, unlike the snapshot model, or an integral part of spatial entities, as in the space-time composites and spatio-temporal objects [77]. Although this trend is related to the three-domain model, it can be classified as a distinct modelling approach considering the following proposals. The focus is on the variation of attributes. However, noticed that references 26 and 27 are focused on attributes while the remaining considers the meaning/semantic of the geographic information as a data set or derivate concepts, e.g., trajectories.

Snapshot

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Object oriented-based models

Object-orientation (OO) is a popular approach used to model geographic entities in T-GIS design. In spatio-temporal data modelling, it has been widely recognized as a powerful tool that captures the meaning of concepts within a problem domain [78]. Since OO is a natural strategy for representing the behaviour of dynamic entities over space and time [79-81], several authors have proposed a significant number of models considering different perspectives and based on such an approach. OO has been the most prolific approach in the spatio-temporal modelling trends because of its flexibility in handling independent objects and their properties. The concept of a *unique object identity* is a key element of the object-modelling approach, and, as such, it has been recognized as a reliable component in tracking changes and the evolution of independent objects and is, therefore, applied in most of the spatio-temporal models. However, it does not offer a continuous identification of the phenomenon since it changes when a new object is created. In contrast to the identity modelling approach (see Section 4.6), the identity disappears or changes when the object dies or mutates. The object orientation in the spatio-temporal modelling was pioneered by Worboys et al. [82,83]. The main strength of this approach is providing conceptual elements to allow the modelling of geographic entities as independent units. The following list includes Object-Oriented and Object-Relational models indistinctively. It must be noted that while OO models only support persistence for objects and usually do not consider neither query language nor relational referential integrity, Object-Relational data modelling supports most of object-oriented concepts (inheritance, distinction between a class and an object, custom or complex data types) as well as relevant relational concepts (relational query language and integrity). In this sense, an object-relational system is said to provide a middle ground between relational databases and object-oriented databases. In most of the cases, geographic databases implement the object-relational model. A large number of models have been proposed by considering these approaches; this section lists 47 relevant references.

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Event-based and Process-based models

While time-stamping approaches focus on the idea of change to enhance spatial data with temporal components, event-oriented approaches “*focus on the dynamic happening as a whole, and not just the time of the event.*” [4]. When there is a change, a time-stamp marks the time of the change; the event-based approach, however, allows the distinction of event attributes and relations besides object attributes and relations [4].

Siabato et al. [17] provide a general discussion about these concepts. The authors show several academic insights about the definitions of *processes* and *events*, and their differences. It is not clear where the former finish and the latter begin. There is not a single or exclusive relationship between them; depending on the phenomena modelled their nature changes. Galton, Worboys, Yuan, Stewart Hornsby, Claramunt, and Thériault have provided valuable discussion as to these conceptual elements. Some definitions seem to be contradictory. According to Galton and Worboys [84], there is a general consensus that the “*key concepts required for the modelling of dynamic phenomena include object, state, process and event*”, but definitions are not so clear. Galton and Worboys [14] states that while *objects* and *processes* can experience *change* and such changes can be described as multiple *states*, an *event* does not experience *change*. An *event* is by definition a completed episode of history that does not experience changes after being; the *event* appears in time and can subsequently appear in another point in time as a subsequent *event* but different from the previous one. Yuan and Stewart Hornsby [4] offer a conceptualization quite aligned with Galton's. In contrast, Yuan [85] asserts that an *event* is a spatio-temporal aggregate of its associated processes, and a *process* is a sequential change of *states* in space and time. While events operate at the coarsest spatial and temporal resolution, *states* have the finest resolutions. Despite differences, both Yuan and Galton agree that a *process* involves different states. Claramunt and Thériault [43] also considers a *process* as the aggregation

of simultaneous or related *changes*; he states that *changes* and *events* are a natural way to define *processes*. An event can be modelled as a set of processes that transform entities. As Worboys [14] states, “*one person's process is another's event, and vice versa*”. For instance, when a volcano erupts the eruption can be catalogued as a process if one considers the behaviour of the lava and the resulted tablelands; however, the eruption itself can be considered as an event, i.e., the volcano erupted at one specific instant. This discussion can be even deeper when considering more general concepts such as continuants and occurrents. “*Ultimately, events and processes are central to the understanding of geographic worlds. They constitute information of interest to many, and perhaps, the majority of applications and scientific inquiries*” [40].

Despite the blurred definitions, a large number of spatio-temporal models considering *events* and *processes* have been proposed. The usefulness and efficiency of these approaches have been demonstrated in the implementation of several case studies, mainly applied to environmental and transport studies. Nonetheless, the modelling, representation, and querying of events and processes are not a straightforward task. The application of spatial and temporal multi-granularities in the representation of a phenomenon adds a significant complexity in the modelling tasks.

Several modelling proposals have combined both approaches; we have therefore included them both in the event- and in the process-based lists. A total of 28 single modelling proposal are listed in this section. 7 out of 28 proposals are multi-approach modelling, thus, subsection 4.4.1 lists 20 references for event-based and subsection 4.4.2 lists 15 for process-based

Event-based models

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- Feature-based models**
- The three main components of geographic information are space, theme, and time [86,87]. These core components can be modelled individually and collectively. A feature relies on such dimensions for its representation and modelling. The following modelling proposals consider one, two or all of them to model dynamic geographic information; yet most of them are focused on the spatial dimension. Feature-based models are also known as entity-based models. In general, models are grounded in an entity-based perception of geographic phenomena and represent geographic entities as feature objects in GIS. This section comprises 9 models.
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Identity-based models

In contrast to modelling proposals in which the modelling focus remain in one of the three main components (space, time, and theme), the *identity-based change* trend focuses on the identity of the evolving object. This characteristic being a significant contribution considering the ID restriction in the Object-Oriented modelling trend (see Section 4.3). Models aligned in this trend are based upon the explicit description of change with respect to states of existence and non-existence for identifiable objects. A key element in the model is the concept of *object identity*, “that unique characteristic that distinguishes one object from another” [88]. The identity is a means of tracking and querying the existence of specific objects and types of objects independently of specific attribute values, properties, or structure (i.e., common elements). For instance, in cadastral applications the evolution of cadastral plots can be physical or juridical. From the physical point of view, the evolution of the plots and parcels results into the creation and deletion of geometries that represents the physical evolution of the plots. A link between the former and new plots is not explicit. When considering the juridical viewpoint, a tracking of the identity of previous and current owners is a key element. In these kinds of scenarios, the identity-based model is better than the approaches focused on physical characteristics (geometry, attributes). A unique identifier of a plot allows one to easily identify its owner's history. In contrast to object-oriented approaches, identity-based modelling allows this unique identifier to remain over time and does not die (disappears) along with objects, the identifier is inherited (transition property). This modelling proposal is quite specific and only 8 models have been proposed, 3 of them mixed with other trends.

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Ontology-driven models

Ontologies have proven to be a reliable means for ordering and integrating specific-domain information. Ontology-based models are focused on the evolution of one specific characteristic; such a characteristic corresponds to the ontology's score domain. Therefore, ontology-driven models apply *domain-specific ontologies*. The following proposals consider the use of ontologies for modelling different behaviours derived from evolution of geographic information. 7 models have been classified in the bibliographic collection considering this core method.

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132. Kauppinen, T., Deichstetter, C., Kepler, J., Linz, U., Väättäin, J. and Hyvönen, E. 2006, <<Ontology-based modeling and visualization of cultural spatio-temporal knowledge>> in: New Developments in Artificial Intelligence and the Semantic Web- Proceedings of the 12th Finnish Artificial Intelligence Conference -STeP 2006-, E. Hyvönen, T. Kauppinen, J. Kortela, M. Laukkanen, T. Raiko, et al. (Eds.). Helsinki - Finland:Finnish Artificial Intelligence Society, (978-952-5677-03-4), pp.37-45, Espoo-Finland:Helsinki University of Technol, Octubre 26-27 2006. doi:10.1.1.106.4711.
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Conceptual Modelling Extensions

The huge spread of mobile and sensing technologies has allowed significant and rich spatio-temporal datasets to be obtained, and, due to this, moving objects have recently arisen as a very active research area. Many research efforts have been addressed in data modelling [89], querying methods [90,91], identification and representation of mobility patterns [92-94], computing with spatial trajectories [92] and pedestrian networks [93], and space-time interpolation and locational inference [97,98,], amongst others. Specific spatio-temporal modelling approaches have been proposed for moving objects [89,99-101], especially for phenomena represented by point geometries. Furthermore, methodologies for the representation of changing areas as moving regions have also been studied. A recent review of existing quantitative methods for analysing movement data was presented by Long and Nelson [53]. The Moving Objects Spatio-Temporal data model (MOST) proposed in Wolfson's research [102,103,104] can be considered a pioneering proposal for the modelling of moving objects. Furthermore, methodologies for the representation of changing areas as moving regions have also been studied [105-107]. Please notice that the following references are exclusively focused on the spatio-

temporal modelling approaches proposed for Moving Objects, and they do not reflect the vast recent bibliography produced in this area, especially during the last years. TimeBibliography list 55 additional references related to Moving Objects. We highlight 21 modelling proposals for moving object son this bibliography.

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146. Jacquez, G. M., Greiling, D. A. and Kaufmann, A. M. 2005, <<Design and implementation of a Space-Time Intelligence System for disease surveillance>>Journal of Geographical Systems, Vol.7 No.1, pp.7-23, May 2005. doi:10.1007/s10109-005-0147-6.
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Graph-based models

While the graph-based modelling approach seems to have been put aside during the 2000s, the current decade shows an active interest in this approach. The simplicity of defining relationships amongst geographic entities and the representation of their evolution results in significant flexibility for the representation of changes, movement, and events, which in turn allows the integration of graphs with other modelling trends. 9 proposals are based on the node-relation function derived from graphs; two main authors cover all the proposals: Renolen and Del Mondo.

Although the three-domain model uses a graph to represent the transitions amongst spatial objects at different locations, the first graph-based modelling approach, called the *History Graph Model*, was proposed by Renolen [108]. The main purpose of the history graph model is to identify all types of temporal behaviour and to manage both objects and events. This model is intended to visualize the temporal element in order to reproduce the evolution of geographic information. On the other hand, Del Mondo et al. [109] propose a discrete, *spatio-temporal graph-based* model oriented to the modelling of evolving, two-dimensional regions. The authors introduce a formal approach for analysing the consistency of relationships of evolving entities. This proposal is an extension of previous research [110] in which the authors modelled the spatio-temporal interactions networks derived from the evolution of entities considering spatial relations, spatio-temporal relations, and temporal filiations, which in turn allow the representation of spatial and temporal connections.

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Agents-based models

Lifespan-based approaches model the spatio-temporal phenomena considering their duration. Such models are based on the definition of *object lifespan* used in temporal database modelling [110]. One approach to determining objects' life spans is to tag every object with a pair of time stamps: one for the time of creation and one for the time of ending. The simple time-stamping model [41] applies this approach. In general, lifespan is defined as the duration of the modelled geographic phenomenon or event. Lifespan are recurrently considered in all modelling approaches but only two models focus on the duration of the geographic phenomena.

Temporal modelling

Another modelling approach that has arisen in the last decade is the evolution from objects to agents. While an object can be defined as an entity described by attributes and with a set of actions, an agent is an object with goals and the ability to control itself and interact in an environment. While agents are characterized by autonomy, reactivity, and proactivity, objects are passive and dependent on external actions. The agent is able to react autonomously to changes in an environment. This difference has been considered by researchers in the spatio-temporal modelling field. The agent-based modelling approach [47,112,113] is indeed a research line that has recently opened in spatio-temporal modelling with enormous sun exploited potential. Agents have properties that objects do not, and perhaps evolution from the object-oriented and event-driven paradigms to the agent-oriented foundations [114] could be a promising pathway for the advantages that the simulation of interaction amongst geographic entities can offer. In this sense, different software that supports agents can offer different possibilities. Intelligent agents can be merged in AI systems for improving spatio-temporal reasoning, e.g., the control and prediction of traffic in transport networks. Autonomous agents can evolve in order to adapt their capabilities to achieve their objectives, e.g., how should a system react in case that a geographic area suddenly changes or disappears (floods, landslides)? The possibilities increase when considering distributed agent systems or cooperative multi-agent systems. Different levels of analysis and reasoning can be achieved when agents from different systems interact. In this section, we highlight eight modelling proposals, most of them derived from case-studies.

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Kinematics/kinetics

Some proposals create an innovative method for representing continuous space-time fields in temporal GIS based on the principles of fluid kinematics, i.e., measures of direction and movement, and kinectis, i.e., considering the cause of change (direction, movement, acceleration). Authors propose a temporal GIS framework that uses velocity as the basic unit of spatio-temporal representation to identify kinematic flows and features indicative of geographic processes, such as divergence and convergence. Kinematics is usually applied to real fluid flow, but some proposals have applied such a concept to a virtual flow that reflects the changes in scalar attribute values over the Earth's surface. Thus, any dynamic phenomena able to be represented by scalar values can be modelled by this approach, e.g., meteorological phenomena. The kinematic representation combines Lagrangian and Eulerian concepts to capture the direction and amount of change of a field in space and time effectively. Three proposals have been published in this very recent modelling approach.

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Modelling proposals for moving-objects

At another level of abstraction, the database community has developed several novel conceptual models to integrate time and space in representational modelling approaches. Early proposals were based on extensions of the standard logical models: (i) the entity-relationship (ER) model [115], (ii) the Object Modelling Technique

(OMT) [116], and (iii) the Unified Modelling Language (UML) [117]. We have found evidence of 19 works dealing with modelling extensions.

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Key References Related to Spatio-temporal Modelling

This section presents three additional lists as for three topics closely related to spatio-temporal modelling: (i) ontological modelling foundations, (ii) temporal modelling, and (iii) time geography. These references complement the bibliography by providing the foundations for most the models above-referenced.

Ontological modelling foundations

The ontological foundations are the background and general accepted concepts on which spatio-temporal models have been supported. This section presents a set of comprehensive studies on which strong theoretical background for T-GIS has been developed. For instance, the studies of Galton [9,117,118] in which he defines key elements namely histories and life-histories, continuants and chronicles, and dynamic collectives, or the well-known SNAP/SPAN ontology presented by Grenon and Smith [13]. Some relevant elements include (i) the dichotomy object/field [9,119]; (ii) the multiple viewpoints from which such representation models are considered, including the hybrid model; (iii) the integration of multiple temporal models in the spatial component providing the roots for modelling spatio-temporal phenomena (linear/cyclic/branching; transactional/event/observational; discrete/continuous) [30,120,121]. These concepts have been broadly accepted as foundations on which most of the models and key concepts listed in this bibliography rely. This section lists 19 works that describe such foundations.

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Lifespan-based models

How to represent time is an obvious and fundamental characteristic in temporal GIS; however, how to do it is a complex issue. Frank [121] proposes several ways to represent time in a GIS. However, time as a specific subject has been studied long before in other fields different than the spatial and spatio-temporal ones. First known reference in studies of time can be traced to Hamilton. Several works regarding modelling of time has been published in the last 50 years, for instance, natural language [122], information systems [123], logic [124,125], and artificial intelligence [126,127]. In spatial systems, time can be perceived moving forwards in a linear fashion for some geographic phenomena, while for other phenomena it moves in a cyclical way. While linear-time phenomena do not repeat at any interval, cyclical phenomena repeat at a defined frequency (e.g., daily and seasonally). Most of the models listed in this bibliography follow a linear, discrete temporal model and consider a discrete view of the world. Without being exhaustive, since this bibliography is not focused in time modelling, the following references correspond to studies that somehow have contributed to the development of spatio-temporal systems. We have selected 39 key works for temporal modelling issues.

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Time geography

Since time geography analyses geographic phenomena in a space-time framework, it is feasible to state that it provided the initial foundations for including temporal and spatio-temporal relations in geographic phenomena analysis and, later on, extending such relations to GIS. Although time geography provided the initial elements for relating space and time systematically, it did not

provide the detailed specifications required for developing standard time geographic computational tools [128]. Nonetheless, the continuous evolution of the original Hägerstrand's spatio-temporal framework and the development of GIScience have contributed to the definition of new concepts and models for the creation of such tools. Significant contributions, such as those proposed by Miller [128-129] and Delafontaine et al. [131], have transformed time geography into a strong, spatio-temporal analytical framework that is fully computationally exploitable. Currently, this framework is still continuously evolving and being applied, mainly, to the modelling and analysis of moving objects. This section presents 39 relevant references that have had a sort of impact in the evolution of T-GIS and spatio-temporal modelling. The references also show the evolution of the time geography analytical framework from a conceptual definition to a computational, analytical tool.

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Other key references in spatio-temporal modelling and reasoning

180+ additional references related to spatio-temporal modelling are compiled in the categories *spatio-temporal analysis*, case studies, and *Temporal GIS* of the *TimeBibliography* [18]. These sections respectively present modelling proposals based on (i) successful T-GIS stories that solve spatio-temporal problems in different domains, e.g., transport, naval, census, and environment; (ii) the development of integrated analytical spatio-temporal frameworks for the analysis of spatio-temporal information; as well as (iii) novel research at the intersection of temporal systems and GIS and whose objective is to explicitly extend current GIS to dynamic real-world phenomena. In addition to these categories, 13 additional references which present spatio-temporal modelling concepts non-classified in the above-listed categories are:

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Final Remarks

This article presents a compiled, annotated bibliography focused on spatio-temporal modelling trends. By analysing the compiled references, we have identified 14 modelling trends by which we have classified the corresponding references. To make this compilation self-contained, other key references of cross-related topics such as

time geography and temporal modelling have been also included. Additions, corrections and comments concerning the bibliography are always very welcome through *TimeBibliography's recommendation* functionalities or emailing the contact author. We apologize with the readers and especially with the authors for any errors, misclassifications and omissions that may result from the collected bibliography. A comprehensive collection of 63 surveys and reviews, ranging from 1982 to 2017, that complements this article is available in *TimeBibliography*, section *Surveys and Reviews*.

Availability in BibTEX Format

The references compiled in this bibliography are available in *TimeBibliography* [18]. The list is regularly updated and it is always available at:

<http://spaceandtime.wsiabato.info>

The must reads

Finally, we would like to highlight the top-ten of the published works that, in our opinion, anyone who wants to be introduced to and informed on spatio-temporal modelling must consider reading.

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Competing Interests

The authors declare that they have no competing interests.

Acknowledgement

The work described in this paper was supported by the Doctoral Program of the Technical University of Madrid (UPM), Grant ref. CH/056/2008, and partially supported by the UPM Training and Mobility of Researchers Programme (Resolutions 23-02-2011/28-06-2012).

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