A qualitative modelling approach for the representation of trajectories: application to the analysis of flight patterns

Jing Wu [a,b], Christophe Claramunt[b], Lamia Belouaer[b] and Min Deng[a]

[a]Department of Geo-Informatics, Central South University, Changsha, China; [b]Naval Academy Research Institute, Lanvéoc-Poulmic, BP 600, 29240 Brest Naval, France

ABSTRACT

Over the past few years, a series of computational and semantic frameworks have been developed to model and represent the spatial and temporal properties of moving entities. Despite the interest of these contributions, it is recognized that there is still a need for a qualitative reasoning support at the abstract and formal levels. The research presented in this paper introduces a qualitative approach for representing and manipulating moving entities. The model combines topological relations with qualitative distances over a spatial and temporal framework. Several basic movement configurations over dynamic entities are identified as well as movement transitions. The whole approach is illustrated in the context of the analysis of flight patterns.

KEYWORDS
Trajectories; spatio-temporal reasoning; flight patterns

1. Introduction

A significant part of real-world objects is in endless movement, and human beings perceive and observe them through the concept of change. Over the past few years, significant efforts have been oriented to the development of temporal (Allen 1983) and spatio-temporal reasoning approaches (Cohn and Hazarika 2001). Qualitative spatio-temporal reasoning provides abstract mechanisms to reason on events and processes (Van de Weghe 2004; Noyon, Claramunt, and Devogele 2007; Muller 1998), while spatio-temporal processes have been categorized and specified by the notion of identity (Peuquet 1994; Claramunt and Thériault 1995; Hornsby and Egenhofer 1997).

Nowadays, continuous proliferation of sensor-based tracking techniques, such as GPS, Wi-Fi and radio frequency identification, provides increasing access to massive collection of movement data in either outdoor or indoor spaces. However, not all the information contained in these massive data sets is useful, especially when one would like to derive the main movement trends and patterns that emerge in space and time. For example, one would like to observe if a given entity is closing or going far away from another entity, or from a set of entities to derive the ones that have crossed another one. A peculiarity of these observations is that they are qualitative as per nature and not exactly quantitative and precise measures of distance. Another important property is that when considering a massive trajectory data set, movement data should be aggregated in order to derive the trajectory trends that can be derived and analysed at the qualitative level.

Qualitative representations of movement have been applied to many areas such as the modelling of human behaviour (Hanheide, Peters, and Bellotto 2012), navigation (Wu, Claramunt, and Deng 2014) and detection of risk events (Ligozat, Vetulani, and Osinski 2009). Amongst many domains of interest, the analysis of transportation patterns is one of the emerging avenues of research that still deserves the development of conceptual and logical approaches that will favour the analysis of emerging trends at both the global and local levels.

The research presented in this paper introduces a qualitative and formal modelling approach whose objective is to qualify the main movements between two entities in space and time. In order to do so, we take a relative point of view of the movement of two given entities, movement being considered by giving a particular importance on the boundary of the one that might be considered as predominant or as a reference. This specific property is relevant, for example, in indoor spaces when analysing the trajectory of a man with respect to a given room, or to some specific places in a large-scale space.

The modelling framework is applied to the analysis of flight patterns. A moving aircraft has, for example, to cross several airspace boundaries when flying from an origin to a destination. When considering a given

jing.wu@ecole-navale.fr

country it might be worth to observe the qualitative behaviour of a flight with respect to a given country (e.g., is it inside or outside the country airspace? is it leaving or approaching the country airspace?), and also to analyse some emerging patterns. These few examples show the main motivation behind our approach that will be more formally developed in the next sections and illustrated by a case study applied to flight trajectories. The main idea behind the approach is to develop a qualitative model that will favour the analysis of local patterns as suggested above, and also to derive some emerging trends at the regional level. Moreover, we will show that the approach can not only summarize some air transportation patterns, but also can be used to search for possible trajectories in case of missing data.

The remainder of this paper is organized as follows. Section 2 briefly reviews related work oriented to the qualitative modelling of movement. Section 3 introduces the basic principles of our approach. Section 4 presents the Qualitative Trajectory Model with a series of movement primitives between a moving entity and a reference entity, and the conceptual neighbourhood diagram. Section 5 presents an application of the modelling framework to the analysis of real-time flight trajectories. Finally, Section 6 concludes the paper and draws some conclusions.

2. Related work

Despite the recent proliferation of spatio-temporal reasoning approaches, there is still a need for the development of qualitative temporal and spatial reasoning models oriented to the modelling of movements and trajectories. Several authors have proposed a series of conceptual frameworks for representing complex geographic phenomena as a hierarchy of events, processes and state, and where, implicitly, the concept of movement is closely related to a process (Yuan 2001). In the context of this paper, the relative movement of a given entity can be informally defined as a change of some qualitative spatial properties with respect to a reference entity. Explicitly, such a notion of movement has been studied by several qualitative spatial reasoning approaches, which are briefly introduced in this section.

Early spatial reasoning models have been oriented to the modelling of topological relations, such as the *RCC*8 or 9-intersection models (Randell, Cui, and Cohn 1992; Egenhofer and Herring 1991). Galton (1995, 2000) introduced a qualitative theory of movement, where motion is primarily interpreted as a change in position, while moving entities can be rigid or non-rigid. Time is modelled using either instants or intervals with an ordering relation, this being often the case in temporal reasoning. The semantics behind moving entities can be also derived from natural language expressions. Stewart Hornsby and Li (2009) explored how textual documents that contain movement verbs and terms can be mapped to elementary abstractions that include source, destination, route, direction, distance, start time, end time and duration properties. Pustejovsky and Moszkowicz (2011) developed a computational semantics based on a temporal logic for the representation of motion as expressed in natural languages.

In order to model the relative movement between two moving entities considered as moving points, the qualitative trajectory calculus studies the configurations that qualify the relative position in time of two moving points, and identifies some basic movements, such as moving towards or moving away from (Van de Weghe 2004). Kurata and Egenhofer (2007) introduced the $9I^+$ calculus, where the concept of a directed line represents the trajectory of a moving entity. Besides, relative directions and velocity have been also considered by Noyon, Claramunt, and Devogele (2007) that developed a relative-based modelling approach that integrates the concept of location, speed and acceleration to qualify the relative motion of two rigid entities, as also perceived and represented by natural language expressions.

Muller (1998) introduced a modelling framework that combines *RCC*8 relations with a temporal algebra, and derived a theory of motion based on mereo-topology. This algebra gives a set of six motion classes: leave, hit, reach, external, internal and cross, which can be associated to natural language expressions. However, the approach developed is not precise enough to characterize some specific movements where distance between the entities considered matters. Gottfried (2011) modelled the relative movement of pairs of moving, rigid entities by taking into account directional information and relative movement. This generates several atomic motion patterns that hold between two rigid entities, but these entities are considered as primitive points, thus not allowing a study of motion patterns at the local level.

This brief review shows that several qualitative formalisms have attempted to bridge the gap between formal and linguistic descriptions of movement. The research presented in this paper differs from previous approaches in several aspects. First, we take into account the role of the entities' boundaries when observing the relative behaviour of two given entities. This characterizes more precisely the relative spatial configurations and evolution of two given entities. Second, modelling qualitatively and over time the distance between the entities considered extends the reasoning capabilities and favours the identification of a series of possible configurations qualified by natural language expressions.

3. Modelling principles

An important motivation for this research is to develop a qualitative modelling approach oriented to the representation of movement. One of the objectives of the model developed is to take into account how humans represent movement patterns. We consider simply connected planar regions in the Euclidean plane. The model is grounded on two complementary qualitative relations: topological and metrics. Topological relations are based on the *RCC*8 algebra, while metric relations are based on relative distance relations between moving entities.

3.1. Qualitative spatial–temporal model

3.1.1. Qualitative topological relations

Qualitative topological relations describe invariant spatial information under topological transformations. Regarding the categories of regions considered in a two-dimensional space, topological relations can be divided into six groups, that is, point-point, point-line, point-region, line-line, line-region and region-region. As the focus of this paper is moving regions, several region-region topological models can be considered, such as the 9-intersection model (Egenhofer and Herring 1991), calculus-based model (Clementini and Di Felice 1994) and the *RCC* model (Randell, Cui, and Cohn 1992). While the two former models derive topological relations by comparing the intersection of the interior, the exterior and the boundary of different planar regions, the *RCC* model is based on a single primitive relation between spatial regions, the 'connectedness' relation. One variant of the *RCC* model, *RCC*8, uses eight mutually exhaustive and pairwise disjoint relations to describe the topological relations between two spatial regions as follows: disconnected (*DC*), externally connected (*EC*), partial overlap (*PO*), equal (*EQ*), tangential proper part (*TPP*) and its inverse (*TPPI*), and non-tangential proper part (*NTPP*) and its inverse (*NTPPI*). The approach developed retained the *RCC* model, although the other models mentioned above will produce some relatively equivalent reasoning formalisms.

3.1.2. Qualitative distance relations

Qualitative distance relations are significant in many disciplines, such as geography (Tobler 1970), spatial cognition (Talmy 1983) and artificial intelligence (Davis 1989). While quantitative distances are based on pure metrics, qualitative distances often use adverbs such as *close, near* and *far-away*. In order to derive these qualitative distances, the qualitative distance denoted by d between an entity A and a reference entity B at a given time t is modelled as the minimum distance between the boundary of A and the boundary of B. Next, qualitative relations represent whatever the relative location of the entities A and B: whether A is outside, on the boundary or inside B. The basic configurations of two given entities A and B over a given interval of time T are modelled as follows:

- $d_{\text{ext+}}$ denotes that d is continuously increasing outside B over a given temporal interval T (i.e., for all t of T);
- $d_{\text{ext-}}$ denotes that d is continuously decreasing outside B over a given temporal interval T;
- $d_{\text{ext=}}$ denotes that d is constant outside B over a given temporal interval T;
- d_0 denotes that d is null over a given temporal interval T;
- $d_{\text{int+}}$ denotes that d is continuously increasing inside B over a given temporal interval T;
- $d_{\text{int-}}$ denotes that d is continuously decreasing inside B over a given temporal interval T; and
- $d_{\text{int=}}$ denotes that d is constant inside B over a given temporal interval T.

3.2. Neighbourhood-based reasoning

Although the notion of conceptual neighbourhood has been initially introduced by Freksa (1992) and applied to the 13 interval relations defined by the temporal logic of Allen (1983), it has been widely used to exploit monotonicity in qualitative spatio-temporal reasoning. In cases of missing data, incomplete knowledge can be augmented to a disjunction of all possible alternatives in order to derive some possible alternatives. Conceptual neighbourhoods of a given set of spatio-temporal relations, which are usually represented by a conceptual neighbourhood diagram (CND), can be applied to evaluate the possible changes of a relation or to measure the similarity between different relations. The nodes of CND are populated by atomic relations applied for example to either regions or intervals. The edges that connect these nodes denote the possible continuous transformations between these relations.

4. Qualitative reasoning over movements

4.1. Qualitative trajectory model

Based on the qualitative *RCC*8 topological relations and the qualitative distance d, the qualitative trajectory model provides a set of movement primitives (*PriMv*) that support the qualitative representation of movement between a moving entity A and a reference entity B over a time interval T.

$$PriMv(A, B) \equiv Holds(TOP_{RCC}, d, T) \tag{1}$$

where $TOP_{RCC} \in \{DC, EC, PO, EQ, TPP, TPPI, NTPP, NTPPI\}$, $d \in \{d_{ext+}, d_{ext-}, d_{ext=}, d_0, d_{int+}, d_{int-}, d_{int=}\}$.

The movement primitives are classified into three categories according to the relative location of a moving entity with respect to a reference entity over a given temporal interval T, that is, outside, on the boundary, or inside a reference entity.

4.1.1. Outside a reference entity

When a moving entity A is disconnected from a reference entity B over a given temporal interval T, three categories of movements can be distinguished: *Approach* (*AP*), *Leave* (*LV*) and *AroundOutside* (*AO*). More formally, the movement primitives identified are as follows:

- *Approach*: A moving entity A is approaching a reference entity B over a time interval T, as shown in Figure 1(a). For all $t \in T$, DC holds and the qualitative distance d is decreasing outside B over T:

$$Approach(A, B) \equiv Holds(DC, d_{ext-}, T) \tag{2}$$

- *Leave*: A moving entity A is leaving a reference entity B over a time interval T, as shown in Figure 1(b). For all $t \in T$, DC holds and the qualitative distance d is increasing outside B over T:

$$Leave(A, B) \equiv Holds(DC, d_{ext+}, T) \tag{3}$$

- *AroundOutside*: A moving entity A is either moving around or static outside a reference entity B over a time interval T, as shown in Figure 1(c). For all tT, DC holds and the qualitative distance d is constant outside B over T:

$$AroundOutside(A, B) \equiv Holds(DC, d_{ext=}, T) \tag{4}$$

4.1.2. On the boundary of a reference entity

When an entity A is moving on the boundary of a reference entity B over a time interval T, five different categories of movements are identified: *Touching* (*TI*), *Overlapping* (*OI*), *CoveringBy* (*CB*), *Covering* (*CI*) and *Equalling* (*EI*), in which *CB* and *CI* are a pair of inverse movements. More formally, the movement primitives identified are as follows:

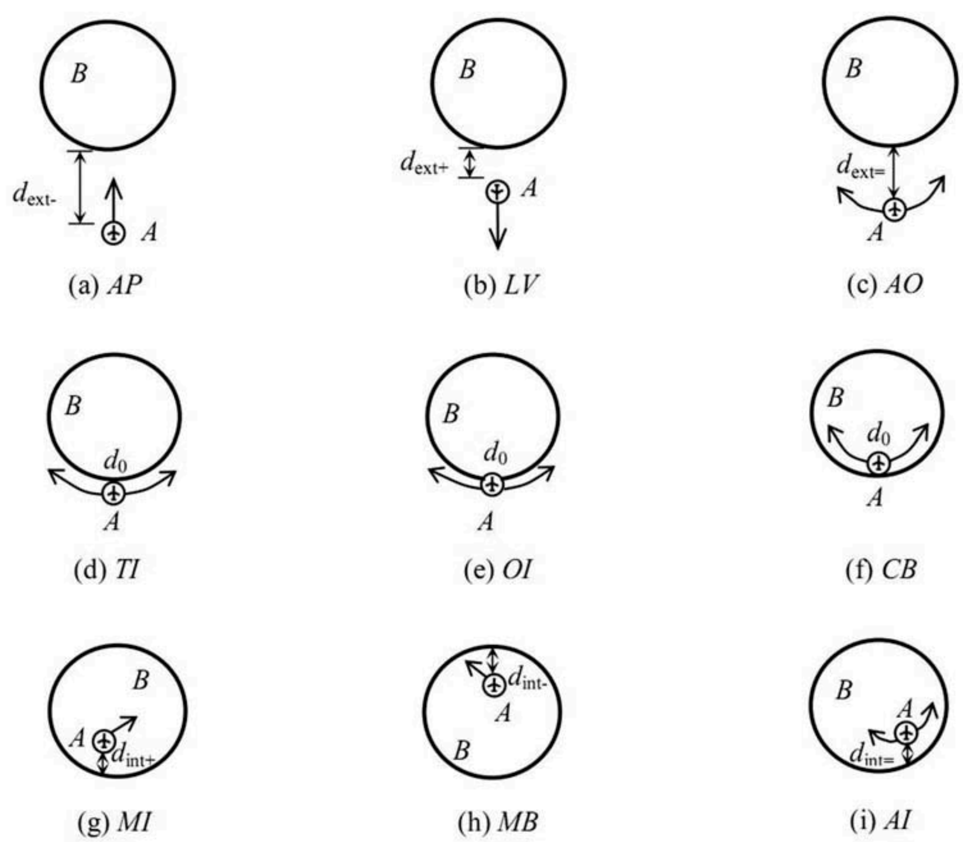

Figure 1. Movement configurations.

- *Touching*: A moving entity A is touching outside the boundary of a reference entity B over a time interval T, as shown in Figure 1(d). For all $t \in T$, *EC* holds and the qualitative distance d is d_0 over T:

$$Touching(A,B) \equiv Holds(EC, d_0, T) \tag{5}$$

- *Overlapping*: A moving entity A is overlapping the boundary of a reference entity B over a time interval T, as shown in Figure 1(e). For all $t \in T$, *PO* holds and qualitative distance d is d_0 over T:

$$Overlapping(A,B) \equiv Holds(PO, d_0, T) \tag{6}$$

- *CoveringBy*: A moving entity A is touching inside the boundary of a reference entity B over a time interval T, as shown in Figure 1(f). For all $t \in T$, *TPP* holds and the qualitative distance d is d_0 over T:

$$CoveringBy(A,B) \equiv Holds(TPP, d_0, T) \tag{7}$$

- *Covering*: A moving entity A is touching outside the boundary of a reference entity B over a time interval T. For all $t \in T$, *TPPI(A, B)* holds and the qualitative distance d is d_0 over T:

$$Covering(A,B) \equiv Holds(TPPI, d_0, T) \tag{8}$$

- *Equalling*: A moving entity A equals a reference entity B over a time interval T. For all $t \in T$, *EQ* holds and the qualitative distance d is d_0 over T:

$$Equalling(A,B) \equiv Holds(EQ, d_0, T) \tag{9}$$

4.1.3. Inside a reference entity

When an entity A moves inside a reference entity B over a time interval T, there are six categories of movements: *MovetoInterior* (*MI*), *MovetoBoundary* (*MB*), *AroundInside* (*AI*), *EmbracingMoveOutside* (*EMO*), *EmbracingMovetoBoundary* (*EMB*) and *EmbracingAroundOutside* (*EAO*), in which *MI* and *EMO*, *MB* and *EMB*, *AI* and *EAO* are three pairs of inverse movements, respectively. Those disjoint configurations are derived from six relative distance behaviours over a given temporal of time: d_{int+}, d_{int-}, $d_{int=}$, d_{ext+}, d_{ext-} and $d_{ext=}$. Similarly the spatial configurations valid are *NTPP* (i.e., when an entity A is inside a reference entity B) and *NTPPI* (i.e., when an entity B is inside a reference entity A). More formally, the movement primitives identified are as follows:

- *MovetoInterior*: When a moving entity A is *NTPP* to a reference entity B and leaving the boundary of B over a time interval T, we say that A is moving to the interior of B, as shown in Figure 1(g). For all $t \in T$, *NTPP* holds and the qualitative distance d is increasing inside B over T:

$$MovetoInterior(A,B) \equiv Holds(NTPP, d_{int+}, T) \tag{10}$$

- *MovetoBoundary*: When a moving entity A is *NTPP* to a reference entity B, and A is moving to the boundary of B over a time interval T, we say that A is moving to the boundary of B, as shown in Figure 1(h). For all $t \in T$, *NTPP* holds and the qualitative distance d is decreasing inside B over T:

$$MovetoBoundary(A,B) \equiv Holds(NTPP, d_{int-}, T) \tag{11}$$

- *AroundInside*: When a moving entity A is *NTPP* to a reference entity B, and A is either moving around the boundary of B or static relative to B over a time interval T, we say that A is around inside B, as shown in Figure 1(i). For all $t \in T$, *NTPP* holds and the qualitative distance d is constant inside B over T:

$$AroundInside(A,B) \equiv Holds(NTPP, d_{int=}, T) \tag{12}$$

- *EmbracingMoveOutside*: When a moving entity A is *NTPPI* to a reference entity B, and A is moving outside B over a time interval T, we say that A is embracing B and moving outside B. For all $t \in T$, *NTPPI* holds and the qualitative distance d is increasing outside B over T:

$$EmbracingMoveOutside(A,B) \equiv Holds(NTPPI, d_{ext+}, T) \tag{13}$$

- *EmbracingMovetoBoundary*: When a moving entity A is *NTPPI* to a reference entity B, and A is moving to the boundary of B over a time interval T, we say that A is embracing B and moving to the boundary of B. For all $t \in T$, *NTPPI*(*A*, *B*) holds and the qualitative distance d is decreasing outside B over T:

$$EmbracingMovetoBoundary(A,B) \equiv Holds(NTPPI, d_{ext-}, T) \tag{14}$$

- *EmbracingAroundOutside*: When a moving entity A is *NTPPI* to a reference entity B, and A is either moving around or static outside of B over a time

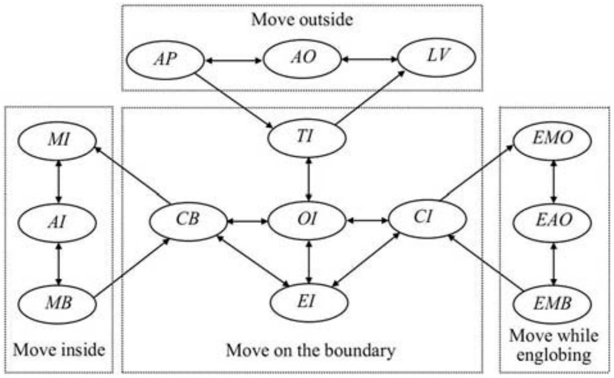

Figure 2. Conceptual neighbour diagram.

interval T, we say that A is embracing B and moving around outside B. For all $t \in T$, $NTPPI(A, B)$ holds, and the qualitative distance d is constant outside B over T:

$$EmbracingMovetoBoundary(A, B) \equiv Holds(NTPPI, d_{ext-}, T) \tag{15}$$

4.2. Conceptual neighbourhood diagram

The movement of an entity can be qualitatively modelled as a sequence of neighbouring spatial configurations which hold for adjacent time intervals. A conceptual neighbourhood diagram (CND) provides additional reasoning capabilities to anticipate future movements and to develop reasoning mechanisms in case of incomplete knowledge. Two movements are conceptual neighbours if there is a continuous transition between them without any intermediary movement. The conceptual transitions that can be derived from primitive movements identified in the previous section are shown in Figure 2. A bidirectional arrow connecting two relations indicates that each relation can be directly transformed into the other by a continuous transition. A one-way arrow shows the direction of continuous transition between the two relations. Consider, for example, the qualitative distinction between AP and MI. A change from AP to MI must pass from the movements on the boundary, since a qualitative distance cannot change directly from d_{ext-} to d_{int+} without passing by d_0.

5. Air flight case study

The modelling approach provides a representation of movement based on an integration of qualitative topological and distance relationships. It gives a relatively intuitive set of modelling primitives that support the qualitative representation of movement that can be applied to a large extent of applications. Let us consider, for example, the case of flight trajectories, a representative example of the transportation domain, and where thousands of trajectories are achieved on a daily basis worldwide. With the systematic development of GPS positioning systems in all aircrafts, and the real-time broadcast of flight trajectories to specialized services, thanks to the automatic dependent surveillance-broadcast (ADS-B) transponder system, multilateration systems (MLATs) and data provided by the Federal Aviation Administration (FAA) in the United States, for instance, a lot of flight real-time tracking systems are nowadays available. The availability of flight trajectories data provides a lot of opportunities for reasoning, searching for trends and some specific behaviours. Our modelling approach is applied to a series of flight trajectories at the regional level in order to derive some significant patterns in space and time, the objective being to provide a global view of the flights related to some selected countries of interest. The different cases identified will be qualified by primitive movement configurations; the case of missing data is also taken into account in order to show the applicability of the conceptual neighbourhood reasoning mechanisms.

5.1. Flight trajectory representation

The modelling approach is applied on top of the aircraft tracking system Flightradar24, which provides real-time information of flight trajectories at the worldwide level (http://www.flightradar24.com/48.86,2.35/7). Let us consider a sample of flight trajectories related to Ireland. A series of primitive movement configurations are identified at a given time instant and are illustrated as follows (Figure 3):

(1) The flight KLM644 is flying close to Ireland, this illustrates the movement configuration AP.
(2) The flight EIN84L is leaving Ireland, this illustrates the movement configuration LV.
(3) The flight PI103 is flying along the boundary of Ireland, this illustrates the movement configuration TI.
(4) The flight STK22GL is overlapping the boundary of Ireland, this illustrates the movement configuration OI.
(5) The flight EZY29CN is touching inside the boundary of Ireland, this illustrates the movement configuration CB
(6) The flight ROU1909 is flying to the centre of Ireland from the Dublin airport, this illustrates the movement configuration MI.

Figure 3. Flight trajectory configurations.

(7) The flight RYR606E is flying to the southeast boundary of Ireland from the Dublin airport, this illustrates the movement configuration *MB*.

Although the information on the flight origins and destinations surely provides some useful data for transportation planning, the analyses of the spatio-temporal trends that emerge for a given country are likely to produce some information of interest. We suggest analysing these patterns by taking into account the way the airspace is occupied by a series of flights at different times of the day and the week. The different primitive trajectory configurations related to Ireland are analysed every half an hour in the morning, afternoon, evening and midnight on a weekday and a Saturday. For instance, Figure 4 shows some noticeable differences in the specific example of Ireland. A general trend is that air traffic within and close to Ireland decreases from high values in the mornings to lower values in the evenings. Air traffic is also higher in the weekend. The number of flights either closing or leaving Ireland (*AP* and *LV*) as well as the number of flights close to the boundaries of Ireland (*TI*, *OI* and *CB*) is, overall, relatively high. Other primitive or aggregated motion patterns as well as some uncommon behaviours can be similarly explored.

5.2. Flight trajectory analysis

A flight trajectory can be regarded as a motion process and represented as a sequence of trajectory primitives that act as the basic units for the modelling approach. Therefore, a trajectory can be modelled as a string of predicates, where each predicate represents a trajectory primitive. Let us consider, for example, the flight AFR77, which is flying from Los Angeles to Paris, and whose trajectory passes through Ireland. This flight trajectory can be decomposed into the following movement

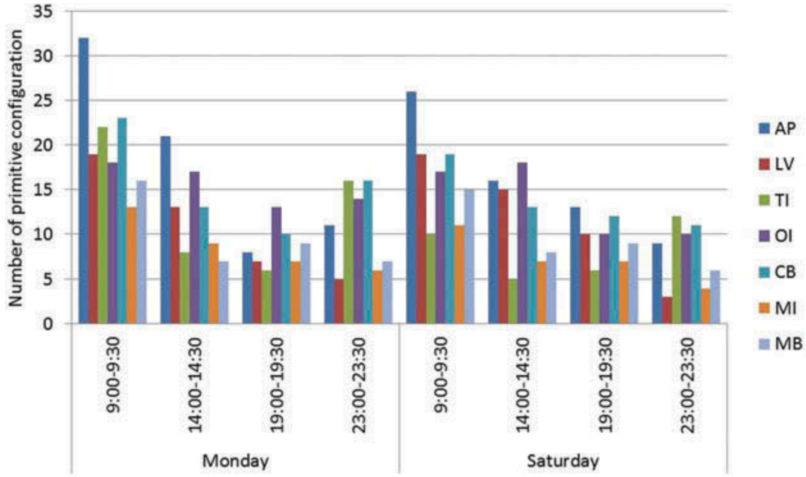

Figure 4. Primitive trajectory configurations over the example of Ireland.

primitives (Figure 5). The semantics of the motion event *PassThrough* can be modelled as:

$$PassThrough(t_1) \equiv \mathrm{events}(AP_{t_1t_2} \wedge TI_{t_2t_3} \wedge OI_{t_3t_4} \wedge CB_{t_4t_5} \wedge MI_{t_5t_6} \wedge MB_{t_6t_7} \wedge CB_{t_7t_8} \wedge OI_{t_8t_9} \wedge TI_{t_9t_{10}} \wedge LV_{t_{10}})$$

where t_i ($i \in [1, 10]$) are the start time when the primitive movements *AP, TI, OI, CB, MI, MB, CB, OI, TI* and *LV* take place, respectively, with $t_1 < t_2 < \ldots < t_{10}$.

For instance, the semantics of the flight trajectories *Arrive* and *Depart* can be represented as follows:

$$Arrive(t_A) \equiv \mathrm{events}(AP_{t_1t_2} \wedge TI_{t_2t_3} \wedge OI_{t_3t_4} \wedge CB_{t_4t_5} \wedge MI_{t_5t_A} \wedge AI_{t_At_{A+\delta}})$$

where t_A is the arrival time of the flight, t_1, t_2, t_3, t_4, t_5 are the start times when the primitive movements *AP, TI, OI, CB, MI* take place, respectively, with

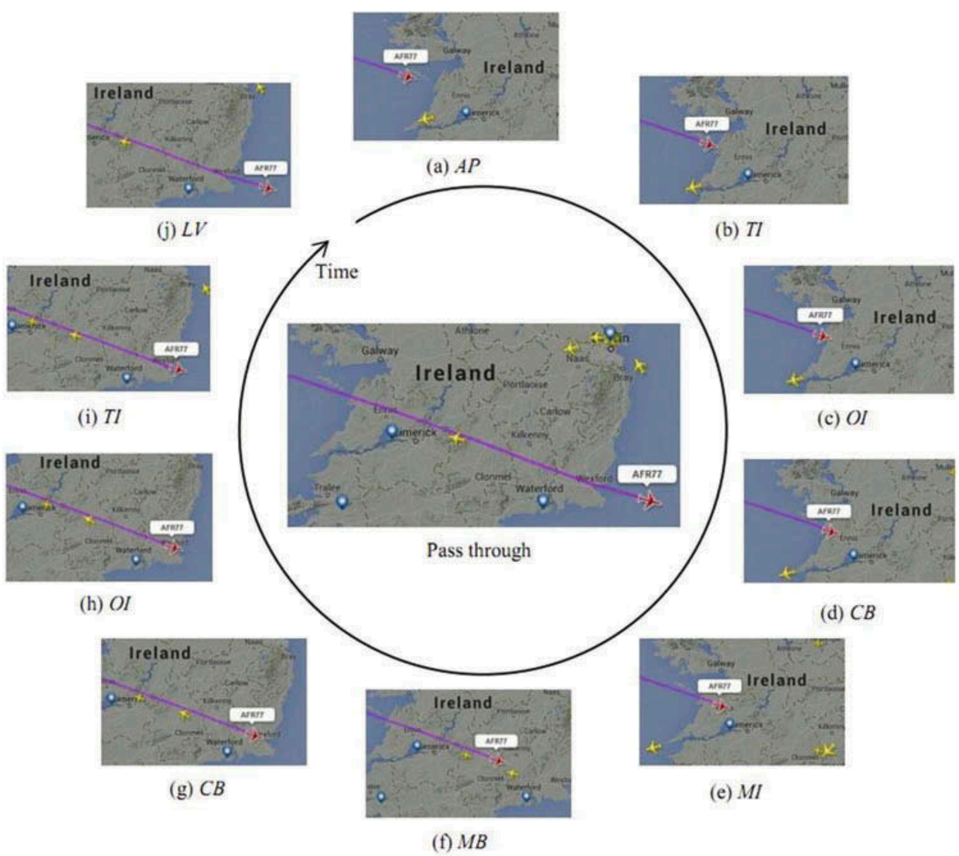

Figure 5. The sequence of motion event *PassThrough*.

$t_1 < t_2 < t_3 < t_4 < t_5 < t_A$, δ is the time interval when the flight stays in the airport before the next take-off, this being approximated as a *AI* primitive movement.

$$Depart(t_D) \equiv \text{events}(AI_{t_{D-\delta}t_D} \wedge MB_{t_Dt_1} \wedge CB_{t_1t_2} \wedge OI_{t_3t_4} \wedge TI_{t_3t_4} \wedge LV_{t_4t_5})$$

where t_D is the departure time of the flight, t_1, t_2, t_3, t_4, t_5 are the end times when the primitive movements *MB, CB, OI, TI* and *LV* take place, respectively, with $t_D < t_1 < t_2 < t_3 < t_4 < t_5$, δ is the time interval when the flight stays in the airport before it takes off, this being again approximated as a *AI* primitive movement.

The trajectory events above illustrate the potential of the modelling approach as applied to some illustrative examples in the case of Ireland. Indeed, a frequency table of flight departure and arrival times can identify some movement patterns at the airport levels (i.e., departures and arrivals), but our approach also provides a slightly different information on flights approaching and leaving a given country and also the ones that pass through (i.e., aggregated process *PassThrough*), thus providing complementary information on trajectory patterns. Let us compare the number of flights that *Arrive* at the airports of Ireland and Iceland, *Depart* from their airports, and *PassThrough* the two countries during four different time intervals in a day from Monday to Sunday, as shown in Figure 6. It appears that the numbers of trajectory events are a little higher on weekdays than on weekends. Friday is also the busiest day in a week, which has more flights that *Arrive* and *Depart* in both countries. Not surprisingly, Ireland has an air traffic much more important than the one of Iceland. Compared with the above three trajectory events, the number of flights which *PassThrough* is inconstant. The busiest time above Ireland is from 7:00 to 9:00 in the morning, when around 60% of the flights *PassThrough* its airspace, except on Thursday, when the number decreases to 47%. However, in Iceland, there are few flights that *PassThrough* from 7:00 to 9:00, while the peak time is from 12:00 to 14:00, especially on Wednesday, with 90% of the flights above Iceland passing through the country. Overall, it also appears that the motion process *PassThrough* is much more important in Ireland than in Iceland.

5.3. Trajectory reasoning

The modelling approach can be also applied to the prediction of the possible trajectory of a flight when, for example, the geo-location signal is missing due to some technical or emergency circumstances. Let us consider the case illustrated in Figure 7, L_0 is an incomplete flight trajectory with P_0 as its last recorded sample point. Let us also assume that the positioning signal is lost when the flight is in the airspace of Iceland. Only one additional sample point P_1 outside the airspace is known and recorded. Because the movement patterns at P_0 and P_1 are *MI* and *LV*, respectively, four possible trajectories can be derived according to the conceptual neighbourhood diagram:

- Trajectory P_0P_1: The flight *PassThrough* Iceland directly without any stop, that is, a sequence of trajectory primitives: $MI \wedge MB \wedge CB \wedge OI \wedge TI \wedge LV$.
- Trajectory $P_0A_1P_1$: The flight stopped at Akureyri airport (A_1) and then took off again leaving Iceland, that is, a sequence of trajectory primitives: $MI \wedge MB \wedge AI \wedge MI \wedge MB \wedge CB \wedge OI \wedge TI \wedge LV$.
- Trajectory $P_0A_2P_1$: The flight stopped at Egilsstadir airport (A_2) and then took off again leaving Iceland, that is, a sequence of trajectory primitives: $MI \wedge MB \wedge AI \wedge MB \wedge CB \wedge OI \wedge TI \wedge LV$.
- Trajectory $P_0A_1A_2P_1$: The flight stopped at Akureyri airport first and then Egilsstadir airport, that is, a sequence of trajectory primitives: $MI \wedge MB \wedge AI \wedge MI \wedge MB \wedge AI \wedge MB \wedge CB \wedge OI \wedge TI \wedge LV$.

This illustrative example shows how the conceptual neighbourhood diagram principles can be applied to predict the possible trajectories of a given flight. Other applications of the CND, such as the suggestion of trajectory options to a flight in an emergency situation, are yet to be explored.

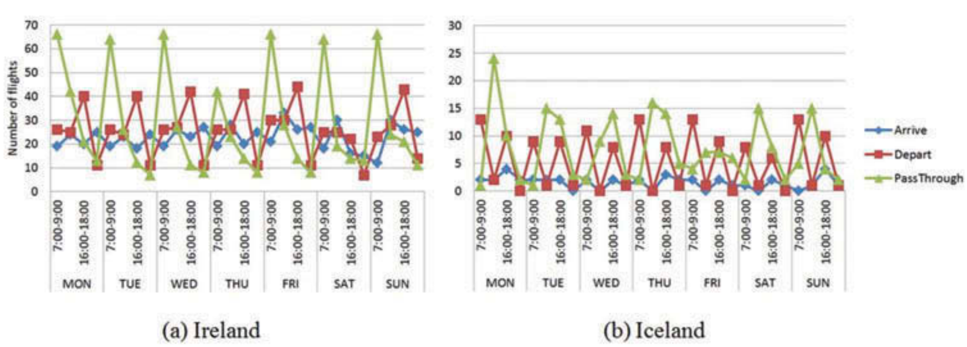

Figure 6. Comparison of trajectory events.

Figure 7. Possible evolutions of a flight trajectory.

6. Conclusion

This paper introduces a modelling approach for the representation of primitive movements between geographical entities. The model is based on two complementary qualitative primitives: *RCC*8 relations and qualitative distances. The framework developed favours the identification of a series of movement primitives that qualify the relative movements of two evolving entities, as well as movement transitions. The modelling approach is applied to the analysis of flight trajectory patterns. We showed that flight trajectories can be analysed at different levels of granularity. The model can either track a given trajectory and even simulate the possible next states of a given flight or, at the aggregated level, characterize the air trajectory patterns for a given region of interest. The model is preliminary and still should be extended by the integration of additional qualitative and quantitative properties such as direction relations or velocities. Most of the analyses developed so far in our paper have been oriented to a two-dimensional geographical space. The integration of a three-dimensional space might offer additional opportunities, for example, to analyse the behaviour of a flight in an approach or take-off procedure. Further theoretical work will be also oriented to the study of sequences of movement and patterns that emerge from a group of moving objects. The modelling approach can also act as a reference algebra that can be implemented within a GIS software as either primitive functions or at the data manipulation level (e.g., integrated within the spatial query language). One of the objectives considered by of our further work is to develop an implementation of these primitive trajectory processes on top of a public domain GIS software.

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ORCID

Jing Wu http://orcid.org/0000-0002-8014-7330

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