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What is This?

Article

Interactive analysis of time intervals in a two-dimensional space

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Abstract

Time intervals are conventionally represented as linear segments in a one-dimensional space. An alternative representation of time intervals is the triangular model (TM), which represents time intervals as points in a two-dimensional space. In this paper, the use of TM in visualising and analysing time intervals is investigated. Not only does this model offer a compact visualisation of the distribution of intervals, it also supports an innovative temporal query mechanism that relies on geometries in the two-dimensional space. This query mechanism has the potential to simplify queries that are difficult to specify using traditional linear temporal query devices. Moreover, a software prototype that implements TM in a geographical information system (GIS) is introduced. This prototype has been applied in a real scenario to analyse time intervals that were detected by a Bluetooth tracking system. This application shows that TM has the potential to support a traditional GIS to analyse interval-based geographical data.

Keywords
GIS, spatio-temporal data analysis, temporal query, time interval, triangular model

Introduction

Considerable work has been done in modelling and reasoning about time intervals, ranging from qualitative relational algebras,[1,2] to rough and fuzzy extensions,[3–5] to applications in temporal queries[6,7] and temporal databases.[8,9] Compared with the many contributions made to the reasoning aspect, methods and tools that visualise and analyse time intervals have received far less attention. This situation may be explained by the limitations of the conventional representation of time intervals, i.e. the linear representation. In this representation, time intervals are modelled as linear segments in a one-dimensional space. The second dimension is often exploited as well (e.g. using a Gantt chart or timetable). However, this dimension is solely to distinguish the intervals of different entities, and thus has no temporal meaning. Thus, in the linear representation, the visual distribution of intervals may vary according to different ordering rules applied to the second dimension. This polymorphism prohibits the existence of a universal visual recognition approach for detecting patterns among time intervals. As a result, this hampers the development of visual techniques and tools to handle interval-based data, for instance techniques of exploratory data analysis (EDA)[10] that greatly rely on information visualisation. Note that there exist other representations of time intervals, e.g. the cyclic representations[11,12] and the calendars.[13] However, they focus on special aspects of time intervals and are not applicable in a broader range of contexts.

This problem also exists in many information systems that deal with interval-based data, for instance geographical information systems (GISs), which consider time as one of the most important components.

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In the recent GIS developments, great efforts have been made in spatio-temporal analysis,[14,15] especially exploratory spatio-temporal data analysis (ESTDA).[16–18] Nevertheless, the existing approaches and tools show limited ability in analysing geographical data with reference to time intervals. In traditional GIS, time intervals are usually represented by cartographical variables (e.g. symbols, labels and colours),[19] animations[20] or spatio-temporal composites.[21] These representations cannot explicitly display the distribution of time intervals, and thus their suitability for pattern detection is limited. Also, the lack of interactivity obstructs their application in ESTDA. Recently, thanks to developments in the field of computer science, a variety of innovative techniques have been introduced to analyse spatio-temporal data.[22–26] In spite of that, as most techniques are still based on the linear time representation, their ability to analyse interval-based geographical data is not satisfactory. On the one hand, time is often directly integrated with the two-dimensional (2D) space into a three-dimensional (3D) space, i.e. the space–time cube.[27–31] Gatalsky et al.[32] implemented the space–time cube into an interactive environment to display geographical events that occur in very short intervals (i.e. instantaneous events). This approach can also apply to events with a temporal extent, for example representing such events as linear segments parallel with the time axis in the cube.[33] However, implementations of the space–time cube suffer from typical problems of 3D visualisation[34,35] which will be specifically explained in the discussion section of this paper. On the other hand, attempts have been made to display time and space through interactively coordinated visualisations.[36] Fredrikson et al.,[37] for instance, utilised a visualisation coordination system (i.e. Snap-Together Visualisation[38]) to analyse aggregates of spatio-temporal data. In this system, temporal, geographical and categorical attributes are displayed in several coordinated views. As the time view of this tool remains based on the linear representation, it is limited to instantaneous events and does not show any potential in analysing interval-based data.

To overcome these difficulties, an alternative representation of time intervals can be considered. In 1997, Kulpa introduced a presentation of time intervals as points in a metric 2D space.[39] He elaborated the use of this diagrammatic representation in interval reasoning and arithmetic.[40,41] Later, Van de Weghe et al.[42] named this representation the triangular model (TM) and applied it to an archaeological case. Recently, Qiang et al.[43,44] have extended the TM to represent and reason about rough and fuzzy time intervals. Beyond their theoretical extensions, these contributions have presumed considerable potential of the TM for visualising and analysing time intervals. However,

until now, the analytical power of the TM has not been thoroughly investigated. To fill this gap, this paper investigates the use of the TM for querying and analysing time intervals. In order to demonstrate the uses of the TM, a prototype tool GeoTM is developed, which implements the TM in a GIS.

The remainder of this paper first introduces the basic concept of the TM ('The triangular model' section). And then, we describe how queries about time intervals can be defined in the TM. The following section introduces the implementation of the TM, i.e. GeoTM, including its graphical user interface and functionalities. In the case study, this implementation is applied in a real scenario to analyse time intervals that were detected by a Bluetooth tracking system. In the discussion, the strengths and weaknesses of GeoTM are discussed and compared with alternative approaches. In the last section, the conclusions of this work are drawn and the directions of future work are proposed.

The triangular model

A crisp time interval I is usually modelled as a pair of real numbers $[I^-, I^+]$ with $I^- < I^+$ denoting the start and end of the interval, respectively. In the linear representation, such a time interval is represented as a finite line segment (Figure 1(a)). The two extremes of the segment respectively represent the start (I^-) and the end (I^+) of the interval, while the length of the segment expresses the duration of the interval $(dur(I))$. This linear representation of time intervals is widely used in our daily life, for example in Gantt charts and historical timelines. In this paper, we assume a crisp time interval I to be closed at both sides, such that $I = [I^-, I^+]$. In different reasoning systems, whether an interval is open (at one or both sides) is defined differently.[43] As the TM does not intend to solve reasoning issues that concern this controversy, whether an interval is open does not affect its representation in the TM.

The transformation from the linear representation to the TM starts from the construction of two lines through the extremes of an interval (Figure 1(b)). For each time interval I, two straight lines (L_1 and L_2) are constructed, with L_1 passing through I^- and L_2 passing through I^+. α_1 is the angle between L_1 and the horizontal axis and α_2 is the angle between L_2 and the horizontal axis, with $\alpha_1 = -\alpha_2 = \alpha$. The intersection of L_1 and L_2 is called the interval point. The start of the interval (I^-), the end of the interval (I^+) and the interval point form an isosceles triangle. The angle α is a predefined constant that is identical for all time intervals, in order to ensure that each time interval is mapped to a unique point in the 2D space. The position of an interval point
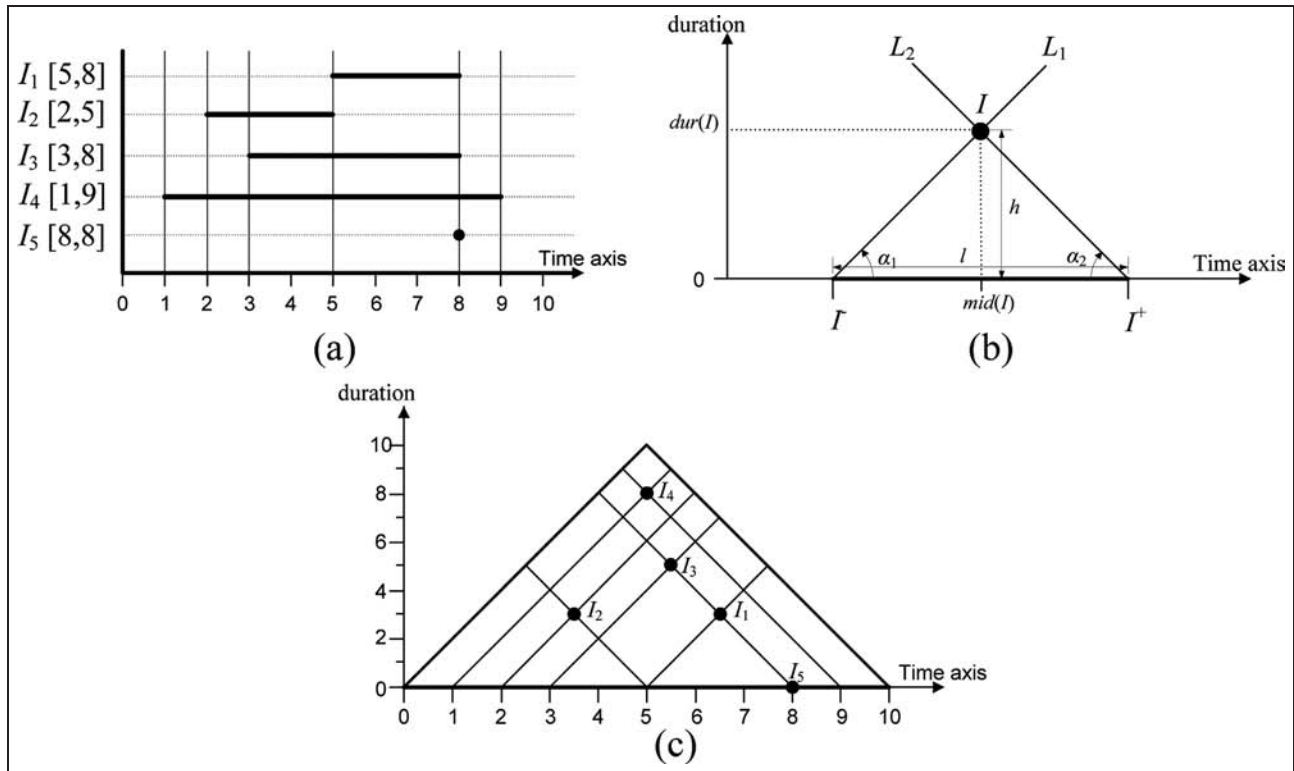
Figure 1. The transformation from the linear representation to the triangular model (TM). (a) The linear representation of time intervals. (b) The construction of an interval point in the TM. (c) The TM representation of time intervals.

completely determines both the start and the end of the interval. α can be different values for specific purposes. In this paper, we set $\alpha = 45°$, to be consistent with earlier work.[39,41,42,44] In this way, all time intervals can be represented as 2D points in the TM (Figure 1(c)). With $\alpha_1 = -\alpha_2$, it is straightforward to deduce that, in the horizontal dimension, the position of the interval point indicates the middle point of the interval, i.e. $mid(I)$. In the vertical dimension, the height of the interval point (h) is proportional to the length of the linear interval (l), i.e. $h = \frac{\tan \alpha}{2} \cdot l$. As a result, the height of an interval point in the TM indicates the duration of the interval, i.e. $dur(I)$. Note that the TM is compatible with time instants, which can be characterised as time intervals with a zero length. Time instants are represented as points that coincide with the time axis, e.g. I_5 in Figure 1(c). Given that time instants are also modelled through horizontally aligned points in the linear representation, both the TM and the linear representation can be considered identical for this specific class of intervals.

Temporal queries in the triangular model

As the TM represents time intervals as points in a 2D space, TM coordinates have temporal semantics. In this section, we will describe how temporal queries can be modelled in the TM. The implementation of these temporal queries will be illustrated in 'The implementation' section.

Queries of Allen relations

According to the outcome of the logical comparison (i.e. smaller than, equal to and larger than) between the starts and ends of two time intervals, Allen[1] defined 13 relations between two time intervals (Table 1), which are referred to as Allen relations. In the TM,

Table 1. Thirteen Allen relations.[1]

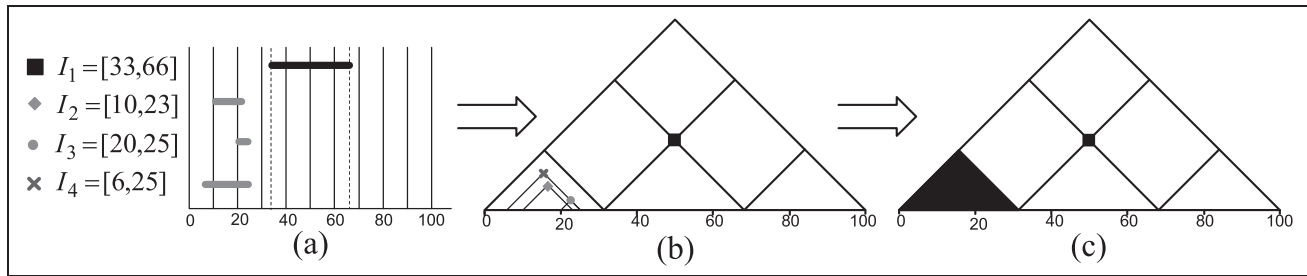|			
I_1 equals I_2	if $I_1^- = I_2^-$	$\wedge\ I_1^+ = I_2^+$	
I_1 starts I_2	if $I_1^- = I_2^-$	$\wedge\ I_1^+ < I_2^+$	
I_1 started-by I_2	if $I_1^- = I_2^-$	$\wedge\ I_2^+ < I_1^+$	
I_1 finishes I_2	if $I_1^+ = I_2^+$	$\wedge\ I_1^- > I_2^-$	
I_1 finished-by I_2	if $I_1^+ = I_2^+$	$\wedge\ I_2^- > I_1^-$	
I_1 meets I_2	if $I_1^+ = I_2^-$		
I_1 met-by I_2	if $I_2^+ = I_1^-$		
I_1 overlaps I_2	if $I_2^- > I_1^-$	$\wedge\ I_1^+ < I_2^+$	$\wedge\ I_1^+ > I_2^-$
I_1 overlapped-by I_2	if $I_1^- > I_2^-$	$\wedge\ I_1^- < I_2^+$	$\wedge\ I_2^+ < I_1^+$
I_1 during I_2	if $I_1^- > I_2^-$	$\wedge\ I_1^+ < I_2^+$	
I_1 contains I_2	if $I_2^- > I_1^-$	$\wedge\ I_2^+ < I_1^+$	
I_1 before I_2	if $I_1^+ < I_2^-$		
I_1 after I_2	if $I_2^+ < I_1^-$		

Figure 2. Temporal relations in the linear model and in the triangular model, taking *before* as an example.

Allen relations can be transferred to spatial relations.[39,41] Given a study interval I [0,100], all examined intervals are located within the isosceles triangle formed by I^-, I^+ and the interval point of I. Let us consider a reference interval I_1 [33,66] and several intervals (I_2, I_3, I_4) that are *before* interval I_1 (Figure 2(a)). In TM, I_2, I_3, I_4 are located in the zone in the left corner of the study interval (Figure 2(b)). Therefore, it is easy to deduce that this zone (i.e. the black zone in Figure 2(c)) encloses all intervals that are before I_1. In like manner, all Allen relations with respect to an interval can be represented by such zones in the TM[37,39] (see Figure 3). In each diagram in Figure 3, the reference interval I_1 has been chosen in the centre of the study period to avoid visual bias. Each black zone represents the set of intervals that are in a specific relation to I_1. Such a set of intervals is denoted as $R(I_1)$, where R stands for a certain temporal relation (e.g. *before*, *after*, etc.). Thus, temporal queries based on Allen relations can be modelled as zones in the TM. The query constraint is expressed by the extent of the zone, which encloses all intervals satisfying the query. The zones expressing temporal queries are called query zones.

Queries of other relations

Besides queries of Allen relations, a variety of queries based on other temporal relations can be modelled in the TM. In this section, we introduce four of them that have been implemented in the current version of GeoTM. First, intervals *in-between* two different time intervals are within a rectangle with sides in α or $-\alpha$ angle to the horizontal axis[41] (Figure 4). $\ll I_1, I_2 \gg$ is used to denote the set of intervals *in-between* I_1 and I_2. $\ll I_1, I_2 \gg$ consists of all intervals whose starts are between the start of I_1 and the start of I_2, and ends are between the end of I_1 and the end of I_2. The formal definition of $\ll I_1, I_2 \gg$ can be found in Equation 1. A set of intervals *in-between* two time intervals is a convex set of intervals,[41] because it can be directly interpreted by Allen relations or combinations of Allen relations. If the rectangle intersects the horizontal axis, the query zone is only the part above the horizontal axis, because there is no valid time interval below the horizontal axis, according to our definition. Additionally, *starts-within*(I_1) is defined as a set of intervals whose starts are in I_1 (Equation 2). Analogously, *ends-within*(I_1) is
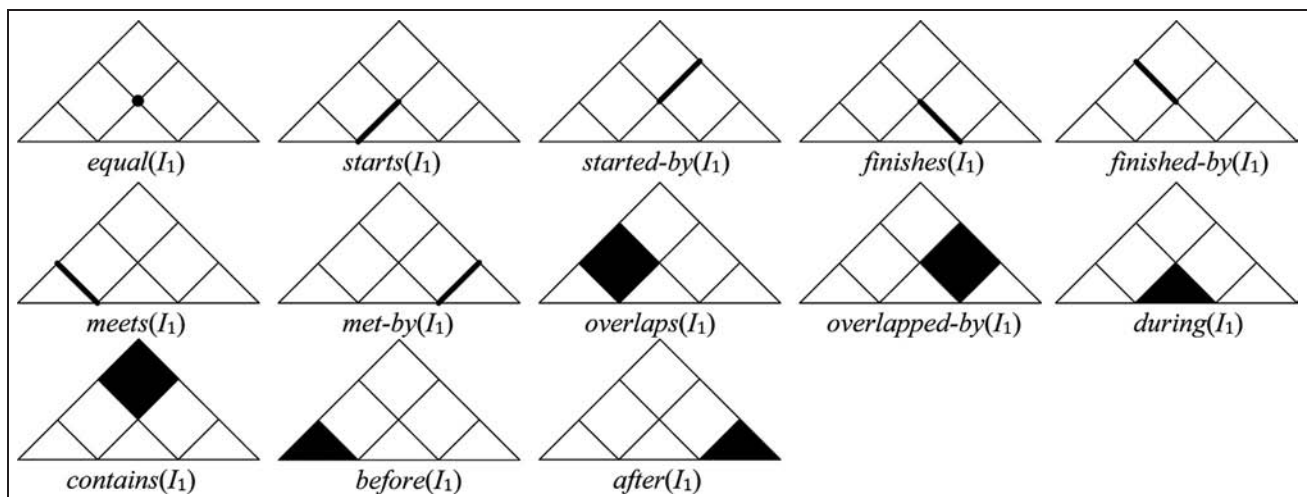

Figure 3. The representation of the 13 Allen relations in the triangular model. Each black zone represents a set of intervals in a specific Allen relation to the reference interval.
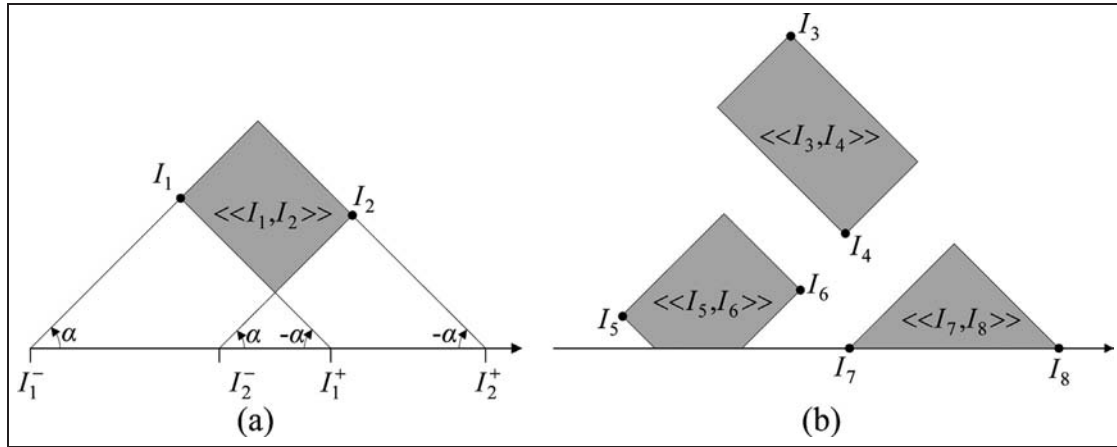
Figure 4. The query for intervals *in-between* two intervals. (a): The formation of the query zone of *in-between* I_1 and I_2 (b): Three examples of *in-between* query zones.
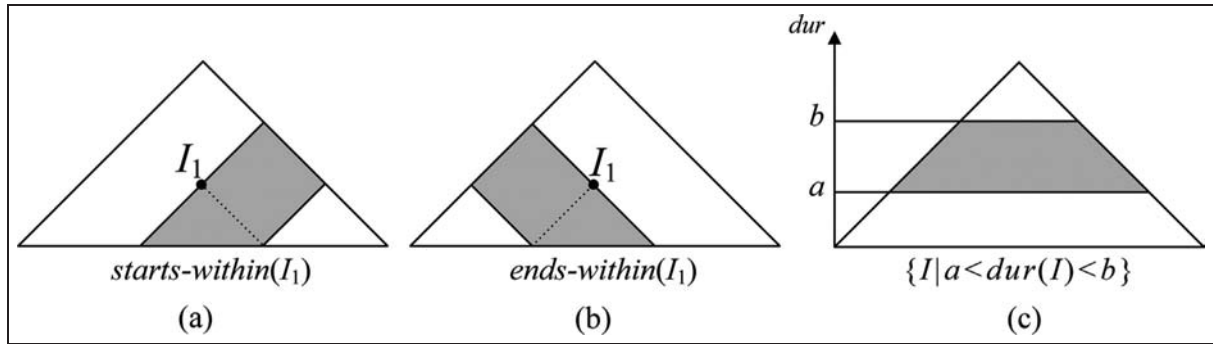

Figure 5. Queries of three non-Allen relations in the triangular model. (a) The query zone of *starts-within*(I_1) containing intervals that *start-within* I_1. (b) The query zone of *ends-within*(I_1), containing intervals that *ends-within* I_1. (c) The query zone of $\{I | a < dur(I) < b\}$, containing intervals whose durations are greater than a and smaller than b.

defined as a set of intervals whose ends are in I_1 (Equation 3). The query zones of *starts-within*(I_1) and *ends-within*(I_1) are illustrated in Figure 5(a) and (b). Moreover, a set of intervals whose durations are in a specific range are located within a range along the vertical axis. For example, in Figure 5(c), the set of intervals $\{I | a < dur(I) < b\}$ is within the zone between a and b along the vertical axis.

$$\ll I_1, I_2 \gg \equiv \{I | \min(I_1^-, I_2^-) < I^- < \max(I_1^-, I_2^-)$$
$$\wedge \min(I_1^+, I_2^+) < I^+ < \max(I_1^+, I_2^+)\} \quad (1)$$

$$starts\text{-}within(I_1) \equiv \{I | I_1^- < I^- < I_1^+\} \quad (2)$$

$$ends\text{-}within(I_1) \equiv \{I | I_1^- < I^+ < I_1^+\} \quad (3)$$

Composite queries

As temporal queries are expressed as 2D zones in the TM, composition of temporal queries can be modelled by spatial operations of the query zones. In the TM,

the query composition follows the same principles of Venn diagrams.[44] The intersection of queries is represented by the intersection of the query zones (Figure 6(a)). The union of queries is represented by the union of the query zones (Figure 6(b)) Furthermore, the subtraction of two queries is modelled as subtracting one query zone from the other, which selects intervals that satisfy only one out of two queries (Figure 6(c)).

The implementation

To demonstrate and exploit practical uses of the TM, we implemented the TM into a prototype software tool called GeoTM. In this section, we will introduce its user interface and functionalities.

GeoTM

GeoTM supports visualising, querying and analysing spatio-temporal data. More specifically, it has the
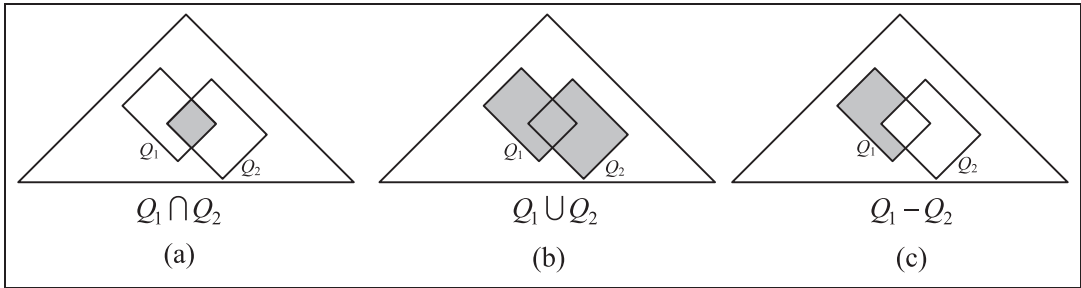
Figure 6. The composition of temporal queries in the triangular model. (a) The intersection of the two queries. (b) The union of the two queries. (c) The subtraction of one query from the other query.
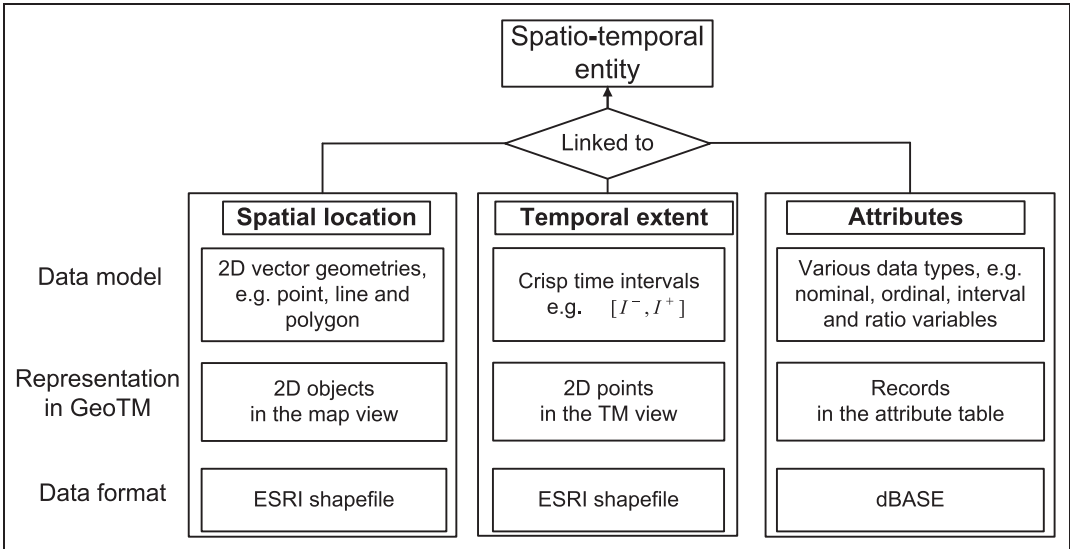

Figure 7. The models and representations of spatio-temporal information in GeoTM.

ability to analyse entities that are referenced to spatial locations and temporal extents. In GeoTM, the spatial locations are modelled as vector geometries (i.e. point, line and polygon), while the temporal extents are modelled as crisp time intervals. Besides their spatial and temporal components, the entities may have other attributes that are stored in the attribute table. The spatial locations, temporal extents and other attributes are linked to entities by unique identifiers (IDs) of entities. GeoTM is built on top of ArcGIS^{TM}, which is a desktop GIS produced by ESRI®. In GeoTM, the spatial locations, time intervals and other attributes are stored in ArcGIS^{TM} compatible formats, i.e. ESRI shapefile and dBase. Figure 7 gives an overview of how the spatio-temporal information is modelled and represented in GeoTM.

The graphic user interface of GeoTM consists of a map view, a TM view and other controls (Figure 8). The map view is used to display spatial locations of entities, which are modelled as points, lines or polygons. The TM view represents time intervals of

entities, using the TM representation. In GeoTM, users can zoom in and out in both views by scrolling or dragging a rectangle. In the map view, objects can be selected by dragging an orthogonal rectangle. In the TM view, special selection tools have been designed to select intervals according to specific temporal queries. The other attributes of entities are stored in the attribute table that can pop up when the user clicks the corresponding button. The map view, the TM view and the attribute table are connected through linked brushing. This means that when selecting objects from any of these three views, the other two views dynamically update according to the selection. Additionally, many common GIS functions are supported in GeoTM, such as the use of multiple data layers. Furthermore, objects in the map view and the TM view can be displayed in different sizes, colours and symbols, in order to express attribute information. In Figure 8, the map view displays the locations of 26 Bluetooth scanners that have been installed in the centre of Ghent, Belgium, and the TM view displays the
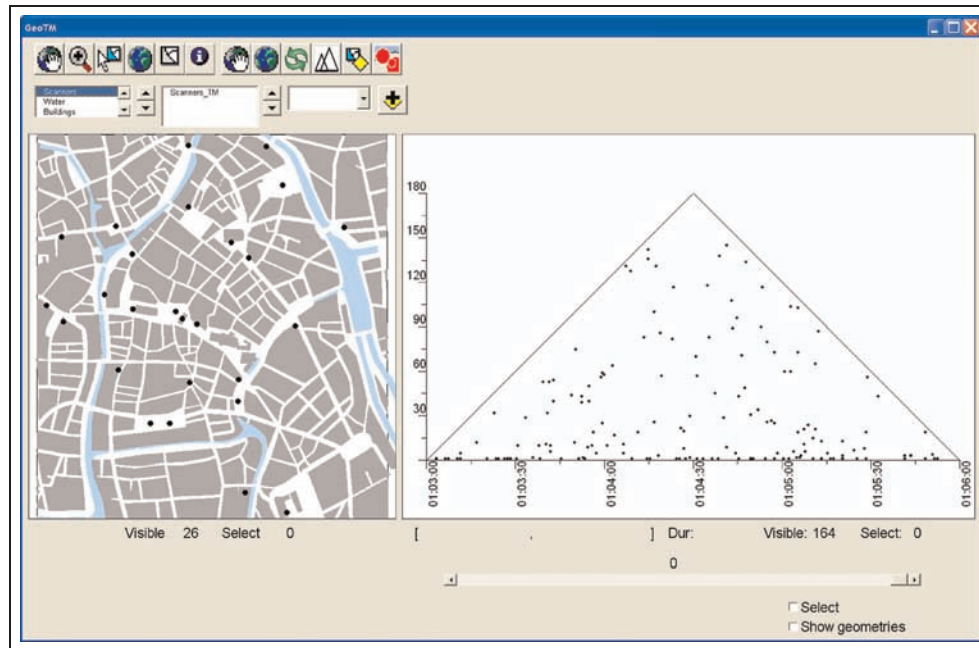
Figure 8. The graphical user interface of GeoTM.

Temporal queries in GeoTM

time intervals of Bluetooth devices that were detected by these scanners between 1:03:00 and 1:06:00 on 23 July 2010 (note that the 24-hour clock is used throughout this paper). In the remainder of this section, we use these time intervals to demonstrate the query functions of GeoTM. The complete scenario of this dataset will be explained in the next section.

Temporal queries in GeoTM

Traditionally, queries on time intervals are determined by formal expressions (e.g. structured query language statements) or by manipulating controls (e.g. buttons, sliding bars and check boxes) in predefined graphical user interfaces. At present, visual and interactive query tools are being increasingly supported in software,[45] including those that define queries by sketching or manipulating graphics on the screen.[46–49] These kinds of query tools have significantly enhanced human–computer interactivity, and therefore play an important role in EDA.[18] Despite the large variety of tools that have been developed to present and analyse temporal information,[50–52] most are designed for visualisation and do not support abundant temporal query functions. As a graphical representation of time intervals, the TM provides a promising platform for visual temporal queries. In GeoTM, temporal queries can be defined by clicking and dragging geometries in the TM view. Users can indicate an interval by moving the mouse cursor to a specific position, and then query for intervals that satisfy an Allen relation to the

indicated interval (Figure 9(a) and (b)). In addition, the query zones of the 13 Allen relations of an indicated interval can be drawn (Figure 9(c)), which offers an overview of the distribution of intervals in different relations to the indicated interval.

Moreover, temporal queries can be defined by dragging a zone in the TM view. In line with the characteristics of the TM space, several special dragging tools have been designed in order to select intervals that satisfy certain temporal queries. The default dragging box is a non-orthogonal rectangle that selects intervals *in-between* two time intervals. With this dragging box, every selected set of intervals is a convex interval set that can be interpreted by Allen relations or combinations thereof. Dragging a rectangle selects a convex interval set *in-between* two intervals (e.g. Figure 10(a)), and dragging a triangle on the horizontal axis selects a convex interval set *in-between* two time instants (Figure 10(b)). Besides convex interval sets, GeoTM supports range queries according to interval duration by dragging a range along the vertical axis (e.g. Figure 10(c)). Furthermore, a range of two parallel lines can be dragged at a or $-a$ angle with respect to the horizontal axis to select the intervals that *start-within* or *end-within* an interval (Figure 10(d)).

Composite queries

All the above-mentioned queries can be composed in GeoTM. Users can make queries successively and compose them by logical operators (e.g. union,
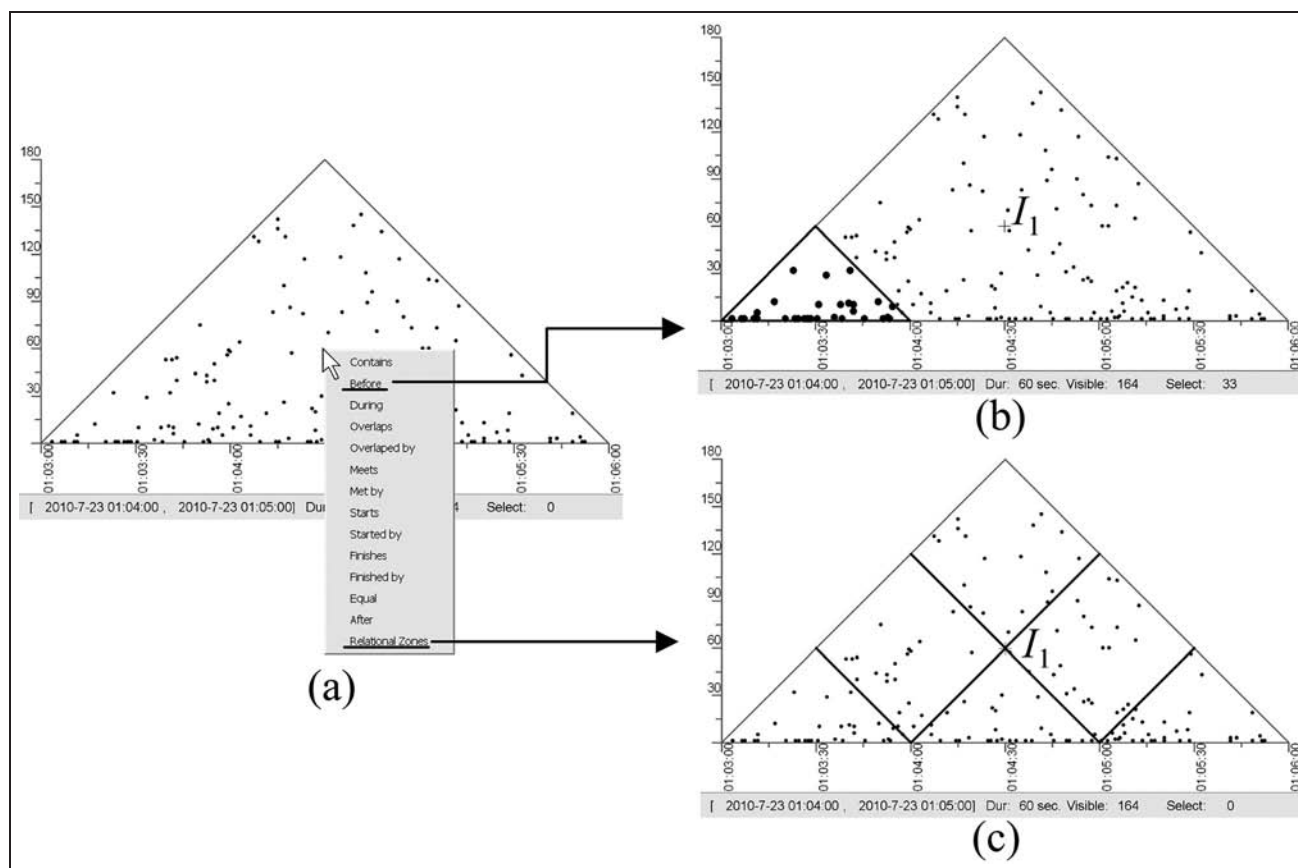
Figure 9. Querying intervals that are *before* I_1 [01:04:00, 01:05:00] on 23 July 2010 and drawing the query zones of I_1. (a) Move the mouse cursor to I_1 and right click to trigger the drop-down menu of Allen relations. (b) With the 'before' option clicked, the zone of *before*(I_1) is drawn and intervals in this zone are selected. The larger dots represent the selected intervals and the cross represents I_1. (c) With the 'Relational zones' option clicked, the query zones of the 13 Allen relations of I_1 are drawn.

intersection or subtraction). Figure 11 illustrates how the composite query *contains*(I_1)$\cap \ll I_2, I_3 \gg \cap \{I | dur(I) > 90 seconds\} \cap ends$-$within(I_4)$ is constructed in GeoTM, given the intervals I_1, I_2, I_3 and I_4. The querying process consists of four steps. In each step, a component query is made, with a selected logical operator. As in this case, component queries are composed with intersection, the result is the intersected area of the query zones. The intervals located in the intersected area are selected, which satisfy the entire composite query.

Case study

Although existing as a communication technology since the mid-nineties, Bluetooth has only recently been employed for positioning and tracking individuals.[30,31,53–56] Despite its limited positional accuracy, Bluetooth tracking is a low-cost alternative for true location-aware technologies. Nowadays, because of the increasingly widespread use of Bluetooth-integrated

devices, such as mobile phones, laptops and handsets, Bluetooth tracking has been used more and more in scientific experiments and observations. In this case, the data were collected from the most basic form of a Bluetooth tracking system, in which a number of Bluetooth scanners were installed at certain strategic points. These scanners continuously make enquiries, listen for responses of other devices in their detection ranges and log the results with a time resolution of 1 second. Therefore, the period when a Bluetooth device is in the detection range of the scanner is a time interval. Technically, this interval starts at the first second that the Bluetooth device is logged by the scanner and ends at the last second that it is logged. Moreover, if a Bluetooth device has left the detection range of a scanner but it re-enters the range again within 30 minutes, the two time intervals, as well as the gap between them, are merged to one time interval. The purpose of doing this is to eliminate the fractional intervals that are caused by unstable signals or Bluetooth devices moving on the boundary of the detection range. In this
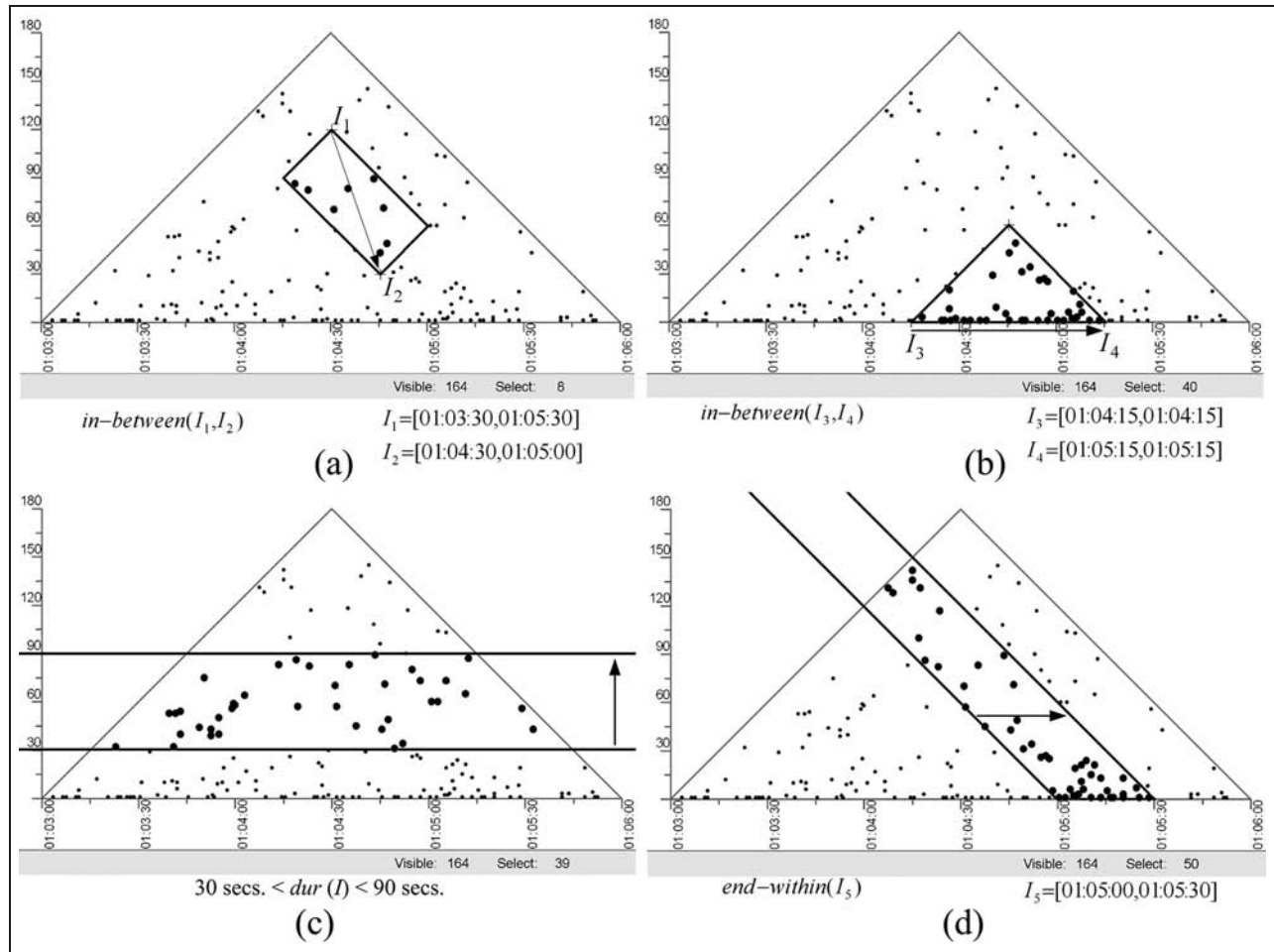
Figure 10. Temporal queries by dragging geometries in the triangular model. (a) Selecting intervals in a convex set *in-between* two time intervals. (b) Selecting intervals in a convex set *in-between* two time instants. (c) Selecting intervals that are longer than 30 seconds and shorter than 90 seconds. (d) Selecting intervals *end-within* [01:05:00, 01:05:30].

way, the scanners generate a dataset of time intervals, in which every single record consists of three major components: the media access control address of the Bluetooth device, the ID of the scanner logging the device and the time interval.

The dataset was collected during the Ghent Festivities 2010, from 10:00 on 17 July to 10:00 on 26 July 2010. Twenty-six Bluetooth scanners were installed in selected locations (e.g. concert stages, parking lots, the tourist information office and major accesses) in the centre of Ghent. When the dataset was loaded to GeoTM, the time intervals were displayed as dots in the TM view and the Bluetooth scanners were displayed in the map view (Figure 12). In the TM view, some regular daily patterns can be observed: the number and durations of logged intervals increases from the afternoon, reach a peak around midnight and start to decrease after midnight. In GeoTM, if specific Bluetooth scanners are selected in

the map view, the time intervals that are logged by these scanners turn to red in the TM view. With this function, users can observe and compare the distribution of time intervals detected at different locations. In the Ghent Festivities 2010, two concert stages were located, at Sint-Baafs Cathedral and Sint-Jacob Church, respectively. By successively selecting the scanners installed near Sint-Baafs Cathedral (i.e. Scanner 1, 2 and 3 in Figure 12) and the scanners installed near Sint-Jacob Church (i.e. Scanner 8 and 9 in Figure 12) in the map view, from the TM view one can observe that the distributions of intervals at these two sites are similar, which gradually increase from the afternoon or evening, and decrease more rapidly late at night or early in the morning of the next day. However, the time intervals detected near Sint-Baafs Cathedral are generally distributed earlier than the intervals detected near Sint-Jacob Church (Figure 13). This finding reveals the fact that the crowd near
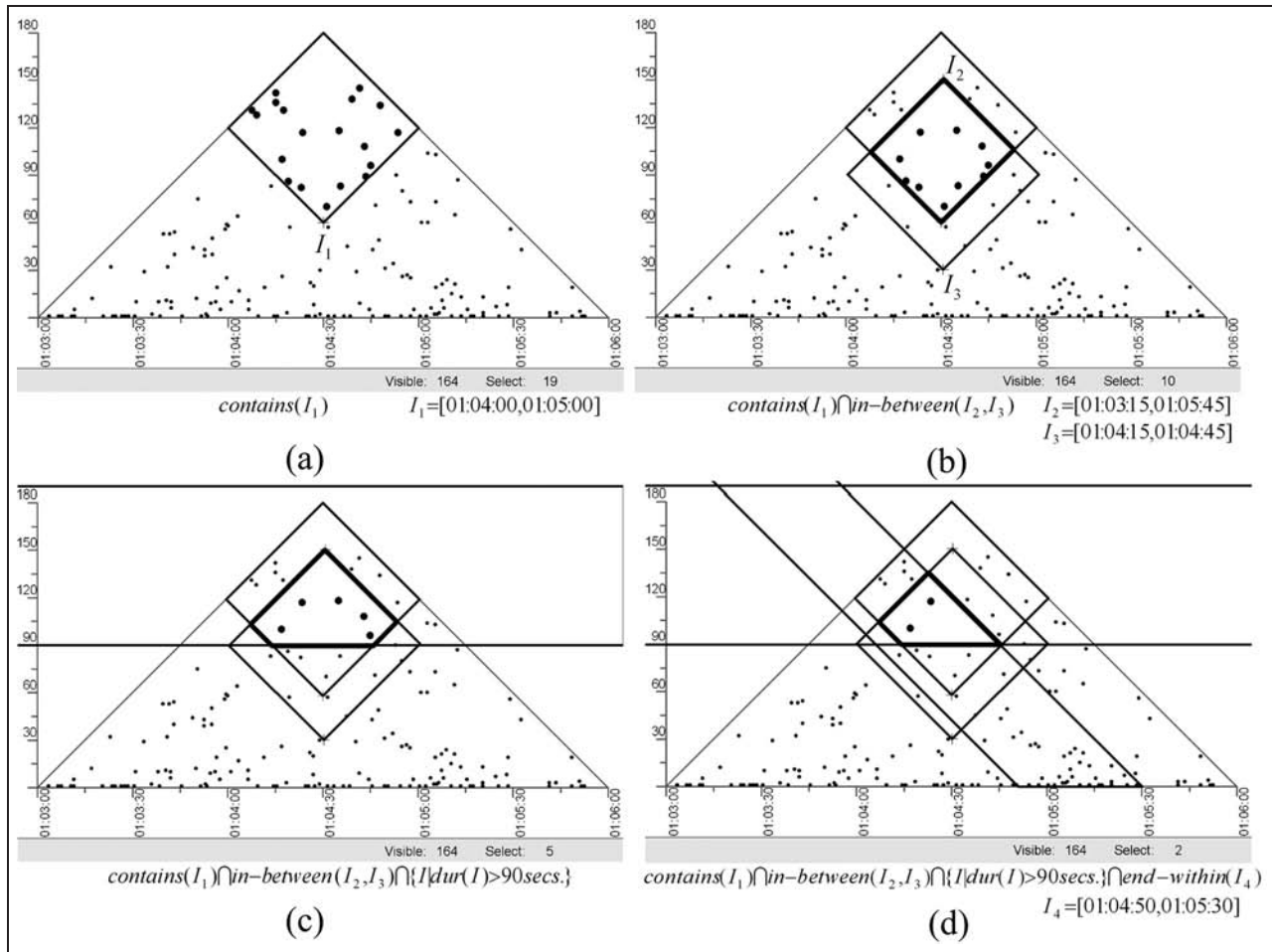
Figure 11. The creation of the composite query: $contains(I_1) \cap \ll I_2, I_3 \gg \cap \{I | dur(I) > 90 \text{seconds}\} \cap ends\text{-}within(I_4)$. In each step, the intersected areas of the queries are marked by bold boundaries and selected intervals are marked by larger dots.

Sint-Baafs Cathedral gathered and dispersed earlier than the crowd near Sint-Jacob church.

In the TM view, users can also zoom into smaller areas to observe the interval distribution during specific hours. Zooming into the period from 16:00 on 18 July to 4:00 on 19 July and the period from 18:00 on 22 July to 10:00 on 23 July (Figure 14), one can see that most interval points are distributed on the bottom, meaning that most detected time intervals in these two periods are relatively short. This reflects the high fluidity of people during the events. Moreover, some linear clusters that extend to the higher area can be observed (Figure 14). Some of these clusters are in $-\alpha$ ($\alpha = 45°$) angle to the horizontal axis (such as C1 in Figure 14). This kind of cluster is formed by intervals that *start-within* a very short period and *end-within* a much longer period, which can be interpreted as a large number of people having Bluetooth devices intensively entering the detection range of the scanners within a very short

period, and these people gradually leaving the ranges of the scanners during a much longer period. On the other hand, some other linear clusters are in α angle to the horizontal axis (such as C2, C3 and C4 in Figure 14), which are formed by intervals that *start-within* a long period and *end-within* a very short period. This kind of cluster can be interpreted as a number of people with Bluetooth devices gradually entering the range of the scanners within a long period and intensively leaving within a short period. These linear patterns cannot be easily detected from traditional visualisation approaches, for example line diagrams. In Figure 15, the detected patterns in the period from 16:00 on 18 July to 4:00 on 19 July (i.e. C1, C2 and C3) do not clearly appear in the corresponding line diagrams, because the clusters of long intervals can be easily diluted by the large number of short intervals.

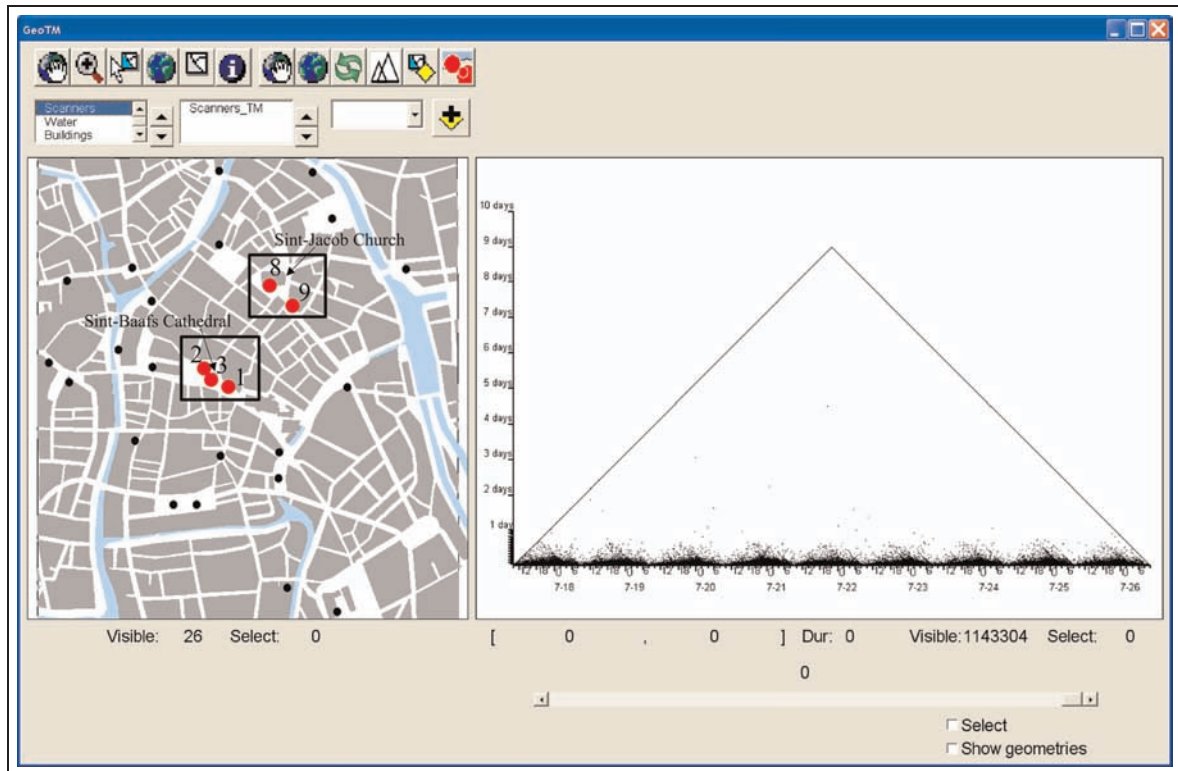Using the query tools in GeoTM, users can select intervals in these observed clusters, and analyse the

Figure 12. The GeoTM interface with the complete Bluetooth dataset loaded. The squares and red dots in the map view indicate the two selections of scanners that generate the results in Figure 13.
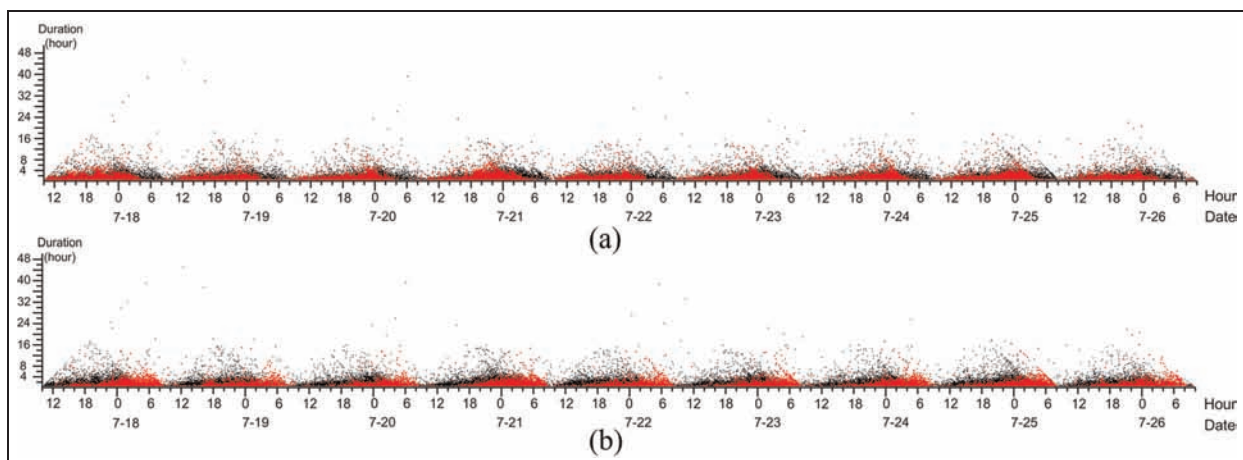

Figure 13. The time intervals logged by the two groups of scanners in Figure 12 become red in the triangular model view. (a) The time intervals logged by Scanner 1, 2 and 3 are red, and the rest remain black. (b) The time intervals logged by Scanner 8 and 9 are red, and the rest remain black.

spatial distribution of the selected intervals. In GeoTM, when a selection is made in the TM view, the dot size of scanners in the map view will be updated, indicating the proportion of intervals logged by every scanner. As we observe that the intervals in Cluster $C1$ more or less *start-within* [17:00, 17:30] on 18 July, we can drag a query zone of *start-within*

[17:00, 17:30] to select the intervals in $C1$ (Figure 16). Then, the updated map view shows dots corresponding to the different scanners in similar sizes, meaning that the selected intervals are more or less evenly logged by the 26 scanners. In order to focus on the people that come for the events of the Ghent Festivities, the user may want to eliminate the short
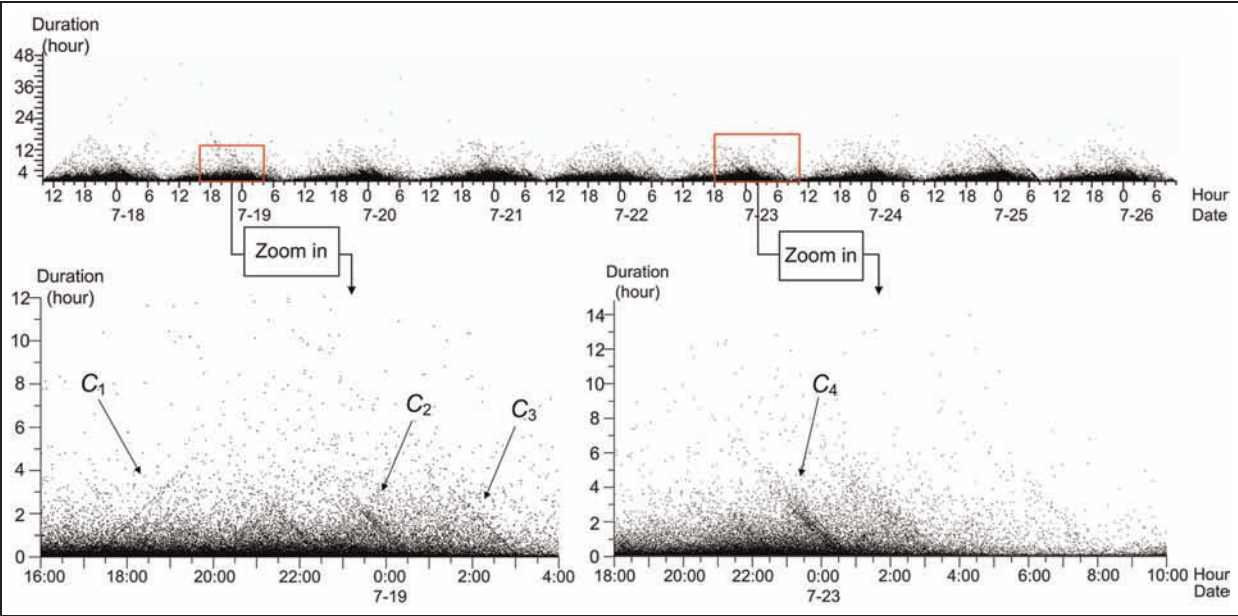
Figure 14. Zooming into the period from 16:00 on 18 July to 4:00 on 19 July and the period from 18:00 on 22 July to 10:00 on 23 July in the triangular model view.
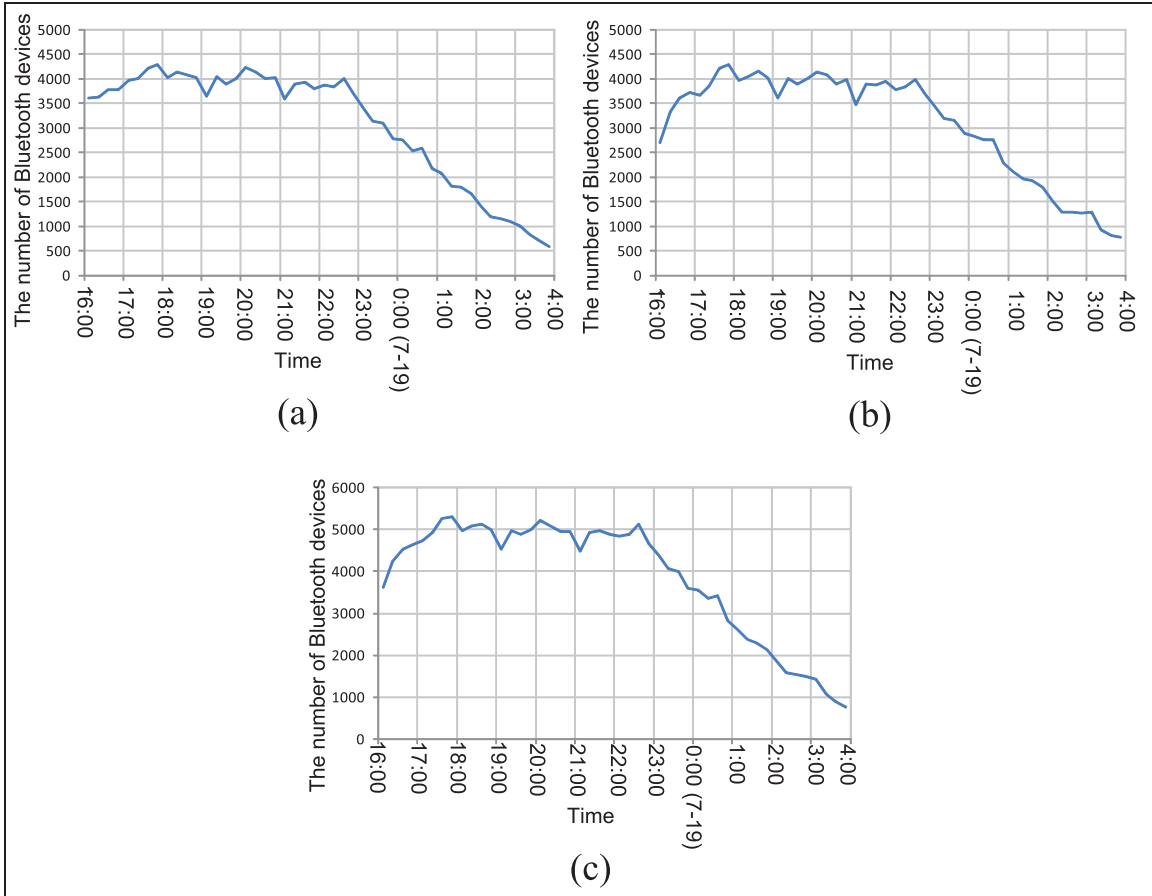

Figure 15. Representing the dataset from 16:00 on 18 July to 4:00 on 19 July with line diagrams. (a) The numbers of Bluetooth devices that entered the detection range of scanners in every 15 minutes. (b) The number of Bluetooth devices that left the range of scanners in every 15 minutes. (c) The total number of detected Bluetooth devices in every 15 minutes.
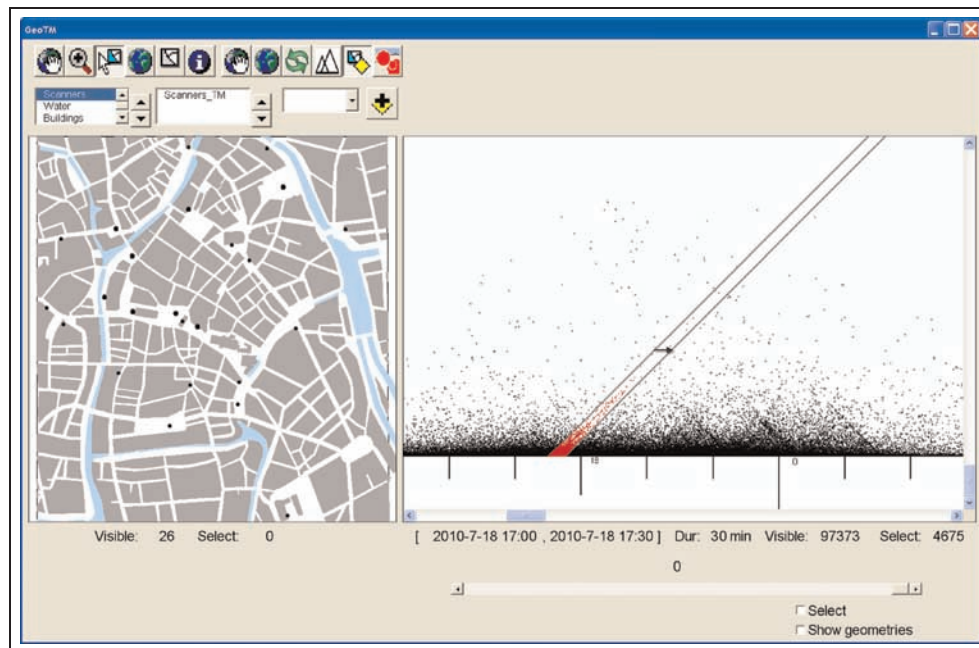
Figure 16. Select intervals that *start-within* [17:00, 17:30] on 18 July.
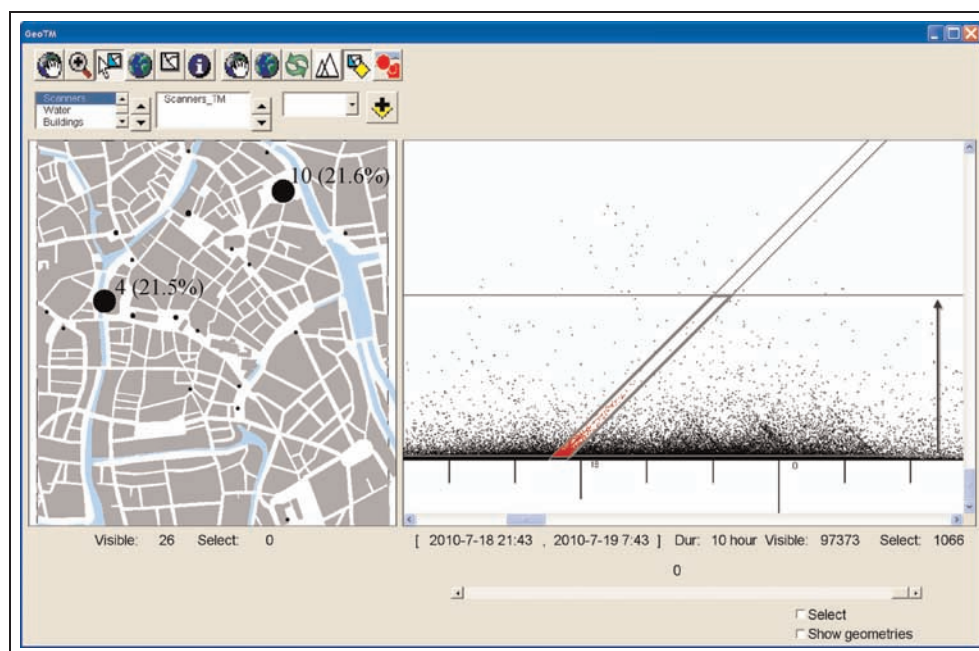

Figure 17. Select intervals that *start-within* [17:00, 17:30] on 18 July and have a duration of between 15 minutes and 10 hours. The numbers in the map view indicate the scanner IDs, and the numbers between brackets indicate the proportions of logged intervals.

intervals of people passing by and the very long intervals of people living in the neighbourhood. To this end, another query zone is drawn to select intervals that have a duration of between 15 minutes and 10 hours upon the previous selection (Figure 17). In the map view, the dot sizes of Scanner 4 and 10 become

much bigger than the other scanners, meaning that large proportions of retrieved intervals are logged by these two scanners (21.5% and 21.6%). Considering Scanners 4 and 10 are installed respectively near the stage at Graslei and the stage at Baudelopark, it is straightforward to infer that a large number of people
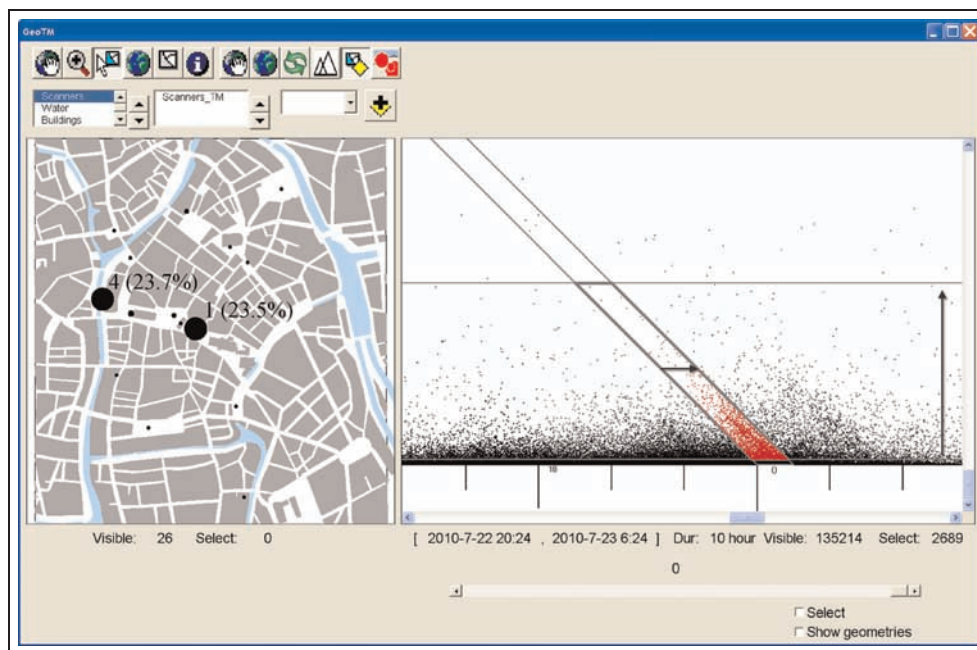
Figure 18. Select intervals that *end-within* [0:00, 1:00] on 23 July and have a duration of between 15 minutes and 10 hours.

intensively went to the events at these two stages between 17:00 and 17:30 and gradually left afterwards. Consulting the schedule of Ghent Festivities 2010,[57] one can find out that the concert of the band Maximum Basie at Graslei and an oriental dance activity at Baudelopark started at 17:00, which probably attracted people there and kept them there for a long time.

In the same way, the user can successively drag query zones of '*end-within* [0:00, 1:00] on 23 July' and 'have a duration between 15 minutes and 10 hours', in order to select the intervals in the cluster *C*4, excluding the short intervals of passing people and long intervals of people living around (Figure 18). Here, the map view shows that a large proportion of intervals are logged by Scanner 1 (23.5%) and Scanner 4 (23.7%). Considering that Scanner 1 and 4 are respectively installed near two stages at Sint-Baafs Cathedral and Graslei, one can infer that a large number of people gradually gathered at these two stages and then intensively left these two stages between 0:00 and 1:00 on 23 July. Consulting the schedule of the Ghent Festivities 2010,[57] we can see that the performances at these two stages ended during this period, which probably caused a wave of people leaving.

Discussion

As an alternative representation of time intervals, the TM shows a promising performance in some aspects

that are inherent difficulties of the traditional linear representation. In the linear representation, a given set of time intervals may show different patterns, when different ordering rules are applied (e.g. Figure 19). The characteristics of the distribution are not easy to observe from an individual display. However, the TM offers a compact and fixed visualisation of time intervals. Because every interval has a unique spatial position in the TM, the structure of a set of intervals is fixed, which potentially benefits pattern detection. When a dataset of intervals is represented in the TM, one can have a first image of the interval distribution. For example, in the dataset of the case study in this article, the distribution of time intervals can be directly observed from the TM visualisation, which shows not only where the intervals are located in time, but also their durations. In this visualisation, some interesting patterns (e.g. linear clusters) can be detected, which gives clues for analysing the phenomena behind these patterns. Moreover, points are apparently more space-saving than linear segments. Within the same display extent, the TM is capable of displaying a higher number of intervals than the linear model. For instance, it would be much more difficult to use linear segments to represent the time intervals in the datasets similar to that of the case study that consists of millions of time intervals.

Furthermore, the TM provides a platform for visual temporal queries. In the TM, temporal queries can be specified by creating 2D zones. These zones give a
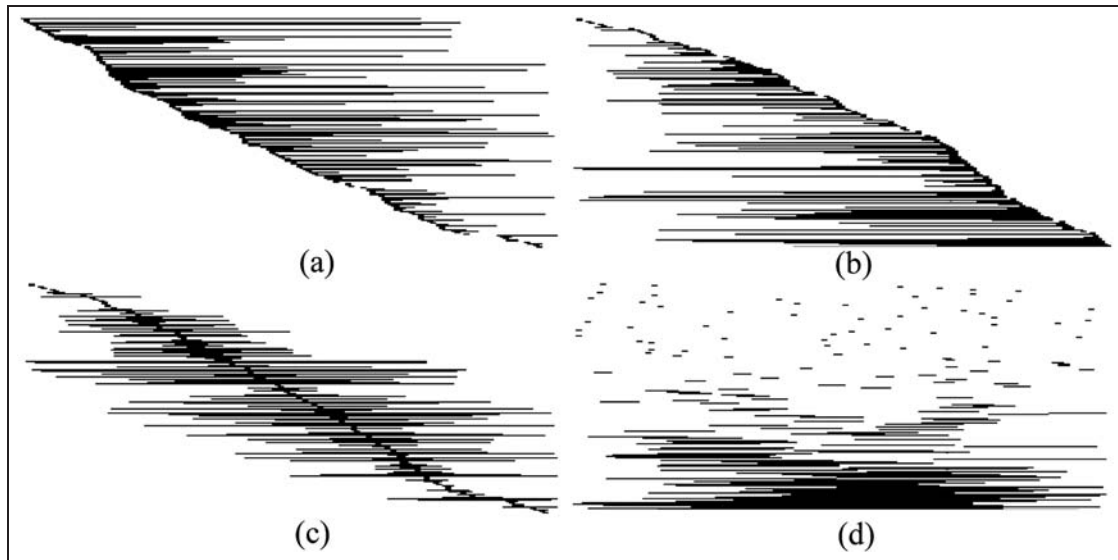
Figure 19. Time intervals in the linear representation, with different ordering rules. (a) Ascending order by the start. (b) Ascending order by the end. (c) Ascending order by the midpoint. (d) Ascending order by the duration.

visual impression of the query range. This unique feature stems from the fact that every interval has an absolute position in the TM and intervals in the same temporal relation are grouped in convex zones. Moreover, in the TM, the composition of temporal queries can be defined by spatial operations, following the concept of Venn diagrams. This graphical representation of temporal queries is likely to be more intuitive than alphanumerical expressions, because previous research shows that humans have excellent ability in processing spatial and graphical information,[58] and the transformation from alphanumeric expressions into graphical representations has gained considerable success in various disciplines.[59] Moreover, the TM supports an integration of the temporal query and the visualisation. In other words, temporal queries in the TM can be directly carried out by creating zones on top of the visualisation of time intervals. In this way, one can directly observe the range of the query over the dataset and instantaneously adapt the query. This feature is valuable when the query constraints are vaguely specified, or tailormade queries need to be designed to select intervals in special clusters, e.g. the observed clusters in the case study. One can instantaneously redefine the query range with respect to the distribution of intervals. On the contrary, the traditional query tools (e.g. dynamic sliders, drop-list and text boxes) are standalone and do not visualise data. They normally cooperate with a data visualisation to do analytical jobs. For example, when using dynamic sliders, one needs to query with the slider and keep an eye on the graph next to it.

With these promising features, the TM shows potential in assisting a GIS in analysing interval-based geographical data. In this work, the TM is implemented in a GIS in order to better exploit this potential. For the moment, not many tools have the capability of analysing this kind of geographical data. As one of the few possibilities, the tools based on the space–time cube concept represent spatio-temporal entities in a 3D space in which the time axis is added to a flattened topography. For example, the tool developed by Huisman et al.[33] represents geographical entities referenced to time intervals as linear segments in the space–time cube. The extents of these linear segments along the time axis indicate the time intervals. However, this tool suffers from some typical problems of 3D visualisation.[34,35] For example, the structure of objects varies when the view point varies. Moreover, foreground objects block one's view of background objects. Also, compared with 2D environments, it is cumbersome to manipulate objects (e.g. selecting objects) in a 3D environment given that the prevalent computer screens, touch pads and mouse pads are 2D. As GeoTM is based on a 2D visualisation, it does not suffer from these difficulties. We contend that GeoTM can bring the advantages of the TM in visualisation and temporal queries to the GIS, enhancing its capabilities regarding, for instance, ESTDA.

Conclusion and future work

In this paper, we have investigated the use of the TM in visualising and analysing time intervals. In order to better demonstrate the use of the TM, we have

implemented it into a software prototype (i.e. GeoTM) that integrates the TM with a GIS. In addition, GeoTM has been applied in a real scenario to analyse time intervals that were detected by Bluetooth scanners in the Ghent Festivities of 2010. As abstracting Bluetooth tracking data as time intervals is a new methodology and there are no mature approaches to analyse these kinds of datasets, GeoTM can be considered as an assistant tool that provides ESTDA functionalities. Although this analytical approach needs further investigation and validation, it provides unique insights into interval distributions, and can reveal interesting patterns that cannot be clearly presented by the other approaches. Moreover, the TM offers a mechanism for temporal queries that we contend is innovative and likely to support analysis effectively because of its graphical, flexible and direct representation on top of the visualisation. GeoTM shows that the querying and analytical power of the TM can be better exploited when it is implemented into an interactive tool. Furthermore, the integration with a GIS brings the merits of the TM in visualisation and temporal query to the GIS, enhancing its capabilities of analysing interval-based geographical data.

In the future, the analytical methodology based on the TM needs to be further investigated, including the interpretations of atomic patterns and metric measurement of the patterns. Also, this methodology will be tested in more cases, preferably covering different research contexts. On the other hand, the usability of GeoTM needs to be further evaluated. To this end, empirical experiments will be systematically designed and conducted to assess whether GeoTM can help people, particularly non-expert people, to solve practical questions. In addition, more user-friendly and interactive functions will be added to GeoTM to improve its usability, helping users to understand the TM concepts and make use of the corresponding functionalities. Other possible extensions exist in supporting the representation of rough and fuzzy time intervals,[22] or the representation of continuous temporal information (e.g. time series) rather than discrete time intervals.[60]

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