Assessment of Logical Consistency in OpenStreetMap Based on the Spatial Similarity Concept

Peyman Hashemi and Rahim Ali Abbaspour

Abstract The growth in the number of users and the volume of information in OpenStreetMap (OSM) indicate the success of this VGI-based project in attracting diverse sets of people from all over the world. A huge amount of information is generated daily by non-professional users and OSM faces the challenge of ensuring data quality. Spatial data quality comprises several basic elements; among them, logical consistency concerns the existence of logical contradictions within a dataset. It is one of the most important elements, but has not been studied much in VGI despite the key role in quality assurance. Because of the participatory nature of data collection and entry in OSM, the common consistency checking routines for spatial data should be revised. Since contributors have different views about objects, data integration in OSM may be considered as a form of multi-representation data combination. In this article, the concept of spatial similarity in multi-representation considering three elements, i.e. directional relationships, topological relationships, and metric distance relationships, is used to build a framework to determine the probable inconsistencies in OSM.

Keywords Volunteered geographic information (VGI) · Logical consistency · Spatial similarity · OSM · Topological relations

1 Introduction

The technological advancements in the geospatial domain such as developments in Web 2.0 mapping provide great opportunities to take advantage of a mass of volunteered users for geospatial data acquisition and enrichment. The well-known

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projects such as OSM, Wikimapia, and Google Mapmaker, which are based on this idea, enable the users to play the role of geospatial data providers. The rising rate of users of such environments is an indication of the level of attraction. For example, the registered number of OSM members was 100,000 in 2009 while this reached over 1,500,000 by the beginning of 2014 (OSM statistics 2014).

Although VGI has proved a successful way to obtain detailed geographical information in a timely and low-cost manner, it suffers from some serious weaknesses (Goodchild and Li 2012). The Achilles' heel of VGI is the lack of metadata on spatial data quality parameters used for quality assurance mechanisms. Despite the professional surveyors, most of the users of VGI-based systems are unfamiliar with the standards on spatial data collection or they may feel no need to follow such rules. This leads to a serious problem when quality control procedures are employed to measure the quality level of spatial data. Thus, compatible, customized spatial data quality parameters and control procedures are required to insure the users to utilize those data by crossing the first step of collection of raw spatial data to spatial information production. The other reason to address the quality issues in VGI is the current movement from only data collection and enrichment towards volunteered geographic services (Sui et al. 2013).

There are several classifications of spatial data quality (Worboys and Duckham 2004; Morrison 1995; ISO 19157:2013), which are the results of efforts started in the 1980s in the geospatial information community. In almost all of them, five main elements of spatial accuracy, attribute accuracy, currency, logical consistency, and completeness are considered. They are more or less utilized in VGI studies to address the quality and uncertainty issues. Among the different elements of spatial data quality, logical consistency is studied less than the others in VGI research. Due to the numerous topological errors and loss of standards, which should be considered by users during data entry, different types of inconsistencies occur in VGI. Although there are mechanisms to discover some inconsistencies such as open polygons in some VGI projects like OSM, other basic errors such as overshoots and undershoots, which are of high frequency, remain unsolved. Therefore, it is necessary that the logical consistency, especially with a focus on topological aspects, be assessed in order to fulfill the spatial quality assurance in VGI.

Literature on the quality study in VGI, especially in OSM, may be generally divided into three categories. In the first category, the data in OSM is compared with reference data, which have higher precision and are generated by a mapping agency (Haklay 2010; Girres and Touya 2010; Zielstra and Zipf 2010; Neis et al. 2011). Comparisons of volunteered spatial data with reference data constitute a considerable portion of the research in this field. There are several reports of evaluations of this type which have been carried out in various countries such as the U.K. (Haklay 2010), France (Girres and Touya 2010), and Germany (Zielstra and Zipf 2010; Neis et al. 2011). Although this approach looks rational, using it in most cases in VGI, where there are no reference data, is impossible. Moreover, the costs and license limitations restrict access to high quality, commercial datasets. The research in the second category concentrates on user activities (Jokar Arsanjani et al. 2013), and the third category is comprised of research on the history of the

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Fig. 1 A sample of the OSM history file

data (Keßler and de Groot 2013; Keßler et al. 2011). Data recorded as the history files in OSM data can play an alternative role as reference data. All OSM data such as nodes, ways, and relations as well as their previous versions are stored in the full history dump (OSM, full history dump 2014). These files contain information such as node position (latitude and longitude), object versions, modified times (timestamp), user identification (user name and id), and tags information (key and value). For instance, the submitted information for a node in the OSM history files, which is actually a gas station, is shown in Fig. 1. This file is in the XML format. This comprehensive history file allows researchers to conduct more statistical analysis on spatial aspects or a contributor's information. Thus, intrinsic quality indicators can be applied instead of reference datasets (Barron et al. 2013).

This paper addresses the logical, topological inconsistencies in VGI with a focus on the popular OSM project. A similarity-based framework is used to deal with this issue. The remainder of this paper is organized as follows: First, there is an introduction to logical consistency in general and then the focus is on the meaning of this concept in OSM. Afterwards, the proposed framework is introduced and its main components are described in detail. The last part of this section is the explanation of the proposed methodology and its evaluation. The final section summarizes the work.

2 Logical Consistency for OSM

The concept of logical consistency was initially introduced for database integration purposes (Kainz 1995). Logical constraints defined for a database are rules that adapt the data to the selected structure and provide the opportunity to optimize the storage/retrieval speed. This concept is then used by the geospatial community to address the different sorts of inconsistencies arising during data entry and analysis in GIS. Logical consistency is highly correlated with positional errors. Because there are numerous sorts of positional errors in VGI-based projects, the logical inconsistencies are of high frequency in these projects, which in turn could have a side effect on the analysis and usage of the information.

Based on ISO 19157:2013 standard, logical consistency can be defined as "degree of adherence to logical rules of data structure, attribution, and relationships". Four main sub-elements considered for logical consistency in this standard are conceptual consistency, domain consistency, format consistency, and topological consistency. Conceptual consistency monitors the adherence to the rules of the conceptual schema. Domain consistency checks the value ranges, which should be in certain value domains while format consistency controls the rate of stored data in accordance with the physical data structure. Although these components of logical consistency are meaningful when a standard geodatabase is discussed, they cannot be applied to OSM datasets. Topological consistency examines correctness of encoded topological characteristics. Despite the other components of logical consistency, those types of inconsistencies addressed in the latter one are of crucial importance in VGI.

There are several common errors such as undershoots, overshoots, and duplicate lines in volunteered data. The Quality Assurance page (OSM, Quality assurance 2014) serves as a directory for known error recognition services for OSM. These mechanisms provide some tools for users to recognize errors. Non-closed areas, dead-ended one-ways, broken polygons, and other similar errors can be detected by these tools. For instance, “keep right” is one of the error detection tools introduced in OSM (2014). Intersections of a highway with another highway and a street are shown in Fig. 2 as an example.

As shown in Fig. 2, many types of errors can be determined in this area using the keep right tool. Many of the recognized errors such as non-closed areas, dead-ended one-ways, floating islands, intersections without junctions, and overlapping ways, which are illustrated in the left part of Fig. 2, are related to inconsistencies in spatial data. If volunteered data is viewed in this way, it looks almost as if it were an incompatible, inconsistent set of data. While one of the main objectives of developing a volunteered geographic information environment is far beyond only achieving standard spatial data, considering its nature of being a social event, data consistency should be determined taking users’ convenience and requirements into account.

Fig. 2 Detected errors in an intersection using “Keep Right” tool (KeepRight 2014)

To illustrate this idea, a part of Wörrstadt city is presented from two different perspectives. The OSM website snapshot and a presentation of the history file in ESRI's ArcMap software are depicted in Figs. 3 and 4, respectively. The maps of OSM are frequently edited by users and the cartographic representations on the website may be very different from what users have provided. These maps are combinations of all the information provided by the users and some edits. For example, although there are no broken polygons or duplicate lines in Fig. 3, history files of the same area show numerous cases with gross errors (Fig. 4).

Fig. 3 Part of Wörrstadt city in OSM map (OSM 2014)

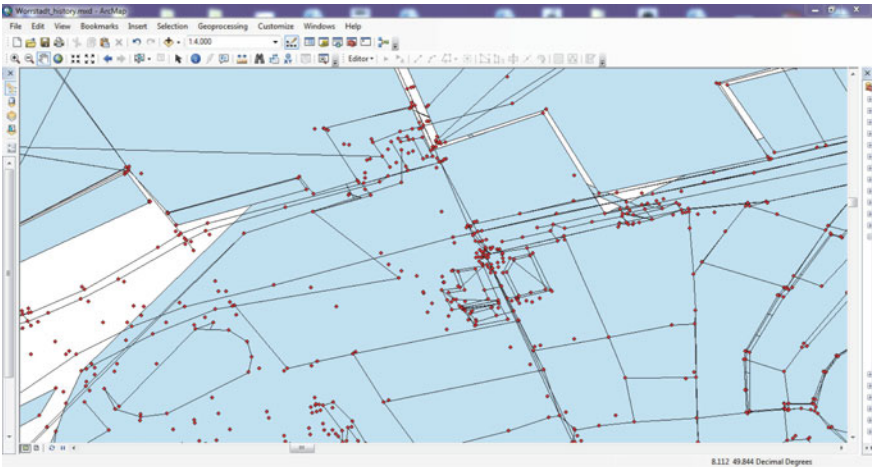


Fig. 4 A sample history file of Wörrstadt city opened in ESRI's ArcMap

While all of the users of OSM can change the objects in OSM, there are several versions of an object in the history file; hence, the consistency evaluation is similar to the assessment of different representations in multi-representations of objects (Egenhofer et al. 1994). In this study, multi-representation means different descriptions (spatial scenes) of the same object by different users, which in turn result in changes in properties of the object and its relationships with the other objects.

3 Proposed Framework

To model the logical consistency with a focus on the topological consistency of OSM data, a framework is developed in this paper based on the similarity measures in scenes according to three main spatial relationships. The proposed methodology is based on changes applied by users rather than comparisons with some reference datasets. The key concept in this methodology is the spatial scenes. Spatial scenes can be defined as follows (Li and Fonseca 2006):

> A spatial scene is a set of geospatial objects together with their spatial relations—topological relations, distance relations, and direction relations—and optionally other sorts of spatial properties, such as shape and relative sizes (areas and lengths), or attributes specifying the semantics of the spatial objects.

When a change is submitted by a user for a spatial object, two scenes of before and after the change are compared to assess their consistency. The spatial similarity is used as a criterion for comparison. This is selected because it is in a direct relation with the human cognition of a place. Similarity is defined as deviation from equivalence (Bruns and Egenhofer 1996). The analogies contribute to significant parts in human cognitions and are used as a general rule for classifications, generalization, and deductive inferences (Li and Fonseca 2006; Tversky 1977). Due to the spatial relations and characteristics in spatial scenes, several factors affect the evaluation of similarity measures. The plurality of these factors complicates the assessment of the similarity.

Two main approaches have been widely used for spatial similarity assessment: conceptual neighborhood approach and projection-based approach (Li and Fonseca 2006). In the conceptual neighborhood approach, similarity is measured by using a relevant network of concepts distances. The shortest path between two concepts in the network is selected as the criterion for similarity. The projection-based approach projects spatial objects and their relations onto the other space, which can be a vector space or a matrix space. This mapping transfers the problem of similarity assessment from the comparison of objects in spatial scenes to a vector or matrix space. There are some cases where a combination of the conceptual neighborhood and the projection-based approach is used (Goyal and Egenhofer 2001). The proposed methodology in this chapter also uses this combined approach to calculate the spatial similarity.

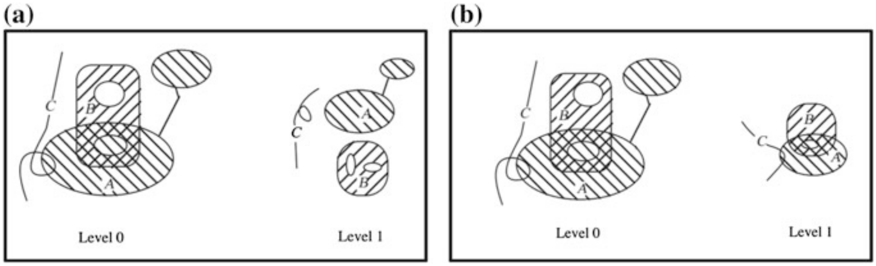
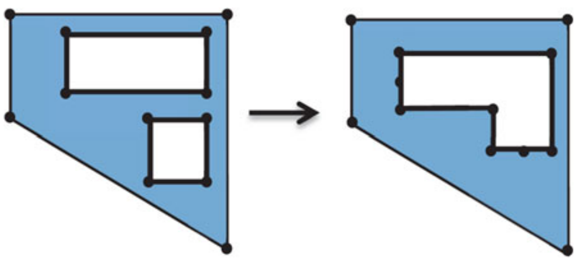


Fig. 5 **a** Two object-similar representations and **b** two relation-similar representations (Egenhofer et al. 1994)

Lower spatial similarity leads to different results in terms of analysis made on spatial data. The changes decrease the similarity rate and cause inconsistency within spatial objects. In other words, the changes in the shape of spatial objects and the relationships between them influence the logical consistency in the dataset. Each topological structure or space has some characteristics such that following them is a guarantee of consistency and validation for features defined by that structure. In multi-representation, topological relations are fundamental information for describing a scene, which should be free of conflict. Topological consistency constraints evaluate structures of the features and adapt to spatial feature relations and the combination of spatial relations (Kainz 1995). The topological relations between two regions are defined based on the well-known Egenhofer's 9-intersection matrix (Egenhofer and Sharma 1993).

There are two types of relations equivalences in multi-representation levels based on the comparison of topological invariants: object equivalence and relation equivalence (Egenhofer et al. 1994). Examples of these two types of equivalences are shown in Fig. 5. In the study of object similarity level, structural characteristics of each feature at different levels are analyzed together. For example, the number of arcs and nodes are counted, although node and edge equalities do not show structural consistency in two levels. In Fig. 6, the number of nodes and edges is equal for two objects, while holes are different; hence, they are partially inconsistent. To assess the relation similarity, relations between different components of an object and relations between an object and neighbor objects should be considered. Based on the possible

Fig. 6 Two representations of the same object



spatial relations, three types of relations are considered for evaluation in this paper: directional, topological, and metric distance relationships. The ways these concepts are employed are discussed in the following sections.

3.1 Directional Relationships

Cardinal directions have a considerable role in the description of spatial structures (Goyal and Egenhofer 2001). This role is highlighted when topological relations between objects are the same for two scenes. The evaluation method used for directional relationships in this study is based on the Goyal and Egenhofer method (Goyal and Egenhofer 2001). In this method, an object is selected as reference and nine geographical directions are used to define the direction-relation matrix (Fig. 7). The detailed direction-relation matrix is a 3 × 3 matrix (Eq. 1) which captures the neighborhoods around the reference object and shows for each tile how much of the target object falls into it (Goyal and Egenhofer 2001).

$$Direction(A,B) = \begin{pmatrix} \frac{area(B \cap NW_A)}{area(B)} & \frac{area(B \cap N_A)}{area(B)} & \frac{area(B \cap NE_A)}{area(B)} \\ \frac{area(B \cap W_A)}{area(B)} & \frac{area(B \cap 0_A)}{area(B)} & \frac{area(B \cap E_A)}{area(B)} \\ \frac{area(B \cap SW_A)}{area(B)} & \frac{area(B \cap S_A)}{area(B)} & \frac{area(B \cap SE_A)}{area(B)} \end{pmatrix} \quad (1)$$

Then a conceptual neighborhood graph (CNG) is used to compute the spatial similarity. The transfer cost from each node (i.e. NW, N, NE, E, SE, S, SW, and W) to its neighbors is assumed to be 1 on that edge. Transfer cost between two arbitrary nodes is the length of the shortest path between those nodes. For example, the cost of transfer between the NW node and the SE node is equal to 4.

Directional similarity between two scenes is defined as the minimum cost for transferring the elements with non-zero values of first direction matrix from their locations to the locations of the elements with non-zero values in the second direction matrix along the CNG to transform the first matrix to the second one (Goyal and Egenhofer 2001).

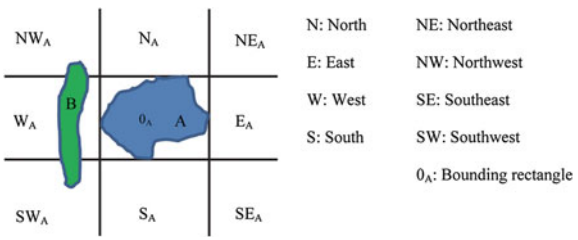


Fig. 7 The directional relation between two regions *A* and *B* using a projection-based system

3.2 Topological Relationships

To analyze the topological relations, topological distance based on 9-intersection matrices is employed (Egenhofer and Al-Taha 1992). Topological distance between two topological relations indicates the corresponding elements with different values. The difference between zero and non-zero elements of 9-intersection matrices is defined by Eq. 2.

$$\phi - \phi = 0;\ \neg\phi - \neg\phi = 0;\ \phi - \neg\phi = -1;\ \neg\phi - \phi = 1 \qquad (2)$$

The topological distance between two topological relations, r_A and r_B is defined as the magnitude of the difference between two related intersection matrices (Egenhofer and Al-Taha 1992), M_A and M_B (Eq. 3).

$$\mathcal{T}_{r_A, r_B} = \|M_A - M_B\| \qquad (3)$$

Topological distances between eight possible topological relations for two spatial objects are shown in Fig. 8, which can be used as a conceptual neighborhood graph between relations as well. For each change made on a feature, the cost for transferring the first topological relation to the second one is considered. Greater values of transfer cost or topological distance increase the chance for topological inconsistency. Computation of topological similarities using the concept of topology distance, the cost network (Li and Fonseca 2006), or five layers graph (Bruns and Egenhofer 1996) results in different consequences. Regardless of which cost graph has been used, it is essential for the model to have the ability to show the changes in topological relations. It is important since the changes in topological relations have a direct impact on the analysis results.

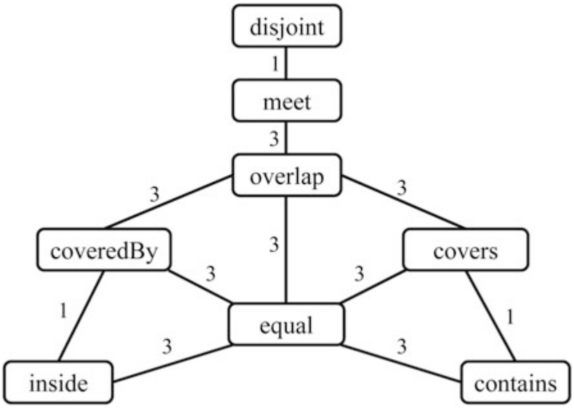


Fig. 8 The revised closest-topological-relationship-graph (Egenhofer and Al-Taha 1992)

3.3 Metric Distance Relationships

It is a challenging problem to define qualitative distance relationships for different types of spatial objects, because the concepts and conditions used in definition of these relations depend on the scale of spatial space. In this paper, the 4-granularity (equal, near, medium, far) metric distance network is used to determine the similarity of the metric distance relationship. There are four nodes and three edges on this network. The transformation cost is set as 1 on each edge. The rate of change depends on which distance for each qualitative distance parameter has been selected. According to our perception based on the different trial and error experiments, the value of 50-m distance is considered as near. For discovering whether the moved object is in the near area, it should be determined if the new object intersects with the 50-m buffer of the old object. In other words, in assessment of metric distance, the exact distance between objects is not calculated and checking to have an intersection with the buffer zone, which is around the reference object, is considered. This assumption is certainly with some approximations.

3.4 Proposed Methodology

The proposed methodology for assessment of logical consistency in OSM is shown in Fig. 9. When a spatial object is altered by a user, the spatial similarity of two scenes, i.e. before and after the change, is compared based on the mentioned relations. For computation of spatial similarity, a reference object must be selected. For this reason, the objects in a radius of 100 m from the changed object are considered as influential features in the selected scene. There is also a possibility to use only well-structured objects such as landmarks as the reference objects. The distance of 100 m is selected according to the density of urban features empirically. This distance can be changed based on the scale, type of region, and required accuracy. Considering the change, spatial similarity before and after alteration with each influential object as a reference object is computed. For greater spatial dissimilarity values, the possibility of inconsistency increases accordingly.

The effective methods and parameters in the calculation of spatial similarity are different. For example, if the changed object is a point and the reference object is a polygon, the most important relationship between these two object is if the point is inside of the polygon or not. Having such capabilities, the users are able to decide about the consequence of the changes.

One of the major affecting parameters on results is the selection of the reference object. In fact, on one hand, selection of all objects within a buffer is unnecessary

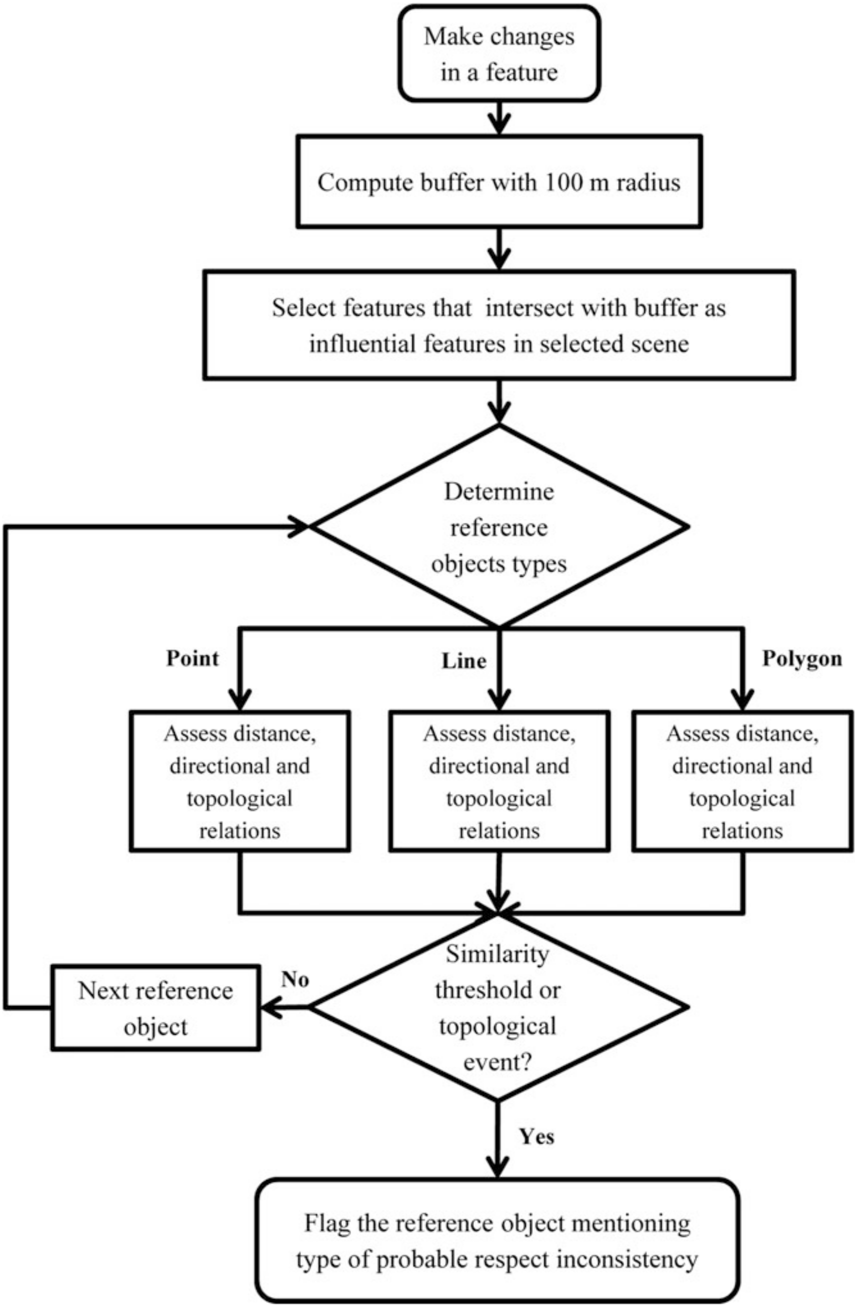


Fig. 9 The proposed methodology for detection of inconsistency in OSM

and on the other hand, selection of objects such as trees as the reference object is irrational, because these sorts of objects have no effects on the spatial cognition of people. Optimum selection of the reference object decreases the computational load of the program and increases its speed. Thus, it is recommended to choose the street crosses in road networks and existing landmarks as reference objects because the relationships between these objects are more accurate (Wang et al. 2011).

To illustrate the proposed methodology, an example of the implementation is described. Imagine the place of a gas station is changed from east of a highway, which is shown in Fig. 10a in the northeast to southwest direction, to the west side of it. Now it is desired to study the changes in the relations. In the first step, a buffer of 100 m distance is generated around the initial location of the gas station in order to find the influential objects (Fig. 10a). After selection of all influential objects (Fig. 10b), it is examined to discover which objects are affected due to the change in the location of the gas station. According to the introduced criteria for topologic situations for a point object, the program finds those lines and polygons for which the relationship type of them with the point is changed (Fig. 10c). The program alerts that the gas station exited from block A and entered block B. Moreover, this change results in the change in the direction of the gas station according to the highway.

To understand the effect of these parameters on the results better, the following example is explained. Imagine you are driving in north Kargar Street and while passing by the engineering college (blue balloon in Fig. 11) you are running out of gas. According to the map, the nearest gas station is located on the east side of Chamran Highway (green balloon in Fig. 11) and normally you need to travel

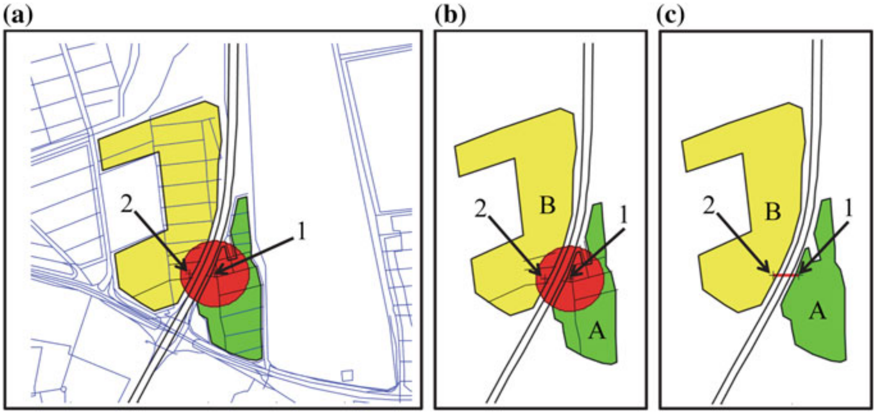


Fig. 10 **a** Change in the position of an object, **b** finding the influential objects, **c** the changed relationships due to the change in the position of an object, *arrow* (*1*) shows the first and *arrow* (*2*) shows the second position of the gas station

1.05 km to arrive (green line in Fig. 11). However, this distance is based on the assumption that the gas station is on the east side of the highway. Now assume that the position of the station is displaced a little on the map (yellow balloon in Fig. 11). Chamran Highway width is approximately 40 m. This error is trivial for a gas station position in a volunteered map. Now if the station is placed on the other side of the highway (west side) on the map, you need to travel the yellow line shown in Fig. 11 to arrive at the destination. If the gas station is really placed where it is shown on the map, someone needs to travel 1.64 km to arrive there. Considering the real distance of 1.05, 1.64 km is acceptable as well. While in reality, one does not arrive at the gas station by travelling a longer distance. The best scenario is to return by the same path (red line in Fig. 11) in which one needs to travel around 2.49 km. Therefore you should traverse 4.13 (1.64 + 2.49 = 4.13) km instead of 1.05 km, around four times more. Considering heavy traffic on the return back path, this case is not pleasant at all. This example indicates the importance of directional parameters beside the positional parameters.

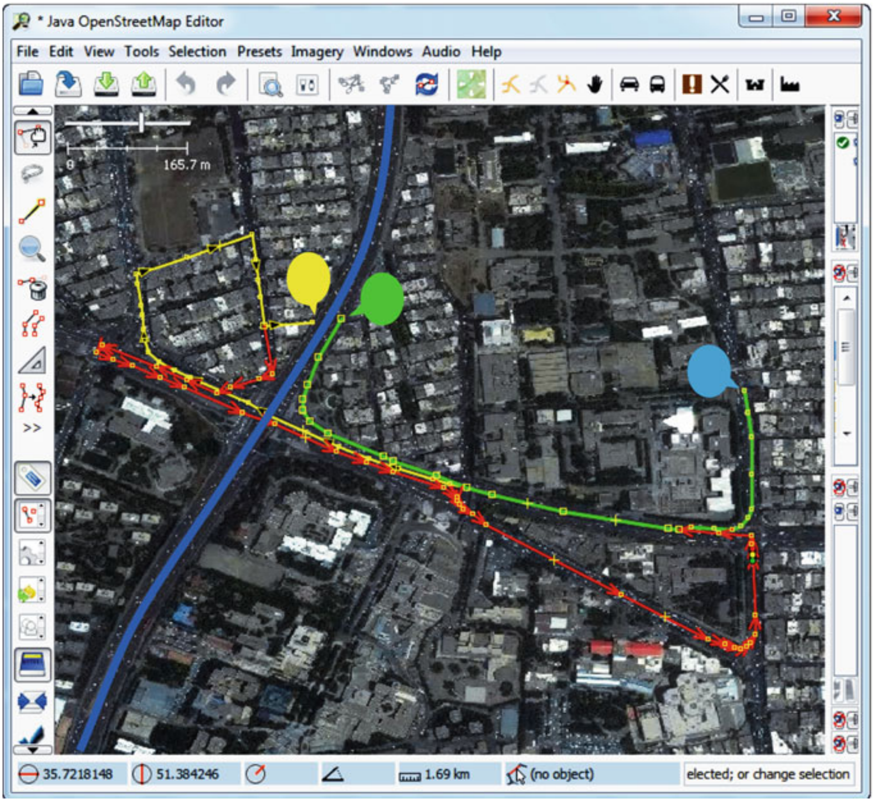


Fig. 11 Start point in north Kargar Street (*blue balloon*), real gas-station location (*green balloon*), imaginary gas-station location (*yellow balloon*), Chamran highway (*blue line*)

4 Implementation

To evaluate the proposed methodology, the dataset of the city of Wörrstadt in Germany in OSM is selected (Fig. 12). The dataset used in this study is based on the files extracted by Körner at extracts of the OSM full history dump (2014). In the first step, the data are unzipped using the osmconvert application. While the current version of the proposed framework is implemented offline in Matlab, results containing inconsistencies are displayed in ESRI's ArcMap. To demonstrate the functionality of the proposed methodology, two sample cases are presented, in which the changes in positions result in inconsistencies. In these cases, looking at the current versions of the maps in OSM shows none of the inconsistencies, but assessment of the history of the objects reveals these inconsistencies.

In the first sample, the change in direction and topological relationships are considered. The direction and topological relationships between Kleine Albanus street (id = 27022096) and the adjacent parking lot (id = 198260983) are changed. These changes cause a serious effect on finding the access way to the parking lot. Figures 13 and 14 show the current and past positions of the street and the parking lot, respectively. Moreover, Fig. 13 shows the current position of Adler pharmacy and Fig. 14 shows the changes of Adler pharmacy locations in time. The direction of the pharmacy is changed relative to both the adjacent parking lot and the Pariser highway (id = 23498981).

Fig. 12 A view of Wörrstadt region in OSM (OSM 2014)

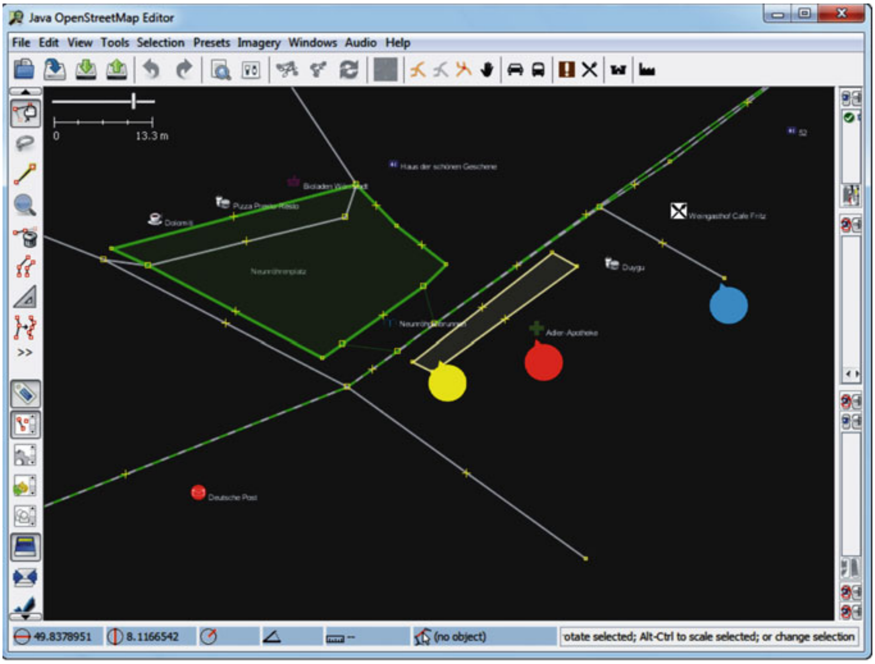


Fig. 13 Current location of Albanus street (*blue balloon*), parking lot (*yellow balloon*), and Adler pharmacy (*red balloon*) in OSM map shown with Java OpenStreetMap (JOSM) editor

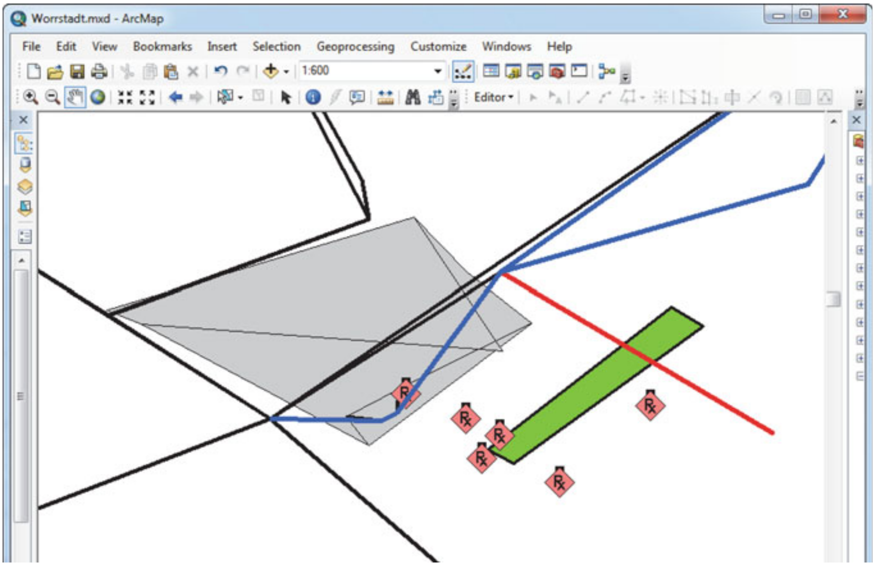


Fig. 14 Previous topological state of Albanus street (*red line*) and parking lot (*green rectangle*) are shown. In addition, changes of the direction of the pharmacy relative to the adjacent parking lot (*green rectangle*) and Pariser highway (*blue lines*) can be seen

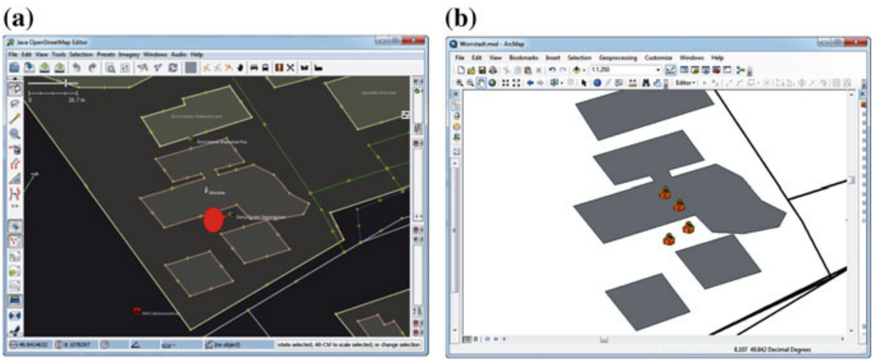


Fig. 15 **a** The current location of Forster school (*red balloon*) in JOSM and **b** changes in location of Forster shown with ArcMap

In the second case, a sample of exit from a polygon is considered. According to assessment of the history file, it is revealed that Forster (id = 280500466) school is outside the bounding polygon after changing. Figure 15 shows the current location and the past locations of this school. The mentioned cases are samples of inconsistencies, which are revealed after assessment of the similarity parameters in two scenes of before and after the changes. Generally, there are numerous inconsistencies like this in OSM. Finding the logical inconsistencies using the proposed framework and reporting them enables the users to be involved in the correction and resolution of inconsistencies more effectively.

5 Conclusion

Data provided by users in volunteered databases is increasing rapidly. While low cost and high update rates are the most important benefits provided by these data, there is a demand to develop methods and parameters for the quality evaluation of volunteer data. Among the different elements of spatial data quality, logical consistency is of crucial importance in quality assurance procedure. In this paper, logical consistency is studied from a different point of view. The idea is to import the features and qualitative relationships of objects with spatial positions to evaluate quality. It was demonstrated that the parameters such as direction, distance, and topological relationships between objects could directly affect human comprehension and analysis results. Because VGI in most cases reflects the cognitions of people from their surrounding environment, it is necessary to assess if the changes cause changes in spatial cognition. While the concept of similarity has a direct relation with spatial cognition, it has high capability to model a part of these changes. An important characteristic of this method is the ability to take advantage of both comparisons of data with reference and with itself. Given the potential of qualitative parameters, they can be added to factors of evaluation for volunteered data. These factors without adding much cost are valuable help to quality evaluation and vandalism recognition.

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