LOGICAL CONSISTENCY FOR VAGUE SPATIOTEMPORAL OBJECTS AND RELATIONS

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KEY WORDS: spatio–temporal vagueness, spatio–temporal databases, spatial data quality, logical consistency, integrity constraints

ABSTRACT:

Vagueness is often considered as an inherent property of spatiotemporal phenomena. In order to reduce this vagueness, integrity constraints should be defined to improve logical consistency of spatiotemporal databases. However, existing constraints are not *adapted* to control logical consistency of *vague* spatiotemporal objects because they are initially defined for crisp (or *non–fuzzy*) objects. When applied to *vague spatiotemporal objects or relations*, such constraints would reject a large amount of data because they don't authorize *partial consistency* in the database. In this paper, we present an approach to define integrity constraints which would be able to take into account spatiotemporal vagueness. We define three categories of constraints - semantic, temporal and spatial - accordingly to the nature of vagueness specific to each one. Then, we explain how these constraints could permit partial consistency of vague spatiotemporal objects and relations by using fuzzy logic.

1. INTRODUCTION

In spatial databases, integrity constraints are used (1) to insure logical consistency, (2) inform about quality level of the database and (3) reduce vagueness. Different properties such as topological criteria (e.g. *line simplicity*), semantic aspects (e.g. *a house has one level at least*) and spatiotemporal relationships (e.g. "*agricultural spreading parcels should be disjoint or adjacent in a spreading period")* (an *agricultural spreading parcel* is an agricultural area in which manures were sown to improve t agricultural productivity) should be controlled through these constraints (Souris, 2006). In general, integrity constraints are *binary* rules based on a crisp (or *non–fuzzy*) description of the space. In effect, all data which don't completely respect a rule defined by an integrity constraint should be rejected. For ill-defined spatiotemporal objects (e.g. *air pollution zone*, *forest stand*, etc.), vagueness is an inherent property which may characterize every data stored in the database. For example, let an integrity constraint saying that "a vague spatial object *A* should *overlap* a vague spatial object *B*". In this constraint, spatial objects can overlap each other '*a little bit*', '*somewhat*' or '*completely*' because there is an uncertainty about the total or a part of the object geometry. *Binary* integrity constraints are not appropriate to control logical consistency of this kind of data because they are not able to quantify this uncertainty. Frank (2001) introduces the concept of partial consistency to deal with inherently vague data (e.g. *a forest stand*). Basing on this concept, our main objective is to categorize integrity constraints in the context of vague spatiotemporal databases. In order to achieve this goal, we propose a taxonomy of spatial and temporal vagueness (cf. section 6).

The paper is organised as follows. In section 2, we briefly present some related works to the problem of increasing logical consistency of vague spatiotemporal objects. In section 3, we present fuzzy logic principles. Then, we present some definitions related to vagueness and its different levels and we propose a definition of vague spatiotemporal objects respectively in the sections 4, 5 and 6. In section 7, we explain the link between partial consistency and integrity constraints in the context of vague spatiotemporal phenomena. Then, we propose a categorization of integrity constraints according to our vagueness taxonomy. Section 8 presents the conclusions and perspectives of this work.

2. RELATED WORKS

Smith (1994) distinguishes two categories of spatial objects: *fiat* objects (i.e. *ill-defined objects*) (e.g. *forest stand, pollution zone*) and *bona fide* objects (i.e. *well-defined objects*) (e.g. *building, road*). For bona fide objects, the vagueness problem has a probabilistic nature and refers the errors in the position or in the values of some attributes. However, vagueness for fiats objects can also correspond to imprecision and fuzziness in the boundaries (e.g. *pollution zone*) or in the classification (e.g. *different components of an historic building*). Fiats objects are conventionally approximated in the databases to be represented like bona fide objects (e.g. *by tracing crisp boundaries for an air pollution zone*). This approximation is a sufficient solution when data will be used to satisfy simple transactional needs (e.g. displaying cartographic and thematic data). Nowadays, spatial data are used in decisional information systems where the need is to analyse a great size of data in order to improve the quality of decisions in very sensible domains like ecological problems. Thus, the reliability of data is very influent on the decision quality. Therefore, the approximation of vague spatiotemporal objects and relations is not appropriate in particular when decisional needs should be achieved. For that, specific models, especially for geometric and temporal aspects, should be used to manage vague spatiotemporal phenomena.
The geometry is the spatial description of the form and position of an object (i.e. an entity of the world). An object can be represented by a point, a line, a region or a combination of these primitives. The position of the object can be expressed in

latitude/longitude or any other coordinate system. For *fiat* objects, crisp forms cannot be used because they don't present a reliable description of the reality. For example, there is a need to store transition zone of a *forest stand* in order to improve its management. When crisp forms are used, it is also possible to have the need to manage vagueness of object position at an instant *t*.

In general, vagueness in geometry can be represented through three categories of models. First, exacts models present an extension of crisp description of space (Clementini and Di Felice, 1997; Cohn and Gotts, 1996; Erwig and Schneider, 1997). Second, fuzzy models are those based on fuzzy logic to quantify vagueness (e.g. (Burrough, 1996; Dilo et *al.,* 2005; Edwards, 1994)). Third, probabilistic models are based on a probabilistic approach to model position and attributes errors (Burrough, 1996; Pfoser et *al.,* 2005). In order to allow modelling of spatiotemporal vagueness, Shu et *al.* (2003) extend MADS specifications to model two kinds of vague spatial objects: (1) *random spatial object (i.e. vagueness is just about the position of the object)* and (2) *fuzzy spatial object (i.e. the form of the object is fuzzy and it present large boundaries)*. Yazici et *al.* (2001) propose a more developed extension of UML formalism by modelling spatial and temporal vagueness of an object. In the same way, spatial relation between crisp or vague spatial objects can be vague (e.g. "near", far", "in the north of", ect.). Dubois et *al.* (2003) studied the modelization of fuzzy temporal and spatial relations through fuzzy logic. Pfoser et *al.* (2005); Dilo et *al.* (2005) presented respectively different methodologies based on fuzzy logic to store and manipulate vague spatial objects and relations. However, modelling vague spatiotemporal relations requires the control of topological properties, semantic aspects and temporal properties of such objects and relations through adapted integrity constraints. Therefore, we interest to the control of logical consistency of data in such models in order to increase their reliability and utility.

3. FUZZY LOGIC

Fuzzy logic (Zadeh, 1965) is a rigorous mathematic approach useful to model ill-defined concepts, such as "*young person*" or "*small person*". This theory is an *extension* of boolean logic where the adherence of universe elements is binary {0, 1}. In the contrast to binary logic, the elements of the universe do not have a strict membership (i.e. *0 or 1*) to the concept of interest but rather one *membership degree* (i.e. a value between *0* and *1*): more this value is close to 1, more the membership degree is high. A fuzzy subset is formally expressed as next:

$$\tilde{A} = \left\{ \left(x, \mu_{\tilde{A}}(x) \right) / \, x \in X \right\} \qquad (1)$$

Where $\mu_{\tilde{A}} : X \to [0,1]$ is the membership function permitting to compute membership degree of an element of the universe *X* to the fuzzy subset *A*. In spatial databases domain, several approaches (e.g. (Dilo et *al.,* 2005; Hwang and Thill, 2005; Yongming and Sanjiang, 2004)) adopted the theory of the fuzzy subsets to resolve different modelling problems. For example, Dilo et *al.* (2005) used the fuzzy subsets to define the vague geometric primitives (*point, line* and *region*) and to express the topological relations between vague spatial objects. In the same way, fuzzy logic can be used to control partial consistency of data. In the next section, we present vagueness taxonomy and kinds of inconsistencies in spatiotemporal databases.

4. VAGUENESS TAXONOMY

Cohn and Gotts (1996) considered the concept of vagueness as the root of different kinds of imperfection that could characterise a spatiotemporal phenomenon. The concept of vagueness is sometimes used as a synonym of the *fuzziness* (e.g. (Duckam et *al.*, 2003)) which could characterise boundaries of some spatial objects. However, the vocation of the term "*vagueness*" is more general and cannot be reduced to boundaries fuzziness (Cohn and Gotts, 1996). For some composed geometries, existence of some components is more certain than some others. For example, the existence of some road segments in the itinerary of an historic personage is uncertain. In addition, the vagueness can characterise just the position and not the form of the object. For example, an historic monument has a known form but its position is vaguely known. Thus, it can be represented in different positions with different possibilities. For that, vagueness is the root of our taxonomy and it corresponds to an inherent property of the world or of the knowledge about this world. In the rest of paper, the term *uncertainty* can be used as a synonym of the term *vagueness*.

Different forms of vagueness could characterise spatiotemporal data such as imprecision, inaccuracy, fuzziness and inconsistency. First, imprecision results from complexity of geographic phenomena and/or limitations of measurement instruments. It corresponds to dispersion around a mean value (Mowrer, 1999). Second, accuracy is the difference between the stored value and another value admitted as true. Third, fuzziness is an inherent property of some of objects which don't have well-defined boundaries (e.g. *forest stand*, *lake*, *etc*.) or the existence of some of its components is uncertain (e.g. *components of a historic monument*). Finally, inconsistency arises when the data violates spatial (e.g. an arc intersects itself) or temporal model (e.g. an instant is placed out of the time axis) properties. Most inconsistency problems have a semantic nature and refer two or more incoherent values in the data set (e.g. the following observations are incoherent '*the population of a great town should be greater than 5 millions*', '*Montreal contains three millions persons*' and '*Montreal is a great town*'). The notion of inconsistency is fundamental in this work because we study its specificities for inherently vague spatiotemporal phenomena where the spatial, the temporal and the semantic aspects are modeled differently to the crisp case.

According to Bédard (1987), vagueness appears differently depending on the abstraction level and the spatial object property. The next section presents these different levels of vagueness.

5. VAGUENESS LEVELS

Bédard (1987) classified vagueness which affects spatial databases in four fundamental levels. First, vagueness in *conceptual level (or first order)* refers the object or relation definition fuzziness (e.g. being or not being such an object?) or the categorisation fuzziness (e.g. being a house *X* of type *A* or type *B*?). Second, vagueness in *descriptive level (or second order)* occurs when the definition of a thematic attribute is fuzzy (e.g. a descriptive attribute "*vulnerability*" has the next fuzzy definition: "*the degree of sensibility of an object to the fire*") and/or some values taken by this attribute are vague (i.e. imprecision for quantitative values and fuzziness for qualitative values). Third, the vagueness in *spatiotemporal level (third order) arises* when the object has (1) a fuzzy geometry (e.g. *a forest stand*), (2) a fuzzy temporality (e.g. *a precipitation period*) or (3) qualitative values for some spatial attributes (e.g. the attribute called "surface" can have the following values: "*little*", "*medium*" and "*great*"). In addition, vagueness can correspond to imprecision for quantitative values describing spatiotemporal object reference (e.g. *area* or *perimeter*). In this level, we can also speak about *positional vagueness* when there is a difficulty to localise the object in the space or/and in the time (e.g. *the position of a moving object at an instant t*). Fourth, *meta-uncertainty* (or *fourth order*) refers the degree of knowledge about the preceding vagueness and it can be called "*uncertainty about uncertainty"*. For example, the information saying that "*the precision of data is +-3m*" reduces the ignorance about the precision of data and helps to improve use of data. Basing on this classification, we propose a definition of vague spatiotemporal object or relation.

6. WHAT IS A VAGUE SPATIOTEMPORAL OBJECT?

Three aspects of vagueness could characterise the description of any spatiotemporal object. Indeed, the *description vagueness* of a spatiotemporal object is the combination of vagueness occurring *in conceptual*, *descriptive* and *spatiotemporal levels*. First, conceptual vagueness refers the fuzziness of the *identification* or the *categorization* of the object or relation. Second, descriptive vagueness arises when there is fuzziness in attributes definition or in attributes values (i.e. *for qualitative values*) or also an imprecision of *quantitative values* (cf. figure 1). Third, spatiotemporal vagueness refers (1) the fuzziness of the form (e.g. fuzziness boundaries or uncertainty about the existence of some components of the object), (2) the vagueness of the position of the object or the relation (i.e. the imprecision or the uncertainty about the spatial extension of the object at an instant t), (3) the temporal fuzziness (i.e. the existence of the object cannot be precisely known) or (4) the vagueness of the temporality position (i.e. the problem to localise the temporality of the object on the time axis).

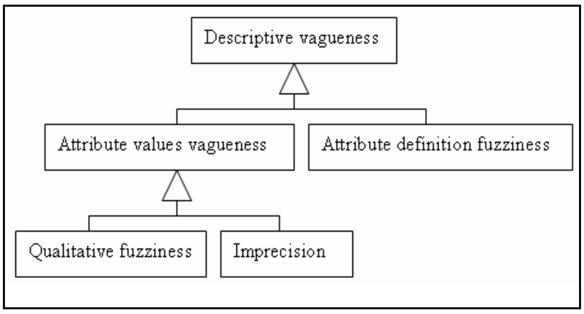


Figure 1. Descriptive vagueness

6.1 Spatiotemporal vagueness

At the spatiotemporal level, vagueness can characterise geometry or temporality of the object or relation. According to the definition of the object geometry, we distinguish two categories of geometry vagueness: *fuzzy geometries and positional vague geometries.* For fuzziness case, we distinguish three fuzzy geometric primitives: *fuzzy point*, *fuzzy line* and *fuzzy region*. Since fuzziness can be a problem of boundaries or of classification (i.e. membership of some components to an object geometry), then fuzzy geometries can exist in (1) a *concentric configuration* or in (2) an *aggregative configuration*. For regions and some cases of lines (cf. figure 4 (the cases *a* and *c*)), *concentric configuration* is made up by a *kernel* surrounded by *a transition zone* which replaces conventional limits. In the case of points and some cases of lines (i.e. lines in a partition of fuzzy regions), these primitives are called fuzzy whether they belong to the broad boundaries of fuzzy modeled objects (cf. figure 3 and figure 4 (case b)). Also, a fuzzy geometry can appeared as an *aggregation* of conventional points, lines or regions distributed on two subsets: (1) a *kernel* (i.e. *certain part of the geometry*) and (2) an *uncertain part* (cf. figure 3). Aggregative configuration expresses another kind of fuzziness where the geometry of the object is made up by a set of primitives where some of them don't surely represent the object (e.g. the membership of one segment to the itinerary of a criminal is inferior to 1 (cf. figure 4)). *Positional vague geometries* occur when the vagueness characterises only the position (i.e. and not the form) of the object because there is a measurement imprecision or a lack of knowledge about the *precise* location of the object (Cohn and Gotts, 1996; Yazici et *al.*, 2001). Since forms of objects are well-known (e.g. an historic building), a positional vague geometry is stored in the database with the same form like crisp geometry. However, a *positional vague geometry* should be associated to a possibility which reflects the uncertainty of the object position. For example, the position of a vehicle at an instant *t* can be modeled as a *positional vague point*. Fuzzy and positional vague primitives can be used in a *simple*, *multiple*, *alternative* or *complex* geometries (Bédard et *al.*, 2004) (cf. figure 2). Formally, the geometry of a vague spatiotemporal object can be defined as a fuzzy subset (cf. section 3).

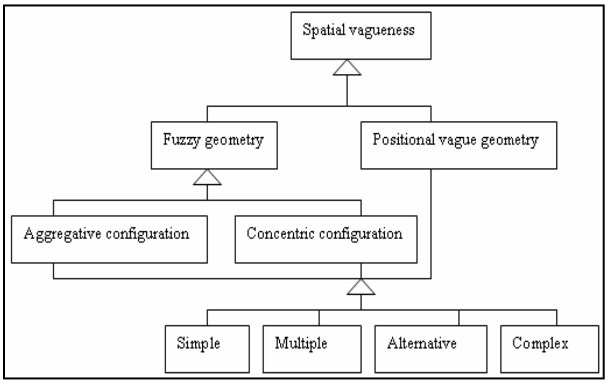


Figure 2. Spatial Vagueness

6.1.1 Vague point: a crisp point is the 0-dimesional geometric primitive which represents a known position (OGC, 2005). A crisp point doesn't have any boundary but it can be a part of a line boundaries. According to the categorization presented in the figure 2, a vague point can be *positional vague, fuzzy concentric* or *fuzzy aggregative*. First, a *positional vague point* may model an uncertain position of an object (e.g. the possibility of the vehicle to be at the position *P1* is *0.6*). Second, a *fuzzy point* could exist in two configurations presented in figure 3. First, the *fuzzy concentric configuration* refers the situation where an instance of the object is an ill-known point in a specific zone. Second, *fuzzy aggregative configuration* refers a set of conventional points subdivided into two subsets: *the kernel* (i.e. *black points in the example*) and the *uncertain part*. For example, the set of places visited by an historic personage in one town can be modeled as an aggregative fuzzy point (e.g. in the second raw of figure 3, the *black points* refer places explicitly cited in historic references whereas the other points correspond to places possibly visited).

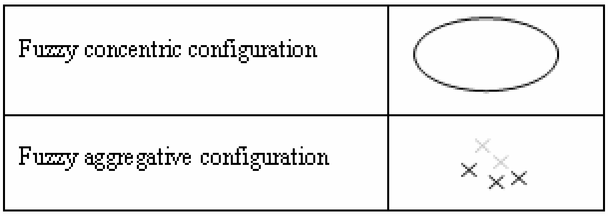


Figure 3. Fuzzy point

6.1.2 Vague line: a vague line can be *positional vague*, *fuzzy concentric* or *fuzzy aggregative*. According to the properties of positional vague geometries, *a positional vague line* is a conventional line which has a possibility to exist in a specific position. The figure 4 presents different cases of a fuzzy line. The first raw of figure 4 shows three cases of *fuzzy concentric lines*. The cases (a) and (c) show two lines for which we respectively ill know the two extremities and the start point. For example, this configuration can be used to represent an itinerary for which the source and/or destination are ill-defined. In the case (b), all of the line is ill-defined and is represented here as an ellipsoid. This kind of lines can model the fuzziness of border lines in a collection of ill-defined regions. The second raw presents the fuzzy aggregative configuration of a line. In the second raw of figure 4, the discontinuity reflects uncertainty of each line segment. The continuous segments represent the *kernel* of the line (i.e. *the certain part of the geometry*) whereas the rest of segments correspond to the uncertain part of the geometry. This kind of lines can model an historic personage itinerary.

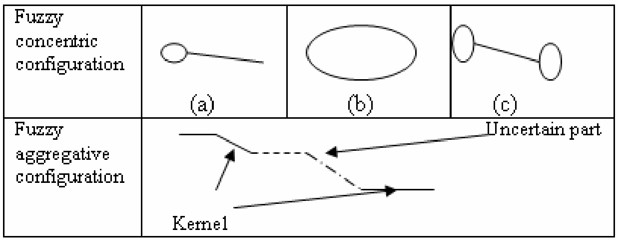


Figure 4. Fuzzy line

6.1.3 Vague region: a vague region can be *positional vague*, *fuzzy concentric* or *fuzzy aggregative*. First, *positional vague region* refers the situation where the region is geometrically well-defined but there is an uncertainty about its existence and/or position (e.g. *an historic building*). In effect, the geometry corresponds to a conventional polygon which has a possibility calculated through a firstly defined membership function (e.g. *a petroleum pollution zone* R_1 *has the possibility 0.7 to be in this position at the instant t*). Second, *fuzzy concentric region* (cf. figure 5) refers the situation where the region has ill-defined boundaries (e.g. *an air pollution zone*). In this case, the *kernel* (the grey polygons in the second raw of figure 4) is surrounded by *broad boundaries* which represent the zone of vagueness. Fuzzy regions can also exist in an *aggregative configuration* (cf. figure 5) (i.e. grey polygons represent the *kernel* whereas white polygons correspond to the uncertain part). For example, fuzzy aggregative regions might be used to model a future exploitation petroleum zone where the *kernel* represents the sub-regions to be *certainly* exploited. In the contrast, the *uncertain part* groups the sub-regions *possibly* exploitable according to the costs, the company budget and resources, etc.

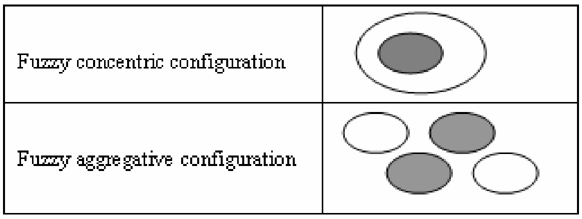


Figure 5. Fuzzy region

6.2 Temporal vagueness

A spatial object or relation can have principally two temporality aspects to be managed: *existence* and *geometric evolution*. In general, two temporal primitives are used to model these aspects: instant (*0-dimensional*) and period (*1-dimensional*). However, this temporality can be vague for many reasons (Pfoser and Tryfona, 2001) like dating techniques or future planning. For example, the birth date of an historic personage or the period of construction of a monument is often vague. Indeed, temporal vagueness can correspond to *positional vague temporality* or to *fuzzy temporality*. *A positional vague temporality* arises when it is difficult to precisely localise the temporal event or period on the time axis. For example, it is sure that a person *X* was died at a given day but we don't have the sufficient knowledge to localise this event on the time axis. Nevertheless, a *fuzzy temporality* arises when the event or the period is inherently vague. For example, a precipitation period and the start instant of a cyclone are respectively examples of a fuzzy period and a fuzzy instant (cf. figure 7). A fuzzy instant is represented by a *minimal instant*, a *maximal instant* and a *membership function*. For a fuzzy period, one of extremities, at least, should be a fuzzy instant. According to (Bédard et *al.*, 2004), these temporal primitives can exist in *simple*, *multiple*, *alternative* or *complex* temporalities.

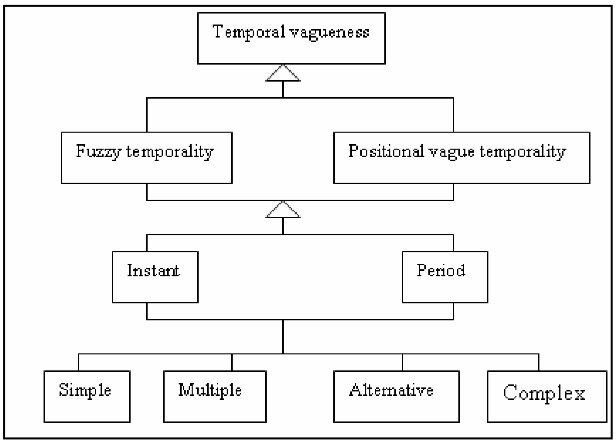


Figure 6. Temporal vagueness

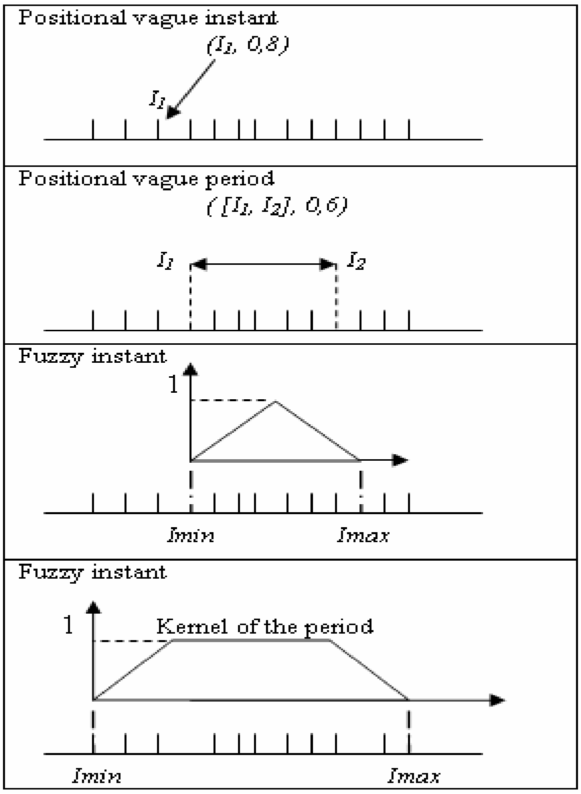


Figure 7. Vague temporal primitives

7. INTEGRITY CONSTRAINTS AND PARTIAL CONSISTENCY

In environmental information systems, there is a need to consider vagueness in order to improve decision about different ill-defined problems like pollution or land cover. To achieve this purpose, data introduced in the database should be useful although it is inherently vague. It is the role of integrity constraints which we present in this section.

7.1 What is an integrity constraint in spatiotemporal databases?

Integrity constraints are important rules that data should verify. Checking these rules at each database update allow to insure semantic coherency of data. In general, these constraints are defined at the conceptual level via specific tools (Bédard et *al.*, 2004) and data inconsistency results from integrity constraints violation. In spatiotemporal databases, integrity constraints should, in addition, allow insuring spatial and temporal consistencies of the objects (Souris, 2006). A spatiotemporal object has also a temporality which should be consistent according to a temporal model and a specific semantic.

7.2 Partial consistency in spatiotemporal databases

In the case of crisp modelling, the vagueness is not allowed in the database and it should be eliminated through *binary* integrity constraints. However, in some cases it is required to manage vagueness in a database and to quantify it. For example, the management of beach nourishment (i.e. an activity allowing to increase the volume of sand in the beaches where there is an erosion problem) in Netherlands requires the consideration of spatial and temporal vagueness (Van de Vlag, 2006). For that, data which describes the phenomenon should be represented through specific model and their logical consistency should be managed differently. According to section 6, there is a need to reduce *meta-uncertainty*. In this way, spatiotemporal objects can be accepted in the database without completely verifying some properties of the class whether their vagueness is known (e.g. *the possibility of a vague position of a vehicle*). Thus, we propose a specific type of integrity constraints which can quantify vagueness of accepted data in order to allow the *partial consistency*. We call these constraints "*fuzzy integrity constraints*" because they are based on fuzzy logic in order to allow partial consistency of vague spatiotemporal data.

7.3 Fuzzy subsets and partial consistency

Integrity constraints for vague spatiotemporal objects must allow a gradual membership and insure a *partial consistency* (Frank, 2001). In this context, fuzzy subsets theory is a rigorous mathematic approach to model vagueness and partial knowledge. Generally, a spatiotemporal integrity constraint can be represented by a formal expression which defines a condition on thematic *attributes*, the *geometry* or the *temporality* of the spatiotemporal object or relation. We model every vague property or vague relation (e.g. "*near*", "*far*", "*in the north of*", etc.) as a fuzzy subset (cf. section 3). Consequently, an integrity constraint is the set of fuzzy subsets where each one models a vague property of object or relation. In the next section, we present existing classifications of integrity constraints and we propose a new one adapted to the vagueness issue**.**

7.4 Classification of integrity constraints

Hendrik, Andreas et *al.* (1997) classified constraints into two main groups: (1) those referring to an object attributes and (2) those defining on relationships between objects classes. In the same way, Fahrner et *al.* (1995) classified integrity constraints in terms of influence on the states of the database. In effect, an integrity constraint can be *static* when it must be checked on a single state of the database. For example, "*the surface of an administrative area must be larger than those of its municipalities*". However, a constraint is *transitional* whether it is used to restrict the number of possible transitions from a state of the database to another. For example, it is possible to require that "*when updating the administrative region relation, its budget should not be decreased"*. Finally, *dynamic* constraints serve to restrict the possible sequences of transitions between possible states of the database. The classification of Cockroft (1997) is typically referenced by most of recent works (e.g. (Rodriguez, 2005; Shu et *al.*, 2003)) on spatial logical consistency. Cockroft (1997) distinguishes three categories of constraints. (1) *Topological integrity constraints* concern geometrical properties of the objects and relations without considering their semantic. For example, "*a polygon should be closed*" or "*an arc should be simple*". (2) S*emantic integrity constraints* are defined to control semantic consistency of the geographical entities. For example, "*a road network must be connected*". However, Cockroft(1997) doesn't distinguish the cases where the integrity constraint defines a metric, an order or a directional condition or when it is purely semantic. (3) *User-defined integrity constraints* refer the rules defined by the experts of the application domain. For example, environmental rules are considered as user-defined integrity constraints (e.g. *the distance between an agricultural spreading parcel and any stream should be greater than 500m"*). Semantically, "*semantic*" and "*user-defined*" integrity constraints are very close and it is very difficult to make the distinction between them. For temporal integrity constraints, Brusoni et *al,* (1999) distinguished *qualitative* temporal constraints (i.e. those controlling topological relations between temporal primitives: *meet*, *before*, *start*…) based on Allen model (Allen, 1983) and *quantitative* temporal constraints (i.e. those controlling metric relations between temporal primitives: "*the temporal distance between P1 and P2 is five minutes"*).

All of previous classifications have been proposed for *crisp* objects. Indeed, they don't consider the different aspects of vagueness. For example, there is a difficulty to classify the constraint saying that *"an air pollution zone **certainly overlaps a** big city"*. The existing constraints classes don't support specificity of the term *"certainly"* (i.e. the kernel of the fuzzy geometry should participate in the relation (cf. figure 8)). For that, we present, in the following, a new categorization of integrity constraints based on the vague spatiotemporal definition and vagueness levels (cf. section 5).

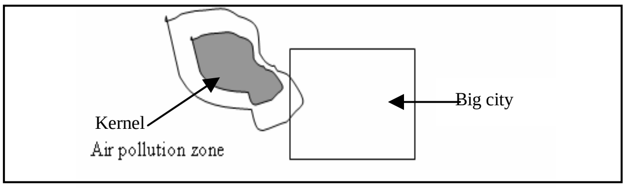


Figure 8. Invalid intersection between a city and a pollution zone

- Different categories of integrity constraints according to uncertainty nature:

According to the categorisation proposed by (M. Salehi, ongoing PhD Thesis; Salehi et *al.,* 2007) and developed essentially for geo-decisional databases, we define an integrity constraint as an expression which can define *spatial*, *semantic* and *temporal* conditions. These kinds of an integrity constraint components or *atoms* are represented in figure 9. According to section 5, inconsistencies occur differently in spatial, semantic and temporal levels. 1) For the spatial level, the question is principally about the validity of object geometry according to the space model. 2) For the semantic level, the consistency concerns principally validity of the model and the data according to the reality, the user specifications and needs. 3) For the temporal level, the consistency concerns data actuality and their validity according to the temporal model. It is current to combine these three kinds of integrity constraint atoms in an integrity constraint (e.g. we can obtain *spatio-semantic constraints*, *spatio-semantic temporal constraints*, etc.). In spatiotemporal databases, spatial and temporal models are separated. They can be linked only through the semantic level. It is difficult to find a "*spatiotemporal*" integrity constraint which should be verified for any spatiotemporal object in absence of any semantic. Spatiotemporal integrity constraints are in general linked to the application context and require some semantic to be specified.

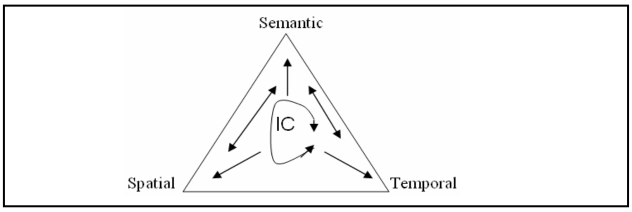
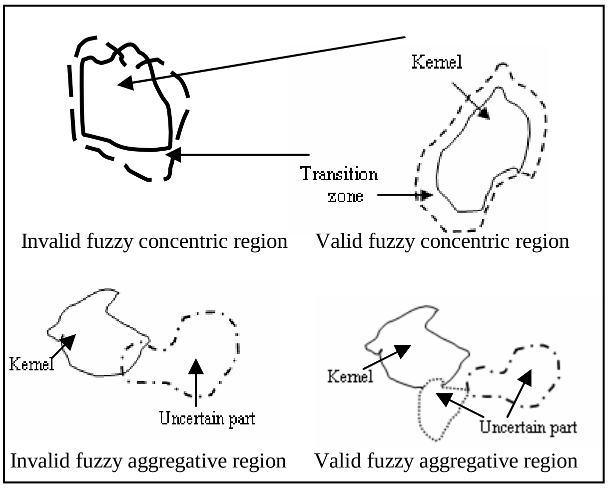


Figure 9. Components of an integrity constraint (Salehi et *al.*, 2007)

- *Spatial constraints*: this class contains constraints defined to control validity and correctness of geometric primitives used to represent vague spatiotemporal objects (points, lines and polygons) such as the simplicity of arcs and the closeness of polygons (Souris, 2006). *Spatial integrity constraints* control validity of any object geometry only according to geometric primitives' definitions and properties (e.g. *the non-intersection between internal and external boundaries of any fuzzy concentric region* (cf. figure 10)). We also consider metric constraints in this category (e.g. the distance between two regions or lines is the minimum of distances between all points of these two objects (i.e. $d\left(A,B\right) = \min\left(d(x,y), x \in A, y \in B\right)$)).

Furthermore, we distinguish two other sub-categories of spatial constraints related to the vagueness context. Firstly, *possibility spatial integrity constraints* should control validity and coherency of possibilities affected to geometries in any dataset. For example, "*any object geometry couldn't have more than one possibility inside the same collection*" or "*The possibility of the kernel of a fuzzy region should be equal to 1*". This type of constraints allows reducing of data redundancy if the geometry is associated to different objects of different collections. For example, a point represents a town center with the possibility 0.7 in a first collection and an historic building with the possibility 0.6 in a second collection. Secondly, *fuzzy geometries integrity constraints* control topological relations between components of these geometries (cf. figure 10). Other constraints can be defined on vague points and lines. Furthermore, constraints on spatial relations (i.e. *topological, metric, directional and order-relations*) between objects require presence of the semantic level. For example, "*an agricultural spreading parcel should not **overlap** any stream*". In effect, we should combine the semantic and spatial levels to define this kind of constraints.



Invalid fuzzy concentric region Valid fuzzy concentric region

Invalid fuzzy aggregative region Valid fuzzy aggregative region

Figure 10. Valid and invalid intersections between boundaries of a fuzzy region

- *Semantic constraints:* an integrity constraint can be purely semantic if it doesn't control any spatial or temporal aspect. In this case, an integrity constraint is defined on object attributes (e.g. "*acidity*", "*pH_level*", etc.) or on semantic relations between objects. According to section 5, attributes values could be imprecise or fuzzy. Integrity constraints on these attributes should verify and quantify this inherent vagueness. For example, "*the attribute pH_Level of the table agricultural_spreading_parcel should receive the values,* ***low, high or medium***". "*Low*", "*medium*" and "*high*" represent the set of fuzzy values.

- *Temporal constraints:* these constraints verify validity of the objects temporalities. A temporal constraint can be: metric (i.e. concerns a metric relation between temporal primitives), topological or a temporal possibility constraint. *Topological temporal constraint* can be defined to control validity of vague object temporality according to temporal model. For example, "*for every temporal period, the start instant should precede the final instant on the time axis*" or "*the minimum instant of a fuzzy instant should precede its maximum instant*". *Temporal possibility constraints* verify validity of possibilities of the temporality of any object according to the temporal model. For example, "*an object temporality should have only one possibility in a valid database state*" or "*a fuzzy period should have at least one of extremities where the possibility is less than one*". *Fuzzy primitives' constraints* control validity of fuzzy temporalities according to the temporal model. For example, "*an instance of a fuzzy instant should occur between the minimum and maximum instants*". Finally, *integrity constraints on temporal relations* (i.e. *topological* and *metric*) can be defined if the semantic level is also present.

- *Spatio-semantic integrity constraints*: these integrity constraints have semantic and geometric references. Vagueness could characterise semantic and/or spatial atoms. In effect, the different kinds of vagueness described for the spatial and the semantic levels might exist and be combined in the same constraint. For example, "*the intersection between two parcels should be* ***low***" (cf. figure 11).

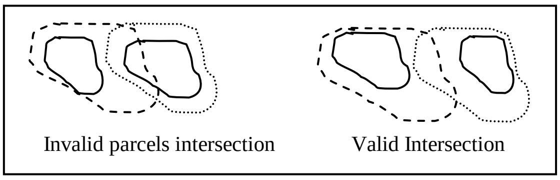


Figure 11. Example of spatio-semantic integrity constraint

- *Temporal semantic constraints:* these integrity constraints have semantic and temporal references. Since vagueness may characterise semantic and/or temporal atoms, the different kinds of vagueness described for the temporal and semantic levels might exist and be combined in the same constraint. For example, "*the agricultural spraying period should precede the period of spreading".*

- *Spatiotemporal semantic constraints:* this class refers the situation where the integrity constraint has spatial, semantic and temporal references. In this case, the different kinds of vagueness described for spatial, temporal and semantic levels might exist and be combined in the same constraint. For example, "*two cultivated areas shouldn't spatially overlap each other in the same time period".*

8. CONCLUSION AND PERSPECTIVES

In this paper, we proposed a classification of integrity constraints where different levels of vagueness are considered. Thus, we proposed a definition of vague spatiotemporal objects based on vagueness levels introduced by (Bédard, 1987). We considered integrity constraint as an expression which can be referenced on three dimensions: *semantic*, *spatial* and *temporal*. Vagueness occurs differently on these dimensions and can be combined in the same integrity constraint. Some examples are presented for every constraints category. Furthermore, integrity constraints for vague spatiotemporal objects and relations are based on the fuzzy logic in order to allow gradual membership and partial consistency.

In perspectives, we will complete our spatiotemporal model by a structure to express spatial and temporal relations between vague spatial and temporal primitives. Then, we will study the formal specification of fuzzy integrity constraints and their implementation through fuzzy logic. This part of the project will extend the project results of M. Duboisset (on-going PhD Thesis) who works on the formal expression of spatial integrity constraints on crisp objects (Duboisset et *al.*, 2005). In addition, the results of this work will be linked to those of M. Salehi (Salehi, 2007) to increase quality of the integration of data used by a SOLAP tool (Rivest et *al.*, 2004).

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