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Constraint Relaxation of the Polygon-Polyline Topological Relation for Geographic Pictorial Query Languages

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Abstract. This work addresses the problem of relaxing spatial constraints for pictorial queries having null answers in geographical databases. It focuses on the polygon-polyline topological relationship and proposes a computational model which is based on the notions of *Operator Conceptual Neighborhood* (OCN) graph and the relative *16-intersection matrix*. The former is addressed to represent the conceptual topological neighborhood between pairs of Symbolic Graphical Objects and indicates how spatial constraints can be relaxed. The nodes of the OCN graph are labeled with geo-operators that have been formalized and their semantics has been enriched in order to capture user query details. The latter is a 16-intersection matrix which provides additional information about the query with respect to the well-known 9-intersection matrix proposed in the literature. It has been conceived to identify, among the approximate answers, the one closer to the user needs. In particular, it allows us to quantify the difference among the user query and the configurations corresponding to the proposed approximate answers on the basis of the OCN graph. The main characteristics of our approach are highlighted through some query examples.

Keywords: pictorial query languages, topological constraints, conceptual neighborhood graph, constraint relaxation, intersection matrix.

1. Introduction

In the spatial domain, qualitative reasoning models are the most widely used approach to represent commonsense reasoning [16]. Qualitative spatial reasoning research areas deal with the development of tools and techniques for reasoning with non-metrical and incompletely specified spatial knowledge [4]. In this context, most studies focused on fundamental aspects of space such as topology, orientation, size, and shape. These topics have been extensively investigated since more than one decade both at mathematical level [5] [7] [10] [43] and within Geographic Information Systems (GIS) [28] [31] [32] [38]. The remarkable amount of studies in these directions aimed at including qualitative reasoning methods in standard GISs in order to overcome the key limitations of these systems to be entirely based on numerical methods [4] [29]. Indeed, numerical approaches for representing and reasoning on spatial information are ineffective to process imprecise or uncertain data [46]. For this reason, advanced GISs must provide an effective and accessible query system to appropriately capture a user's desired search criteria and a user's mental model of the query [19] [20] [21]. Specifically, the user's mental model of the query is the user's perception regarding the semantics of the query in his/her mind.

In general, geographic queries can be better expressed by using graphical metaphors in query languages which are powerful to express the user's mental model of the query [34]. In the field of spatial databases many authors studied the way to formulate queries using graphical configurations, for instance [2] [21] [35] [40]. In particular, in [21] and [22] the authors proposed a pictorial query language, called *Geographical Pictorial Query Language* (GeoPQL) to address the user's mental model of the query. They defined a set of Symbolic Graphical Objects (SGOs) to graphically represent the spatial configurations of geographic entities (i.e., *point*, *polyline*, and *polygon*), the spatial relationships between pairs of SGOs, as well as the spatial operators based on an Object-Calculus.

In the case of null answers to queries do not matching with the content of the database, often in the literature approximate answers are proposed to the user by relaxing query constraints. In this paper we focus on techniques of qualitative reasoning. Accordingly, the purpose of this work is the definition of an approach that allows the user to solve queries with null answers, and supports him/her in the selection of the spatial constraints to be relaxed or maintained.

In this paper, we refer to GeoPQL and we focus on the topological relationship between a polygon and a polyline (the cases of polyline-polyline and polygon-polygon will be investigated in a future work). First of all, with respect to previous works of the authors, in this paper, we revise and formalize the GeoPQL geo-operators. Then, we introduce the *Operator Conceptual Neighborhood* (OCN) graph and the relative *16-intersection matrix*. The former, whose nodes are labeled with geo-operators, is addressed to represent the conceptual topological neighborhood between pairs of SGOs and is used for relaxing constraints. Specifically, in order to obtain approximate answers, it indicates how the pictorial query can be modified through the transition from a given topological relationship to the adjacent thereof. The latter is a 16-intersection matrix which provides additional information about query details with respect to the well-known 9-intersection matrix proposed in the literature [10].

With respect to the well-known matrices proposed in the literature, where for each cell only null or non-null intersections are given, our approach provides, for a given topological relationship, the number of connected components that are in the intersection between the SGOs. Our 16-intersection matrix allows us to quantify the difference among the user query and the configurations corresponding to the approximate answers proposed to the user on the basis of the OCN graph.

As illustrated in the Related Work, Discussion and Conclusion Sections, the benefits and the contributions of this work with respect to other approaches (including previous proposals of the authors) are manyfold: (i) it allows us to capture query details that the 9-intersection matrix proposed by Egenhofer is not able to specify; (ii) it provides a framework where both the geo-operators and the 16-intersection matrix have been formalized; (iii) it reduces the computational costs. In fact, with respect to the 9-intersection matrices proposed by [8] [9], our 16-intersection matrix allows us to reduce the number of elements to be evaluated from 27 to 10.

The paper is structured as follows. In Section 2, the GeoPQL operators are revised and formalized, and the notion of OCN graph is given. In Section 3, the 16-intersection matrix is formally defined. Successively, some examples are provided in order to show our proposal. In Section 4, we describe how approximate answers can be computed. In Section 5 the related work follows, which also contains a subsection devoted to the comparison of our 16-intersection matrix with other intersection matrices proposed in the literature. Finally in Section 6 the discussion and conclusion are given.

2. GeoPQL operators and OCN Graph

In this paper, among the possible geographical pictorial languages proposed in the literature, we focus on GeoPQL [21] [22]. We start by recalling the notion of Symbolic Geographical Objects (SGOs) which has been introduced in [21].

Definition 1. [SGO]. *Given a Geographic Information System, a Symbolic Geographical Object (SGO) is a 5-tuple* $\psi = \langle id, geometric\_type, objclass, \Sigma, \Lambda \rangle$ *where:*

- id *is the SGO identifier assigned by the system to uniquely identify the SGO in a query;*
- $geometric\_type$ *can be a point, a polyline or a polygon;*
- $objclass$ *is the geographical concept name belonging to the database schema and iconized by the SGO, identifying a geographical class (set of instances) of the database;*
- Σ *represents the set of typed attributes of the SGO which can be associated with a set of values by the user;*
- Λ *is an ordered set of pairs of coordinates, which defines the spatial extent, and position of the SGO with respect to the coordinate reference system of the working area.*

The GeoPQL algebra consists of 12 binary geo-operators, which are *logical* (Geo-union (UNI), Geo-any (ANY), Geo-alias (ALS)), *metrical* (Geo-difference

(DIF), and Geo-distance (DIS)), and *topological* (Geo-disjunction (DSJ), Geo-touching (TCH), Geo-inclusion (INC)[1], Geo-crossing (CRS), Geo-pass-through (PTH), Geo-overlapping (OVL), Geo-equality (EQL)). Our focus is on the polygon-polyline relation, therefore in this paper we will consider a subset of the topological operators, namely, disjoint (DSJ), inclusion (INC), touch (TCH), and pass through (PTH). Indeed, the remaining operators are not considered because in the case of the polygon-polyline relation they are not applicable (see for instance CRS which is defined between two polylines, OVL which is defined between two polygons, or EQL which is defined for two polylines or two polygons).

The formal semantics of the above mentioned operators is formally given in the Definition 2 below. Before introducing it, we present the notation we use in our approach, which differs from the one usually adopted in the literature as explained below.

Given a polygon $\mathcal{P}$ and a polyline $\mathcal{L}$, in our approach, $\mathcal{P}_i$, $\mathcal{P}_{b_p}$, $\mathcal{P}_{b_l}$, $\mathcal{P}_e$ denote the interior, single boundary points, boundary lines and exterior of the polygon $\mathcal{P}$, respectively, and $\mathcal{L}_{i_p}$, $\mathcal{L}_{i_l}$, $\mathcal{L}_b$, $\mathcal{L}_e$, denote single interior points, interior lines, boundary points (or end points) and exterior of the polyline $\mathcal{L}$.

With respect to the existing proposals, where there is no distinction between isolated single boundary points and boundary lines of a polygon, and between isolated single interior points and interior lines of a polyline, in our approach the different notations, namely $\mathcal{P}_{b_p}$, $\mathcal{P}_{b_l}$ for a polygon, and $\mathcal{L}_{i_p}$, $\mathcal{L}_{i_l}$ for a polyline, are respectively introduced. They allow us to distinguish different configurations, as for instance the ones shown in Figure 1, where the intersection between a polygon and a polyline consists of one isolated point, case (a), or a line, case (b). These configurations correspond to two different pictorial queries that the user can draw to represent the TCH geo-operator but they have different computational models, as we will see in the next section.

(a) (b)

Fig. 1. Boundary point vs boundary line intersections

For the sake of simplicity, in the rest of this paper we will consider the $geometric\_type$ component of a SGO. In particular, due to the focus of our paper, we will concentrate on the *polygon* and *polyline* geometric types.

[1] Note that in our approach the operators *cover* and *covered-by*, extensively used in the literature, can be represented by using the INC geo-operator.

Definition 2. [Geo-operators]. *Let $\mathcal{SGO}$ be the set of all possible SGOs. Given a polygon $\mathcal{P}$, and a polyline $\mathcal{L}$ both in $\mathcal{SGO}$, the binary geo-operations DSJ, INC, TCH, and PTH are formally defined as follows, where $k \in \{i,b_p,b_l,e\}$, and $j \in \{i_p,i_l,b,e\}$:*

- *DSJ (geo-disjunction):*
  $\mathcal{P}_k$ *DSJ* $\mathcal{L}_j$ *iff* $\mathcal{P}_k \cap \mathcal{L}_j = \emptyset \; j,k \neq e$
- *INC (geo-inclusion):*
  $\mathcal{P}_k$ *INC* $\mathcal{L}_j$ *iff* $\mathcal{P}_k \cap \mathcal{L}_j = \mathcal{L}_j$, $j,k \neq e$
- *TCH (geo-touching):*
  assume $S = \mathcal{L}_j \cap \mathcal{P}_k \neq \emptyset$ *where* $j \neq e$ *and* $k = b_l, b_p$. $\mathcal{P}_k$ *TCH* $\mathcal{L}_j$ *iff* $\forall\ x \in S$*, and* $\forall\ I(x)$*, where* $I(x)$ *is a neighborhood of* x*, only one of the following holds:*
  $I(x) \cap \mathcal{L}_j \cap \mathcal{P}_e = \emptyset$ *or* $I(x) \cap \mathcal{L}_j \cap \mathcal{P}_i = \emptyset$.
- *PTH (geo-pass-through):*
  $\mathcal{P}_k$ *PTH* $\mathcal{L}_j$ *iff* $\mathcal{P}_k \cap \mathcal{L}_{i_l} \neq \emptyset$, $k = i, e$.

According to the definition above, for instance, both the configurations given in Figure 1 correspond to the TCH operator, where in the case (a) one single interior point of the polyline is in common to the boundary of the polygon, and in case (b) one interior line of the polyline is in common to the boundary of the polygon. Note that, in the case (b) we assume that the number of isolated single points which are in common between the boundary of the polygon and the polyline is zero.

In the following, we address the notion of *deformation* in line with [12]. It is a unary operation consisting of one among *movement, rotation, size or shape modifications*. Indeed, in this paper we prefer to use the term *modification* rather than *deformation* because the latter, in our opinion, is more appropriate to describe only the size and shape modifications. Furthermore, we assume that the size modification of a polygon/polyline has upper and lower bounds in order to guarantee that the polygon/polyline remains invariant and neither coincides with or subsumes the entire embedding space, i.e., $\mathcal{R}^2/\mathcal{R}^1$, nor collapses to a point.

The notion of modification allows us to introduce below the definition of Operator Conceptual Neighborhood graph for topological relations, whose rationale is the same underlying the *conceptual neighborhood graph* defined in [12].

Definition 3. [OCN graph]. *Given two SGOs, the related Operator Conceptual Neighborhood (OCN) graph is a graph where nodes represent one (or more) geo-operator(s), and an arc directly connects two nodes if and only if it is possible to obtain one (or more) geo-operator(s) from the other(s) by applying one modification operation.*

In essence, two nodes are adjacent if and only if the operations they denote can be transformed into one another by continuously modifying the related SGOs [12]. The OCN graph related to the polygon-polyline topological relation is shown in Figure 2. Note that in our approach any pictorial query expressed by the user, involving one polygon and one polyline, will be associated with one of the OCN graph nodes.

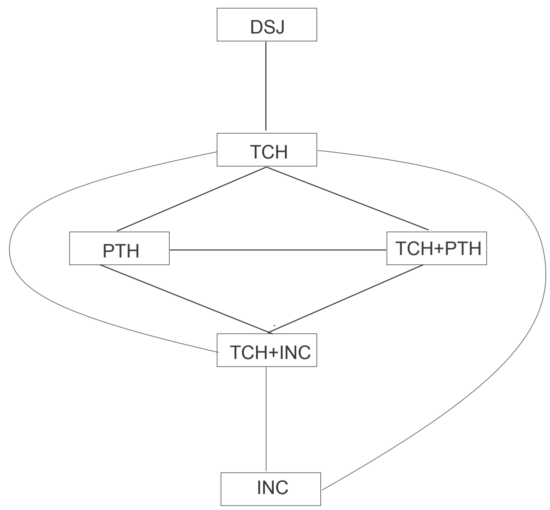

Fig. 2. OCN Graph of the polygon-polyline relation

Now we give a brief description about the rationale underlying the OCN graph shown in Figure 2. From the DSJ node it is possible to transit only to the TCH node. Depending on the configuration of the polyline, we have 11 possible basic situations (see Figure 3) classified according to three main groups on the basis of the following elements of the polyline which are in common to the boundary of the polygon.

Group I - There is no boundary point of the polyline in common to the boundary of the polygon. The boundary of the polygon contains:

- one single internal point of the polyline (3-(a));
- one internal segment of the polyline (3-(b)).

Group II - There is one boundary point of the polyline in common to the boundary of the polygon. The boundary of the polygon contains:

- one boundary point of the polyline (3-(c));
- one internal segment including one boundary point of the polyline (3-(d));
- one internal segment and one boundary point of the polyline (3-(e));
- one single internal point and one boundary point of the polyline (3-(f)).

Group III - Both boundary points of the polyline are in common to the boundary of the polygon. The boundary of the polygon contains:

– both the polyline boundary points (3-(g));
– one internal segment including one boundary point of the polyline, and the other polyline boundary point (3-(h));
– one internal segment of the polyline and both the polyline boundary points (3-(i));
– the entire polyline (3-(j))
– one single internal point of the polyline and both the polyline boundary points (3-(k)).

Due to space limitations, the details about the transitions among the remaining nodes of the OCN graph are skipped.

3. Polygon-Polyline computational model

In this section we introduce the *16-intersection calculi* matrix (*16-intersection matrix* for short) which is on the basis of our approach. The 16-intersection matrix differs from the classical 9-intersection matrix for two main reasons. First, it extends the 9-intersection matrix by introducing the distinction between isolated single boundary points ($\mathcal{P}_{b_p}$) and boundary lines ($\mathcal{P}_{b_l}$) of the polygon, as well as the distinction between isolated single interior points ($\mathcal{L}_{i_p}$) and interior lines ($\mathcal{L}_{i_l}$) of the polyline. Second, each cell in the matrix contains a number providing additional information with respect to the 9-intersection matrix, corresponding to the number of connected components that are in the intersection between the pair of SGOs. Below, the formal definition of the 16-intersection matrix is given.

Definition 4. [16-intersection matrix]. *Given a polygon $\mathcal{P} \in \mathcal{SGO}$, and a polyline $\mathcal{L} \in \mathcal{SGO}$, the 16-intersection matrix is defined as follows:*

$$\begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 0 \ldots n & - & - \\ 0 \ldots n & - & 0 \ldots n & 0 \ldots n \\ 0,1,2 & 0,1,2 & - & 0,1,2 \\ 1 \ldots n & - & 1 \ldots n & 1 \ldots n \end{pmatrix} \end{array}$$

where each element $(\mathcal{L}_j, \mathcal{P}_k)$, $j \in \{i_p, i_l, b, e\}$ *and* $k \in \{i, b_p, b_l, e\}$ *is defined as follows:*

$$(\mathcal{L}_j, \mathcal{P}_k) = \begin{cases} \mid I \mid & (j = i_p, k = b_p), (j = b, k \neq b_l) \\ \mid C \mid & (j = e, i_l, k \neq b_p) \\ - & \textit{incomparable} \end{cases}$$

and:

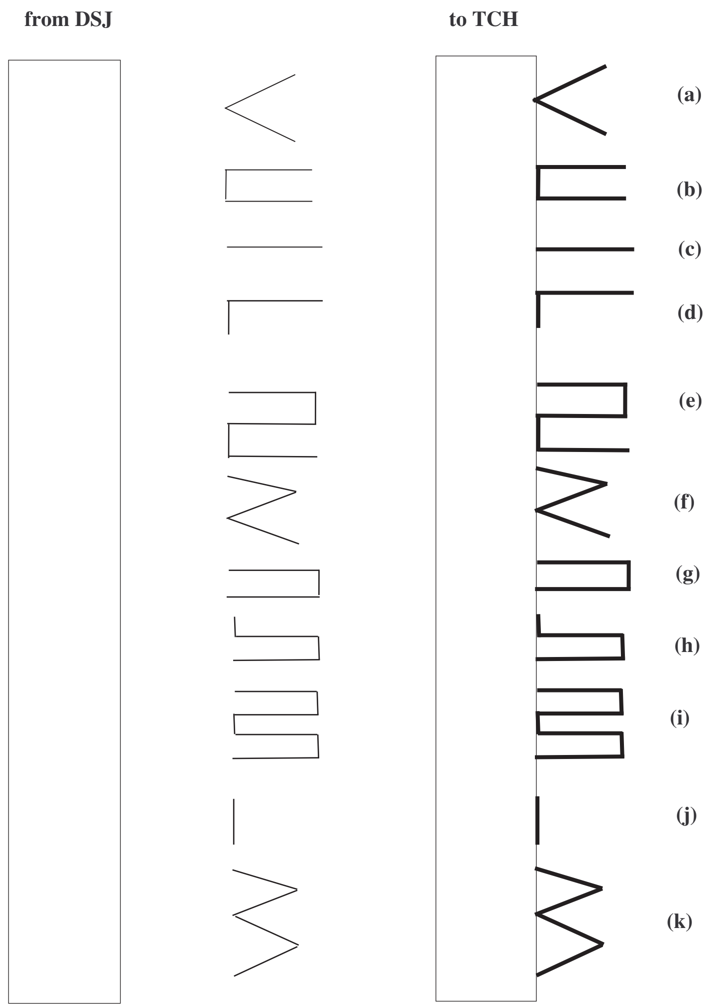

Fig. 3. Transition from DSJ to TCH

- I *is the set of isolated single points in* $\mathcal{L}_j \cap \mathcal{P}_k$*;*
- C *is the set of connected components in* $\mathcal{L}_j \cap \mathcal{P}_k$*.*

Note that, since the end points of a polyline are two, in any 16-intersection matrix the sum of the numbers in the third row is always equal to two.

For instance, the element $(\mathcal{L}_e, \mathcal{P}_i)$ of the matrix above denotes the number of connected components (polygons) contained in the intersection between the internal points of the polygon and the external points of the polyline. Similarly, the element $(\mathcal{L}_{i_p}, \mathcal{P}_{b_p})$ denotes the number of isolated single points contained in the intersection between single interior points of the polyline and single boundary points of the polygon.

In six cases the elements of the matrix are incomparable. In fact, in three cases, namely $(\mathcal{L}_{i_p}, \mathcal{P}_{b_l})$, $(\mathcal{L}_{i_l}, \mathcal{P}_{b_p})$, $(\mathcal{L}_b, \mathcal{P}_{b_l})$, the comparison is performed between isolated single points and lines, and in the other three cases, namely $(\mathcal{L}_{i_p}, \mathcal{P}_i)$, $(\mathcal{L}_{i_p}, \mathcal{P}_e)$, $(\mathcal{L}_e, \mathcal{P}_{b_p})$, the comparison is between isolated single points and portions of the $\mathcal{R}^2$ space.

In order to further clarify the issue, in the following subsection a query example is shown.

3.1. Query Example

Let us consider the following user mental model of a query, for short here referred to as *q*:

Find all the regions that are passed through by a river.

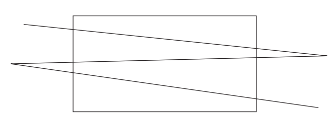

Fig. 4. A pictorial query representing q

This mental model of the query, which involves the PTH operator, can be specified in GeoPQL by using different pictorial representations. For instance, the one shown in Figure 4 is a possible pictorial query of q. The 16-intersection matrix corresponding to the configuration given in Figure 4 is the following:

$$(m_1) \quad \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 6 & - & - \\ 3 & - & 0 & 4 \\ 0 & 0 & - & 2 \\ 4 & - & 6 & 3 \end{pmatrix} \end{array}$$

In fact, we have:

- six points which are single boundary points of the polygon and single interior points of the polyline (element $(\mathcal{L}_{i_p}, \mathcal{P}_{b_p})$ of the matrix, see Figure 5-(a));
- three connected components (polylines) which belong to the polyline and interior of the polygon (element $(\mathcal{L}_{i_l}, \mathcal{P}_i)$ of the matrix, see Figure 5-(b));
- four connected components (polylines) which belong to the polyline and the exterior of the polygon (element $(\mathcal{L}_{i_l}, \mathcal{P}_e)$ of the matrix, see Figure 5-(c));
- two boundary points of the polyline which are exterior points of the polygon (element $(\mathcal{L}_b, \mathcal{P}_e)$ of the matrix, see Figure 5-(d));
- four connected components (polygons) that are internal to the polygon and external to the polyline (element $(\mathcal{L}_e, \mathcal{P}_i)$ of the matrix, see Figure 5-(e));
- six connected components (polylines) that are external to the polyline and are the boundary lines of the polygon (element $(\mathcal{L}_e, \mathcal{P}_{b_l})$ of the matrix, see Figure 5-(f));
- three connected components (polygons) that are external to the polygon and external to the polyline (element $(\mathcal{L}_e, \mathcal{P}_e)$ of the matrix, see Figure 5-(g)).

A simpler pictorial representation of q is, for instance, shown in Figure 6. Indeed q can be represented in an equivalent way by one of the two pictorial queries shown in Figures 4 and 6 representing the PTH operator, but the corresponding 16-intersection matrices are different. The 16-intersection matrix corresponding to the simpler pictorial query of Figure 6 is shown below:

$$(m_2) \quad \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 1 & - & - \\ 1 & - & 0 & 1 \\ 1 & 0 & - & 1 \\ 1 & - & 1 & 1 \end{pmatrix} \end{array}$$

In the next section this matrix will be used to show an example clarifying how it can be employed in the case the user query has a null answer. In particular, we will see how it allows us to determine, if there exists, a satisfactory approximate answer to the user needs.

Figure 7 illustrates the pictorial formulation of the query, shown in Figure 6 in the GeoPQL working area, on the geographical database of Italy. This query then is translated and visualized to the user in an eXtended SQL language, called XSQL [21]. Note that during the drawing phase which involves modifications, deletions and shift of the pictorial representation, the textual query is continuously updated. The query is translated into ArcView® [17] and executed on ArcMap® (the geographical database of ArcView®) [18]. Figure 8 shows the highlighted regions which are the answer to the query. As we can see the pictorial query is translated to XSQL and shown in the top-left working area. Note that in the implemented system, all ArcView® basic browsing and drawing functions are integrated with the pictorial functions developed in GeoPQL. These functionalities facilitate the visual analysis and geo-processing of the query in the system.

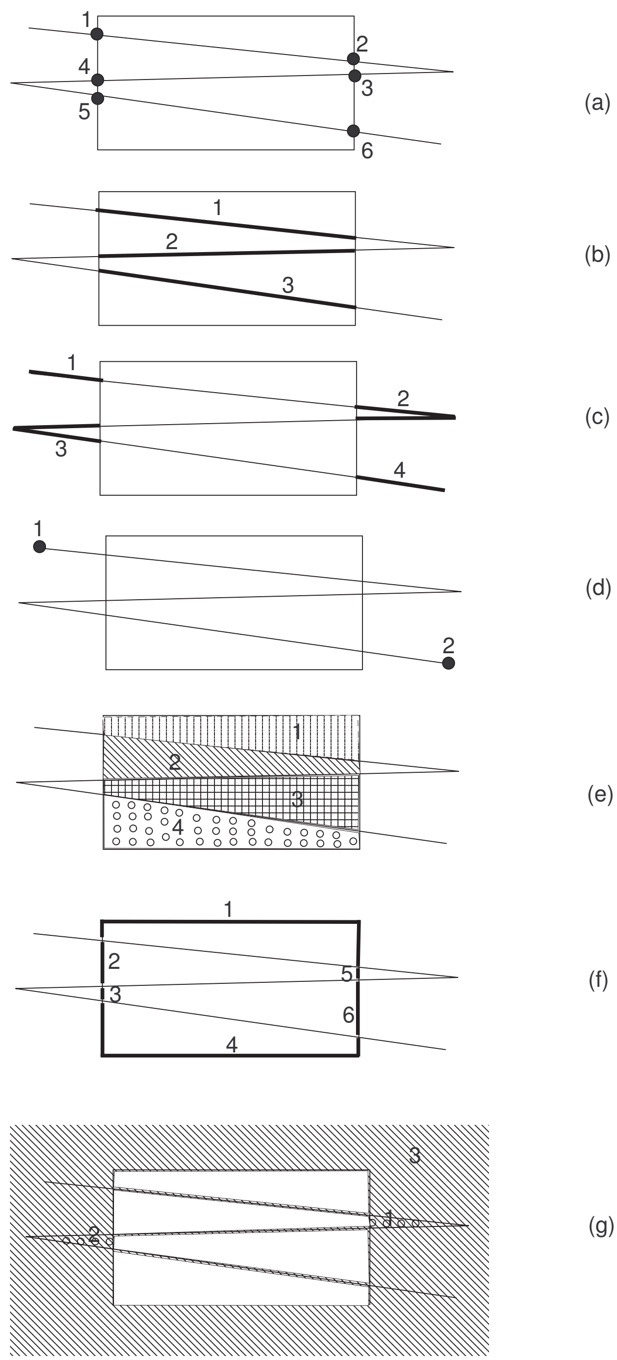

Fig. 5. Graphical representation of the elements of the matrix m_1

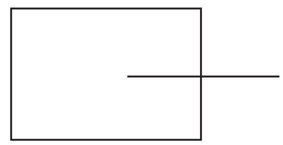

Fig. 6. A simpler pictorial representation of q

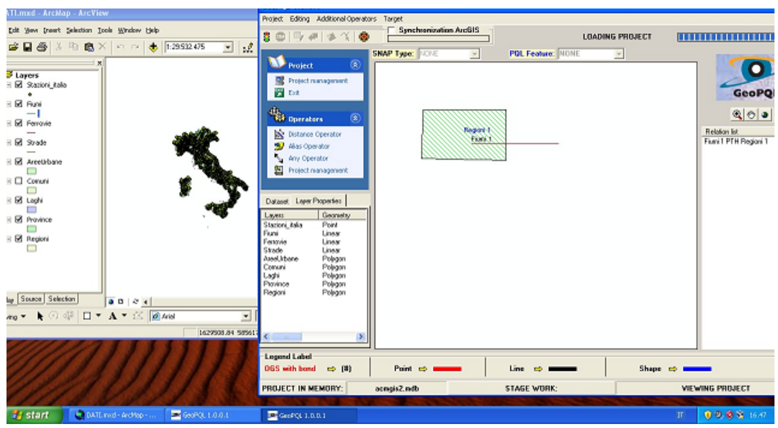

Fig. 7. Pictorial formulation of query q

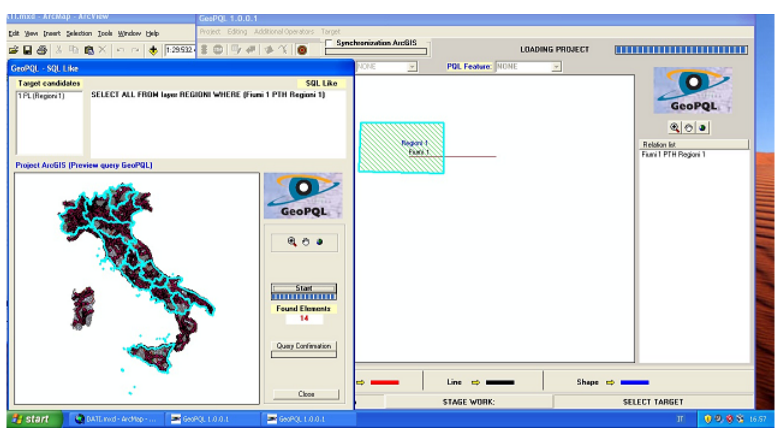

Fig. 8. Visual representation of the query results

4. Computation of approximate answers

Consider again the user query q of the previous subsection. Suppose the user draws the simpler pictorial query shown in Figure 6 and that there is no answer in the database to this query. In our approach, in order to provide an answer, we identify the possible configurations that can approximate the user query, according to the semantics of the geo-operators given in Definition 2, and the OCN graph of Figure 2. Successively, we compute the 16-intersection matrices of the configurations corresponding to the user query and the possible identified approximations. Each identified matrix is compared with that corresponding to the user query and one, among the identified matrices, is selected on the basis of the less number of different cells' contents. For instance, in this example four possible approximations of the user query are identified, which are shown in Figure 9. They are obtained by continuously modifying the polygon or the polyline represented in Figure 6 by applying one unary operation among *movement, rotation, size or shape modifications*, as already mentioned in Section 2. The pictorial query drawn in Figure 9-(a) corresponds to the TCH+PTH node, both the pictorial queries given in Figure 9-(b) and Figure 9-(c) correspond to the TCH node, whereas the one shown in (d) corresponds to the TCH+INC node.

In the following, the 16-intersection matrices (i), (ii), (iii), and (iv) corresponding to the pictorial representations (a), (b), (c), and (d) of Figure 9 are given, respectively.

$$\text{(i)}\quad \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 1 & - & - \\ 1 & - & 0 & 1 \\ 0 & 1 & - & 1 \\ 2 & - & 2 & 1 \end{pmatrix} \end{array}$$

$$\text{(ii)}\quad \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 0 & - & - \\ 0 & - & 0 & 1 \\ 0 & 1 & - & 1 \\ 1 & - & 1 & 1 \end{pmatrix} \end{array}$$

$$\text{(iii)}\quad \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 0 & - & - \\ 0 & - & 1 & 1 \\ 0 & 1 & - & 1 \\ 1 & - & 1 & 1 \end{pmatrix} \end{array}$$

$$\text{(iv)}\quad \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 0 & - & - \\ 1 & - & 0 & 0 \\ 1 & 1 & - & 0 \\ 1 & - & 1 & 1 \end{pmatrix} \end{array}$$

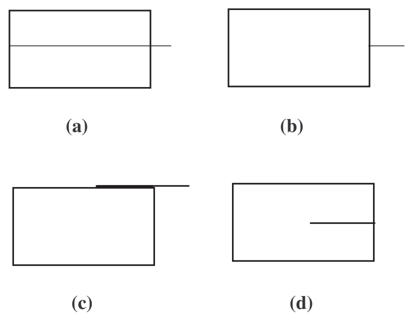

Fig. 9. Possible approximations of the query q

In order to select, among the four configurations given in Figure 9, the one that better approximates the user query q, the matrices (i), (ii), (iii), and (iv) are compared with the matrix m_2 (see Subsection 3.1). Given a matrix j, j = i,ii,iii,iv, $\Delta(m_2, j)$, denotes the number of cells with different contents between m_2 and j. For instance, in the case $j = i$, $\Delta(m_2, i)$ = 4 because the matrices differ for 4 elements, which are $(\mathcal{L}_b, \mathcal{P}_i)$, $(\mathcal{L}_b, \mathcal{P}_{b_p})$, $(\mathcal{L}_e, \mathcal{P}_i)$, and $(\mathcal{L}_e, \mathcal{P}_{b_l})$. Note that in the case of the matrix m_2, the first two elements are, respectively, 1 (because only one boundary point of the polyline is an interior point of polygon), and 0 (because there is no boundary point of the polyline that belongs to the boundary points of the polygon), while in the matrix (i) they are 0, and 1. In the last row of the matrix (i), the first two elements are increased by 1 with respect to the matrix m_2.
Similarly, we obtain the following results by comparing the matrix m_2 with the matrices (ii), (iii) and (iv), respectively:

$\Delta(m_2, ii)$=4
$\Delta(m_2, iii)$=5
$\Delta(m_2, iv)$=4

The user can choose indifferently among the configurations corresponding to the minimal values, in this case $\Delta(m_2, i)$=$\Delta(m_2, ii)$=$\Delta(m_2, iv)$=4, which corresponds to one among the configurations shown in Figure 9-(a), 9-(b), and 9-(d), respectively. Finally, if the answers to these configurations are still null, the further configuration shown in Figure 9-(c) can be chosen.

5. Related Work

In the last few years, a number of proposals focused on the problems regarding the topological relations between SGOs. Some papers study the conceptual neighborhood of topological relations between polylines [41] or the evaluation of semantic similarity between concepts [23] [27] [45], which is widely addressed in the context of the Semantic Web [11] [24] [25] [26]. Similarly, other proposals discuss conceptual neighborhoods [12], qualitative spatial reasoning [1] [46], models [36] [37] [49], metric refinements [13].

Some authors address the topic from the ontological [47], the user interface and human interaction points of view [22] [36] [44], as well as the general theory of geographical representation in GISs [30]. Similarly, other authors discuss the integrity constraint problem in spatial databases [48]. With regard to the operators and algebras for geographical data, in [22] the authors introduce the oriented polylines and extend the set of operators proposed in [19] [20] [21] [29]. In [42] the authors discuss the extension of GeoPQL to the cardinal and positional operators, as well as the OLAP operators.

With regard to binary topological relations the 4-Intersection, and 9-Intersection models [10] have been proposed, and a comparison between them has been made [15]. Regarding the 9-intersection model, the definition of binary topological relationships based on the interior (A°), boundary (∂A), and exterior (A^{-}) of a 2-dimensional point set embedded in $\mathcal{R}^2$ have been introduced [14].

Concerning the topological relationships between geographical features, there is a number of different proposals in the literature, see for instance [3] [6] [8] [9] [12] [14] [37]. For instance, in [3] the authors refer to the calculus-based method and investigate 17 relationships between polyline-polygon relations in which some configurations, such as the relationship between a polyline entirely lying on the boundary of the polygon, are not considered. In [37] the authors present an extended model for describing topological relations between sets (objects) in GISs and they focus on two polygons. However, they do not consider the relationships between polygons and polylines, such as the cases in which a polyline partially or totally overlap the boundary of the polygon. In this paper, we analyze the aforementioned cases, and enrich the semantics of the geo-operators involved in such configurations in order to capture these details.

In [6] the authors focus on six kinds of topological relations between a polyline and a polygon, and illustrate a hierarchical representation of these relations. They propose sixteen polyline-polygon topological relations as well as a conceptual neighborhood graph defined at two levels, basic and composite. The basic relations are further classified at coarse and detailed levels. The composite relations are classified according to three levels which are set, element, and integrated level. At each level, topological invariants are developed based on the intersection between the polyline and polygon boundaries. However, the formalization of topological operators and their possible combinations are not delineated. In our work, we formalize the geo-operators and investigate the combination of topological relationships, and we define the OCN graph on the basis of the conceptual neighborhood of such relations, as well.

In [8] [9], starting from the Geographical Pictorial Query Language proposed in [21], a preliminary study regarding constraint relaxation in the case of queries which produce null answers is proposed. The comparison among the intersection matrices proposed in the aforementioned papers, the well-known

9-intersection matrix of Egenhofer, and our 16-intersection matrix will be extensively described and discussed in the next subsection.

5.1. Comparison with the other existing matrices

In this subsection the 16-intersection matrix proposed in this paper will be compared with two different kinds of intersection matrices proposed in the literature. They are the 9-intersection matrix proposed by Egenhofer [10], and the 9-intersection matrices proposed in [8] [9]. In order to better clarify the issue, consider Figures 1(a) and 1(b) in Section 2. Recall that $\mathcal{P}_i$, $\mathcal{P}_b$, and $\mathcal{P}_e$, indicate the internal, boundary and external points of the polygon $\mathcal{P}$, and $\mathcal{L}_i$, $\mathcal{L}_b$, and $\mathcal{L}_e$ denote the internal, boundary and external points of the polyline $\mathcal{L}$, respectively. In the cases of Figures 1(a) and 1(b), the 9-intersection matrices proposed by Egenhofer both coincide, and are defined by the following matrix:

$$\begin{array}{c} \\ \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{ccc} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \end{array} \\ \begin{pmatrix} \emptyset & \neg\emptyset & \neg\emptyset \\ \emptyset & \emptyset & \neg\emptyset \\ \neg\emptyset & \neg\emptyset & \neg\emptyset \end{pmatrix} \end{array}$$

Indeed, with this matrix, there is no way to distinguish, for instance, that the intersections between the internal points of the polyline and the boundary points of the polygon are one isolated single point in the case of Figure 1(a), and one polyline in the case of Figure 1(b) (the element ($\mathcal{L}_i$, $\mathcal{P}_b$) is just non-empty).

Let us consider now the proposal defined in [8] [9]. In the mentioned papers, given a topological relationship, three 9-intersection matrices, here referred to as *3×9-intersection* matrices, are defined, corresponding to *point*, *polyline*, and *polygon intersections*. These matrices necessarily require to compute 27 elements. For instance, in the case of Figure 1(a), we have the following 3×9-intersection matrices:

$$\begin{array}{c} \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & 1 & \infty \\ 0 & 0 & 2 \\ \infty & \infty & \infty \end{pmatrix} \begin{array}{c} \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & 0 & 2 \\ 0 & 0 & 0 \\ \infty & 1 & \infty \end{pmatrix} \begin{array}{c} \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

where, for instance, the element ($\mathcal{L}_i$, $\mathcal{P}_b$) of the first matrix is set to 1 because the intersection between the internal points of the polyline and the boundary points of the polygon is formed by one single point. The same element in the remaining matrices is set to 0 because this intersection does not contain either polylines or polygons, respectively. This does not hold for the 3×9-intersection matrices corresponding to Figure 1(b), which are given below:

$$\begin{array}{c} \\ \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & \infty & \infty \\ 0 & 0 & 2 \\ \infty & \infty & \infty \end{pmatrix} \begin{array}{c} \\ \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & 1 & 2 \\ 0 & 0 & 0 \\ \infty & 1 & \infty \end{pmatrix} \begin{array}{c} \\ \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

In fact, in this case, the element ($\mathcal{L}_i$, $\mathcal{P}_b$) of the first matrix is set to infinite because this is the cardinality of the intersection between the internal points of the polyline and the boundary points of the polygon. The same element is set to 1 in the second matrix, meaning that such an intersection contains one polyline, and 0 in the third matrix because this intersection does not contain any polygon.

Let us analyze the 16-intersection matrix proposed in our work. In the case of the configuration of Figure 1(a), the 16-intersection matrix is the following:

$$\begin{array}{c} \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \overset{\begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array}}{\begin{pmatrix} - & 1 & - & - \\ 0 & - & 0 & 2 \\ 0 & 0 & - & 2 \\ 1 & - & 1 & 1 \end{pmatrix}}$$

whereas, in the case of Figure 1(b) it is:

$$\begin{array}{c} \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \overset{\begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array}}{\begin{pmatrix} - & 0 & - & - \\ 0 & - & 1 & 2 \\ 0 & 0 & - & 2 \\ 1 & - & 1 & 1 \end{pmatrix}}$$

With respect to the 9-intersection matrix of Egenhofer, the 16-intersection matrix allows us to distinguish the configurations of Figures 1(a) and 1(b). In fact, for instance, the element $(\mathcal{L}_{i_p}, \mathcal{P}_{b_p})$ is set to 1 in the former case, meaning that one isolated single point is in the intersection between the internal points of the polyline and the boundary points of the polygon, and it is set to 0, in the latter case, because such an intersection does not contain any isolated single points. Furthermore, the element $(\mathcal{L}_{i_l}, \mathcal{P}_{b_l})$ is set to 0 in the former case because there are no internal lines of the polyline which are contained in the intersection with the boundary lines of the polygon, whereas the same element is set to 1 in the latter case because this intersection contains one polyline.

As a final example consider now Figure 4. In this case the 9-intersection matrix proposed by Egenhofer is:

$$\begin{array}{c} \\ \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{ccc} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \end{array} \\ \begin{pmatrix} \neg\emptyset & \neg\emptyset & \neg\emptyset \\ \emptyset & \emptyset & \neg\emptyset \\ \neg\emptyset & \neg\emptyset & \neg\emptyset \end{pmatrix} \end{array}$$

and the 3×9-intersection matrices are:

$$\begin{array}{c} \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ \infty & 6 & \infty \\ 0 & 0 & 2 \\ \infty & \infty & \infty \end{pmatrix} \begin{array}{c} \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 3 & 0 & 4 \\ 0 & 0 & 0 \\ \infty & 6 & \infty \end{pmatrix} \begin{array}{c} \mathcal{L}_i \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{pmatrix} \mathcal{P}_i & \mathcal{P}_b & \mathcal{P}_e \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 4 & 0 & 3 \end{pmatrix}$$

whereas the 16-intersection matrix is the following:

$$(m_1) \; \begin{array}{c} \\ \mathcal{L}_{i_p} \\ \mathcal{L}_{i_l} \\ \mathcal{L}_b \\ \mathcal{L}_e \end{array} \begin{array}{c} \begin{array}{cccc} \mathcal{P}_i & \mathcal{P}_{b_p} & \mathcal{P}_{b_l} & \mathcal{P}_e \end{array} \\ \begin{pmatrix} - & 6 & - & - \\ 3 & - & 0 & 4 \\ 0 & 0 & - & 2 \\ 4 & - & 6 & 3 \end{pmatrix} \end{array}$$

It is easy to see that, according to our approach, the above matrix contains in a compact form all the significant values (i.e, different from zero and infinite) which can be found in the 3×9-intersection matrices. For instance, the element ($\mathcal{L}_i$, $\mathcal{P}_b$) of the first of the three matrices, which is set to 6, corresponds to the element $(\mathcal{L}_{i_p}, \mathcal{P}_{b_p})$, equal to 6, of the 16-intersection matrix above. Analogously, the element ($\mathcal{L}_e$, $\mathcal{P}_b$) of the second of the three matrices corresponds to the element $(\mathcal{L}_e, \mathcal{P}_{b_l})$ of the 16-intersection matrix (which are equal to 6 in both cases).

Therefore, with respect to the 3×9-intersection matrices, the 16-intersection matrix, first of all, allows us to significantly reduce the number of elements to be evaluated from 27 to 10. Furthermore, in D'Ulizia et al. the formalization of the 3×9-intersection matrices has not been given, whereas in our proposal the geo-operators and the 16-intersection matrix have been formalized in Sections 2 and 3, respectively. Finally, in [8] [9], constraint relaxation is performed according to a similarity graph which is inherently different from our OCN graph. In fact, in the former, nodes are labeled with pre-defined configurations and arcs are labeled with integers standing for the "distance" among the configurations associated with the involved nodes. In our proposal, nodes are labeled with geo-operators, arcs are not labeled, and the possible configurations that approximate the user query are identified according to the semantics of the geo-operators given in Definition 2 and the OCN graph of Figure 2.

6. Discussion and Conclusion

In this paper, we studied the problem of relaxing spatial constraints for pictorial queries having null answers in geographical databases. We focused on the polygon-polyline topological relationship and proposed a computational model which is based on the notions of *Operator Conceptual Neighborhood* (OCN) graph and the relative *16-intersection matrix*.

The benefits of our approach are manyfold. First, from a user point of view, as extensively analyzed in the previous section, it allows us to capture query details which the traditional 9-intersection matrix of Egenhofer is not able to provide. Second, in our approach the formalizations of the geo-operators and the 16-intersection matrix have been given. Third, from a query processing point of view, we save the cost of calculating seventeen more cells with respect to the 3$\times$9-intersection matrices [8] [9]. Thus the gain (ratio) of the number of intersection operations by the 3$\times$9-intersection matrices over the 16-intersection matrix is 2.7.

In the case of different topological relationships to be examined in a given query, the saving according to our approach becomes even more significant. Figure 10 illustrates that the difference between the number of intersection operations of the 16-intersection matrix and the 3$\times$9-intersection matrices is high for high number of topological relations.

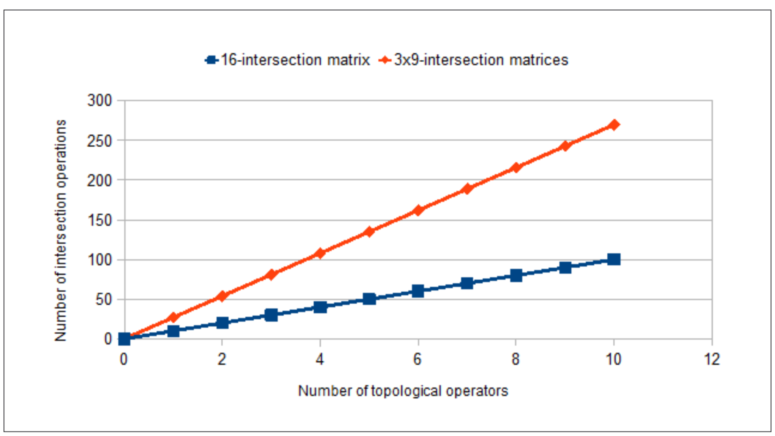

Fig. 10. Number of intersection operations

With respect to the 9-intersection matrix, we have an extra cost of calculating one more cell, which is worth performing in order to provide more accurate results.

Regarding the implementation of our proposed 16-intersection matrix, the open source Java libraries JTS Topology Suite [33] is invoked in GeoPQL. JTS Topology Suite is an API of 2D spatial predicates and functions and provides a consistent, and robust implementation of fundamental 2D spatial analysis methods. It conforms to the Simple Features Specification for SQL published by the Open GIS Consortium-OGC® [39]. GeoPQL takes advantage of some special techniques of JTS, which produce performance gains for storing and manipulating spatial data. These techniques include: (i) in-memory spatial indexes for storing and executing quickly queries over large data objects, and (ii) the technique of Monotone Chains used to improve the runtime performance in the intersection detection operations [33]. The implementation of our 16-intersection matrix relies on revisiting and enhancing the mechanism of the 9-intersection matrix computation provided in JTS, in the case of the polygon-polyline SGOs discussed in Section 2.

In this paper we focused on a class of queries addressing the polygon-polyline topological relationship. In the case of pictorial queries involving cardinal or positional operators (e.g., “the lakes which are in the north of Rome”), or SGOs with holes (e.g., “the administrative subdivisions of Switzerland which contain Campione - belonging to Italy), our approach needs to be further investigated.

As a future work we also plan to analyze and extend our proposal to the cases of the polygon-polygon, and polyline-polyline topological relationships. Furthermore, the development of a platform on the Web, and its integration with GeoPQL, is another issue to be tackled in the future.

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