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SketchMapia: Qualitative Representations for the Alignment of Sketch and Metric Maps

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Abstract: More and more private citizens collect and publish environmental data via web-based geographic information systems. These systems face two challenges: The user interface must be intuitive and the processing of geographic information must account for cognitive impact. We propose to use sketch maps as the medium for interaction, because they reflect a person’s spatial knowledge. Information from sketch maps is distorted, schematized, incomplete, and generalized and metric maps are not. This article employs qualitative representations for the alignment of sketch and metric maps. We suggest a set of cognitively oriented aspects in sketch maps stably computed by people and evaluate qualitative representations to formalize these aspects. This allows us to align and integrate geographic information from sketch maps.

Keywords: cognitive map, qualitative alignment, qualitative representation, sketch map

1. INTRODUCTION

Geographic information is traditionally acquired and merchandized by mapping agencies and industrial data suppliers. Lately, new developments in information and communication technologies have revolutionized the information processing and opened new possibilities for private citizens to participate in the acquisition and dissemination of geographic information. Although user-generated content is well-established for many applications such as the ranking of articles, vendors, or restaurants on the internet, this development is rather new for geographic information. Because information about the environment is accessible to everyone through direct experiences, private
citizens started to voluntarily collect geographic information and publish it on websites as volunteered geographic information (VGI) (Goodchild, 2007).

New forms of information acquisition and information dissemination require different mechanisms for human-computer interaction. Current geographic information systems rely on a metric base map. Users insert or query data via a formal language and spatial operators implemented in the system. These systems have rather high requirements regarding users’ technological background and expertise. Furthermore, they require metrically precise data as input. Our approach addresses the challenges of future geographic information systems: (i) to be more intuitive for users, (ii) to handle imprecise information from users, and (iii) to possess lower technical requirements. Therefore, we suggest using hand-drawn sketch maps as a visual interaction mechanism. Sketch maps are often used in human-to-human communication as they are easy to produce and express spatial knowledge.

The information represented in sketch maps reflects users’ spatial knowledge that is based on observations rather than on measurements. Human cognitive maps are typically distorted, schematized, incomplete, and generalized. Thus sketch maps are as well. In this article, we suggest a new comprehensive procedure for qualitative alignment of sketch maps that addresses the above-mentioned cognitive impact and processes information in a cognitively oriented way. Hand-drawn sketch maps have been extensively used to investigate how humans memorize spatial knowledge. Cognitive maps (Tolman, 1948) and cognitive collages (Tversky, 1993; Kitchin & Freundschuh, 2001) have been suggested as metaphors to describe mental organization of geographic information.

Sketch maps are used to externalize the individuals’ mental image of the environment. Being aware of the typical cognitive impact in cognitive maps (Thorndyke, 1979; Tversky, 2002, 2003a) we develop a qualitative alignment framework called SketchMapia, which aims to maintain robustness against cognitive impact. We experimentally justify a set of qualitative sketch aspects that are not affected by cognitive impact such as distortion and schematization, but are preserved properly in sketch maps. We then investigate and test qualitative formalizations to represent these sketch aspects. Finally, we propose a procedure that identifies correct correspondences between sketch and metric map elements.

Our goal is to align information from sketch maps and the metric base map in a VGI system. A metric map preserves the Euclidian properties of the measured space, i.e., its representation is consistent with respect to distance, direction and scale. In this article we focus on city maps as one kind of metric map. The major contributions of this article are (i) the identification of a set of reliable sketch aspects communicated by people in sketch maps and (ii) the evaluation of qualitative representations that formalize these sketch aspects.

This article builds upon the authors’ previous work on the cognitive aspects of SketchMapia (Wang & Schwering, 2009; Wang et al., 2010, 2011),
segmentation of sketch maps (Broelemann, 2011; Broelemann & Jiang, 2013), investigations of qualitative representations (Chipofya et al., 2011; Jan et al., 2013; Jan et al., 2014), and the alignment (Chipofya et al., 2013). This article is the first to give a comprehensive overview of the whole framework describing how the different steps interact and build upon each other. This comprehensive framework includes the extraction of sketch elements, the descriptions of their qualitative relations, and the alignment within and across qualitative representations.

The remainder of the article is structured as follows: We give an overview of related work and introduce an application for SketchMapia. We describe the cognitive basis of SketchMapia and outline suitable qualitative sketch aspects for alignment. Next, we describe the three steps of the framework: the processing, the qualitative description and the alignment within and across qualitative representations. The approach is evaluated and we conclude by discussing the proposed approach and outline directions for future work in the final section.

2. MOTIVATION AND RELATED WORK

The work presented in this article is mainly motivated by two research fields: spatial cognition and qualitative spatial representation. In spatial cognition, many approaches focus on how people think and communicate about various spaces that they inhabit and create. We take these psychological insights into account while developing a cognitively oriented alignment procedure. Furthermore, we introduce the related work in the area of qualitative spatial representations, alignment and computational approaches that use sketch maps as a human-computer interaction interface.

2.1. Cognitive Impact on Sketch Maps

From 1960s until the early 1980s, many researchers used sketch maps as technique to investigate human cognitive maps. Lately, sketch maps have experienced a comeback within a broader application area of human-computer interaction. Research on sketch maps started with the seminal work by Lynch (1960), who analyzed inhabitants’ mental images and understanding of cities. Based on Lynch’s work, other researchers investigated how people perceived their environment and studied typical distortions and schematizations between elements in sketch maps and real world elements (Appleyard, 1970; Banerjee et al., 1977; Cadwallader, 1976, 1979; Day, 1976; Lloyd & Heivly, 1987; Wong, 1979). It has been documented that sketch maps reflect conceptions of reality, but not reality itself (Lloyd & Heivly, 1987; Tversky, 1999). Consequently, sketch maps omit, regularize, and exaggerate informa-
tion, and use inconsistent scale. This leads to different kinds of errors in sketch maps.

2.1.1. Errors of Distance. Distance estimates in sketch maps are affected by factors such as hierarchical organizations, amount of information along the route and landmarks. For relative distance estimates in sketches, elements within one category like buildings or water body are perceived as closer than those in different categories (Hirle & Jonides, 1985). Routes with many turns, many landmarks, or many intersections are judged longer (Sadalla & Magel, 1980; Sadalla & Staplin, 1980; Thorndyke, 1979), thus represented longer in sketch maps. Most remarkably, distance judgments are not necessarily symmetric.

2.1.2. Errors of Direction. Direction estimates are distorted as well, e.g., people mentally rotate the directions of geographic entities around the axes created by themselves. Likewise, directions are commonly straightened in memory (Tversky, 2003a): curvatures get straightened, nonperpendicular intersections are squared and nonparallel streets get aligned (Appleyard, 1969, 1970; Byrne, 1979; Thorndyke, 1979). These errors of directions in cognitive maps can also be found in sketch maps.

2.1.3. Schematic Structure. Like cognitive maps, sketch maps are schematized. They include information important to the sketcher and eliminate the irrelevant one. For example, people conceive routes as sequences of start points, reorientations, progressions, and destinations (Tversky, 2002). These elements are insufficient to convey the exact configuration of the world. In fact, they may severely distort the configuration of the world, thus also the sketch map.

2.1.4. Other Notable Errors. There are other errors of spatial memory and spatial judgment which also appear frequently in sketch maps (Tversky, 2002). For example, people make errors of quantity, shape, size, angles of intersections, as well as errors due to perspective (Poulton, 1989; Tversky, 1992). These errors in cognitive maps do not randomly occur or occur solely due to ignorance; rather, they are a consequence of ordinary perceptual and cognitive processes (Tversky, 2003a). Sketch maps reflect many characteristics of cognitive maps.

2.2. Qualitative Sketch Alignment

Alignment of spatial information requires identifying two spatial configurations that are similar. The alignment is based on associations or correspondences established between the elements of one scene and those of the other.
Numerous digital sketching systems were developed. In this section, we do not review sketching systems, because SketchMapia starts with images of hand-drawn paper-pencil sketch maps instead of digital ink. We review only those approaches for sketch mapping that are similar to our approach with respect to the spatial analysis or alignment methods.

Spatial-Query-by-Sketch proposed by Egenhofer et al. (Carduff & Egenhofer, 2005; Egenhofer, 1996, 1997; Nedas & Egenhofer, 2008) is a design of a sketching query language for Geographic Information Systems (GISs). Untrained GIS users can easily draw the desired spatial configurations. These sketches can be represented symbolically and processed against a spatial database. Five types of spatial relations are distinguished: coarse binary topological relations which is based on the 9-Intersection Model, detailed topological relations, metric refinements, coarse cardinal directions, and detailed cardinal directions. The spatial database is queried for the area where the same spatial relations hold between corresponding spatial objects.

CogSketch developed by Forbus and his colleagues (Forbus et al., 2003; Forbus et al., 2008) is a sketch understanding system. It is used for modeling spatial reasoning and learning and supporting engineering design education. The spatial skills and spatial learning are investigated while gathering and analyzing sketching on different aspects such as spatial language, spatial representation, analogy, and gesture. CogSketch uses qualitative relations such as topological and orientation relations to describe the relations among sketched elements.

Qualitative Matching proposed by Wallgrün et al. (2010) represents a sketch map as a set of qualitative constraint networks (QCN) one for each aspect of space. Each QCN is based on a specific qualitative spatial calculus. A matching problem is then defined as follows: For each possible association of nodes from one QCN with those from the other, find all consistent combined QCNs that satisfy the constraints from both original QCNs. Because the number of potential solutions can be large, only optimal solutions are sought. The number of potential solutions examined during the search is reduced by using heuristics based on qualitative spatial reasoning.

Spatial Scene Similarity by Nedas (2006) and Nedas and Egenhofer (2008) proposed a similarity measure to compare two spatial scenes that takes into account (i) the similarity between objects in the two scenes; (ii) the similarity between the binary relations among objects in the two scenes; and, (iii) the ratio of the total number of objects in both scenes to the number of objects that have been matched—or equivalently, not matched. Establishing the alignment itself involves searching the space of all possible associations from one scene to the other and selecting that set of associations that maximizes the similarity. They achieve this by constructing an association graph whose nodes are the associations, whereas edges are the set of combined constraints between pairs of associated elements. The final solutions to the query comprise all maximal complete subgraphs of the association graph.
3. APPLICATIONS

We develop SketchMapia with an application for VGI in mind. Geographic information from mapping agencies and industry is gradually being replaced (or enhanced) by individuals acting as data suppliers who make geographic information freely available on web repositories such as WikiMapia\(^1\) and OpenStreetMap.\(^2\) More recently, VGI systems are extended to collect sketched data as well. The walking papers project\(^3\) has introduced a service through which OpenStreetMap volunteers can contribute geographic data by sketching missing features on a printed section of OpenStreetMap. The Hand Drawn Map Association\(^4\) collects and publishes sketch maps. Sketchmap.co.uk\(^5\) is a VGI application where users annotate a metric base map by sketching upon it. Numerous applications on sketch maps were developed in the last few years in combination with metric maps, however, none of them processes the sketched information automatically.

SketchMapia provides this functionality of automatically processing sketched information. In our scenario, users draw a sketch map by hand on a piece of paper (Figure 1). Today, sketch maps can be easily digitized by taking a picture of it with a mobile phone. The user uploads the digitized sketch map to SketchMapia and selects the corresponding metric map.\(^6\) SketchMapia

\(^1\)http://wikimapia.org/
\(^2\)http://www.openstreetmap.org
\(^3\)http://www.walking-papers.org
\(^4\)http://www.handmaps.org/
\(^5\)http://sketchmap.co.uk/
\(^6\)SketchMapia requires a sketch map and its corresponding metric map of roughly the same area as input. The corresponding metric map can be identified in different ways: the user can identify landmarks via their unique addresses and post codes, geo-reference any points on the sketch map or specify the corresponding bounding box on the metric map.
analyzes the geographic information from the sketch map, aligns it with the corresponding metric map and integrates the information with other sources of information. This way, additional sketched information such as information on the usage of the buildings—bakery, pub, uni, and FH (University of Applied Science)—can be transferred to the data repository. Sketch maps can be used to contribute information about landmarks (Figure 1), complete nonmapped areas (e.g., the sketcher’s favorite hiking trails), or describe the locations of vernacular places such as downtown (Anacta et al., 2013). You could also use sketch maps to describe routes (e.g., the route to the nearest bakery). Often, we use landmarks to retrace our steps on a route, although we might not necessarily recall names of landmarks and streets. SketchMapia aligns this (approximate) information about streets and landmarks with metric maps to complement what we recall with what is stored in metric maps.

3.1. Cognitive Basis of SketchMapia

Even though sketch maps are highly distorted and schematized, humans are very good at understanding sketched information. Many aspects of sketch maps do not match reality, but humans are still able to retrieve relevant and accurate information and interpret it at the right level of abstraction. This section describes elements captured in sketch maps. We explain which aspects in sketch maps are typically not affected by cognitive impact and thus can be used as reliable aspects for sketch map alignment.

3.2. Elements in Sketch Maps

In his seminal work, Lynch (1960) identified five key elements of the image of a city: paths, nodes, edges, districts and landmarks. Tversky’s analysis of mental structures (Tversky, 2003b) revealed four critical elements: landmarks, paths, links, and nodes. Based on their work, we analyzed the elements in sketch maps and propose four different types of elements in urban sketch maps that convey important information for the alignment: streets segments, junctions, landmarks and city blocks.

Street Segments are important features structuring space in an urban environment. Researchers found empirical evidence that the street grid is used to organize information and is well reflected in sketch maps, particularly in areas with regular street grids (Evans, 1980; Jones, 1972; Zannaras, 1976). When people start drawing a sketch map, street segments are the most frequently drawn elements (Huynh & Doherty, 2007). Street connectivity and the street network are central for human path planning. Street segments in the sketch maps are connected (mostly linear) features. In our representation, street segments are represented as line segments and are connected to other street segments.
Junctions are the end-points of street segments. Junctions play an important role for street segment alignment, because they capture the connectivity information of various street segments forming a street network. At the edge of the piece of paper, street segments are not further connected to other street segments, but end in “hanging end-points.” This is because the sketch map shows only a small section of the whole map. In our approach, we simply subsume hanging end-points under junctions and represent them as points.

Landmarks are the most salient elements in an environment and are therefore essential to characterize an environment. The anchor point theory (Golledge & Spector, 1978) confirms that landmarks act as anchors for structuring the environment. As the most salient elements in an environment, landmarks are very important for the alignment. In our representation, landmarks are extended objects and represent geographical entities. They are vectorized and approximated by polygons. Although street segments tend to be drawn more frequently at the beginning of the drawing process, the frequency soon decreases in favor of landmarks (Huynh & Doherty, 2007).

City blocks are important areal features for sketch map alignment. They are relatively large areas in a city. We define city blocks as the smallest area completely surrounded by street segments. In our representation, a city block plays the role of a container for other spatial objects such as buildings and parks. City blocks have crisp boundaries. People do not always sketch complete city blocks. They may sketch a network of the streets without any loop because they have omitted other streets segments, in particular at the edge of the piece of paper. We therefore consider city blocks as areas bounded not only by the street segments, but also by page-boundary.

### 3.3. Cognitively Oriented Sketch Aspects for Alignment

To successfully align a sketch map with its corresponding metric map, we need a set of relevant sketch aspects which can be used for alignment. These are typically those sketch aspects which are not subject to schematization, distortion or any other cognitive impact. The following set of sketch aspects was identified based on a series of experiments (Wang et al., 2009, 2010, 2011). To evaluate these sketch aspects, we compare 42 sketch maps of three study areas with their corresponding metric maps and computed the accuracy of identified sketch aspects. These sketch aspects showing a high level of accuracy are suitable for alignment. They are described next and visualized in Figure 2.

**3.3.1. Topology of Street Segments in Street Network.** This sketch aspect describes the connectivity of street segments at junctions. In sketch maps, street segments are usually connected; isolated street segments are rarely found. Despite the distorted shape and size of street segments, the topology of street segments is well preserved with very high accuracy rate: 98.0% with
3.3.2. Orientation of Street Segments in Street Network. This sketch aspect describes binary directional relations of two street segments that coincide in at least one junction point. The reference street segment is represented by marking out the start and end points. The line that goes through the start and the end points of the reference street segment divides the plane into right and left. We distinguish six directional relations: front, front-right, front-left, back, back-right, and back-left. Among overall 1108 street segments extracted from our study areas, only 26 street segments are not placed with the correct directions with respect to their reference street segments. The accuracy rate of orientation of street segments represented in street network is 97.7%.

3.3.3. Orientation of Landmarks with Respect to Street Segments. This sketch aspect describes the position of a landmark with respect to its nearby oriented
street segments. The same as sketch aspect (B), an oriented street segment is represented by its start point and end point. The position of the referent landmark can be either to the right of or to the left of the reference street segment. The accuracy rate of orientation of landmarks with respect to street segments is 94.9% calculated from 490 landmarks.

3.3.4. Order of Landmarks and Junctions along a Route. This sketch aspect describes the linear ordering of landmarks and junctions along a route. A route is defined as connected street segments. We distinguish three order relations before, after, and overlap and three kinds of linear orderings:

- only landmarks as referent objects on one or both sides of the route
- only junctions as referent objects on one or both sides of the route
- both landmarks and junctions as referent objects on one or both sides of the route.

In total 41 sketch maps are examined. One sketch map is excluded because it does not contain enough landmarks. The accuracy rate is presented as follows:

- landmarks only: 97.9% with 233 landmarks (left), 97.2% with 320 landmarks (right), and 95.8% with 574 landmarks (both sides)
- junctions only: 99.3% with 287 junctions (left), 100% with 306 junctions (right), and 98.2% with 615 junctions (both sides)
- landmarks and junctions: 98.0% with altogether 545 landmarks and junctions (left), 97.8% with altogether 645 landmarks and junctions (right), 96% with 1196 altogether landmarks and junctions (both sides).

Choosing the combination of both landmarks and junctions as referent objects is the best solution. Its accuracy is approximately equally high and the number of referent objects and thus the informative value is higher. The visualization in Figure 2 shows only the ordering of both landmarks and junctions located at both sides of the route without distinguishing the sides. We choose the route with the maximum number of referent objects in our study.

3.3.5. Order of Landmarks and Street Segments around Junction. This aspect describes the circular ordering of nearby landmarks and connected street segments as referent objects around a junction. Similar to sketch aspect (D), we distinguish different types of referent objects:

- only landmarks as referent objects
- only street segments as referent objects
- both landmarks and street segments as referent objects.

The resulting order is built on a clockwise circular ordering of surrounding landmarks and connected street segments. In total 41 sketch maps are
examined. One sketch map is excluded because it does not contain enough landmarks. The accuracy rate is presented as follows:

- landmarks only: 99.3% with 141 landmarks
- street segments only: 98.4% with 320 street segments
- landmarks and street segments: 98.7% with 524 landmarks and 320 segments.

Using landmarks and streets as referent objects has the advantage that the number of referent objects, and thus the information value is higher.

3.3.6. Topology of City Blocks. The topological relations between city blocks capture their adjacency. Because street information is incomplete in sketch maps, we find aggregated city blocks covering larger areas quite often in our study. We include both enclosed city blocks and open ones in our study. Only atomic city blocks which cannot be further divided into smaller ones are analyzed. We distinguish two topological relations: touch and disconnect. The accuracy rate is 99.7% with 375 city blocks.

3.3.7. Topology of City Blocks and Landmarks. This sketch aspect describes topological relations between city blocks and landmarks. Both city blocks and landmarks are represented as 2-D regions. We distinguish two topological relations inside and outside. For in total 490 landmarks, only 21 landmarks are misplaced in wrong city blocks. The overall accuracy rate is 95.3% with 490 landmarks and 375 city blocks. Missing and aggregated city blocks (if their topological relations are correct) are not counted as errors in our study.

4. THE SketchMapia FRAMEWORK

The following sections provide an overview of the information that SketchMapia extracts from sketch maps and how this information is used to establish an alignment between the sketched environment and the corresponding environment shown on a metric map.

The SketchMapia framework receives a sketch map and its corresponding section of a metric map as input. The sketched elements are extracted from the sketch map (step 1, Figure 3). As mentioned in the previous section, seven sketch aspects referring to topology, orientation and ordering information are considered relevant for sketch map alignment. In step 2, sketch and metric map are qualified using existing qualitative formalizations. The sketch aspects are formalized as qualitative constraint networks (QCN). In step 3a we align both QCNs for the sketch and the metric map and generate a set of match candidates, i.e., a set of pairwise matches between elements of the sketch map and those of the metric map within one qualitative representation. Step 3b brings together the match candidates for each sketch aspect and produces a consistent alignment across different sketch aspects. Those street segments,
Figure 3. Steps of the SketchMapia framework: extraction of elements (step 1), descriptions of their qualitative relations (step 2), and alignment within and across qualitative representations (step 3).

junctions, landmarks and city blocks are matched, which get the most support across different qualitative sketch aspects. The following sections describe each step in further detail.

4.1. Step 1: Element Extraction

We apply standardized algorithms to transform the sketch map into a black and white image with homogeneous illumination (Sezgin & Sankur, 2004).
Figure 4. Segmentation and structural recognition of objects in sketch maps.

and separate texts and symbols (Tombre et al., 2002). The remaining map contains only region-based objects such as street segments, junctions, landmarks. To identify, localize and recognize these sketched elements, we first partition the image into regions that represent objects (segmentation) and then classify objects based on their geometric appearance (semantic recognition) (Broelemann, 2011).

The segmentation algorithm is a variation of the watershed algorithm (Cousty et al., 2009). This algorithm iteratively floods the image starting at seeding points to partition the image into regions that represent the objects of the sketch map. Each region is represented by a set of pixels belonging to this region. We develop mechanisms to deal with visual artifacts (e.g., as a result of noise in the original image) and typical drawing effects found in hand-drawn sketch maps such as small gaps between lines, and streets with open ends or closed streets where side streets start (Broelemann & Jiang, 2013). Figure 4 shows the result of the segmentation, where the sketch map is separated into regions and one region represents exactly one object in the sketch map.

The semantic recognition uses pattern recognition classifiers (Duda et al., 2000) together with probabilistic relaxation techniques (Kittler & Illingworth, 1985) to identify the most probable class for each object. We are able to distinguish street segments with junctions and landmarks using attributes like shape (e.g., curvature or elongation), size, and compactness of the region as well as relations between regions such as connectedness, distance, or length of the common border. These attributes and relations can be computed from the segmentation result. By adding hierarchical relations, we are also able to compensate over-segmentation errors from the watershed algorithm. For a better semantic recognition, the information of the written text has to be used. However, this goes beyond the scope of this article.

4.2. Step 2: Qualitative Spatial Representation

Here, we propose a qualitative spatial representation for each sketch aspect identified earlier. Unlike metric maps, sketch maps do not have a single, global
reference frame. Rather the sketched elements themselves act as referencing object. Although topological relations (criteria A, F, and G) are globally computed, orientation (criteria B, C) and order relations (criteria D, E) can only be computed at a local level. Due to cognitive impact, orientation and order relations of distant objects are likely to be distorted. Thus, our qualitative representations of orientation and order information are computed only on a local level between nearby objects. Street segments or junctions are used as reference objects to localize nearby landmarks and other street segments. Nearness is defined via the relative metric distance and the distance in a Voronoi diagram (Aurenhammer, 1991): A buffer around the reference objects defines the relative metric distance. An object is called nearby or local, if its footprint intersects with the buffer around the reference object and shares a line in the Voronoi diagram with the reference object. Objects in a street network are nearby or local, if they are directly connected, i.e., street segments being connected to the same junction or junctions being connected to the same street segment.

4.2.1. Topology of Street Segments in Street Network. DRA7, a coarsened version of the dipole relation algebra (DRA) (Moratz et al., 2000), is used to capture the connectivity information of street segments in a street network (Wallgrün et al., 2010; Chipofya, 2012). It captures the topology of sets of oriented line segments called dipoles. A dipole is an ordered pair of points in $\mathbb{R}^2$ which can be written as $A = (a_s, a_e)$, where $a_s$ and $a_e$ are the start-and end-point of $a$, respectively. A basic DRA relation between two dipoles $A$ and $B$ is represented by a 4-tuple $s_B e_B s_A e_A$ where $s_B$ is the position of the start-point of dipole $B$ with respect to dipole $A$. The other three elements of the relation $e_B, s_A,$ and $e_A$ are defined analogously. For DRA7, the possible positions of the start-/end-point of one dipole with respect to another dipole are $s$ (coincides with the start-point), $e$ (coincides with the end-point), and $x$ (coincides with neither start-point nor end-point).

For sketch map alignment, we use the start and end points of street segments (junctions) to define dipoles. Figure 5 shows the qualitative constraint network for topology of street segments. For example, the junctions $a, b, c, e$ and $f$ define the dipoles $ab, bc, ef$ and $bf$. The relations for $(ab, bc)$, $(bc, bf)$, and $(ef, bf)$ are $exxx$, $xxxx$, and $xexe$, respectively. The seven basic relations of DRA7 include the three listed above, $sese$, $eses$, $xexe$, and $xxxx$ for disconnected street segments.

4.2.2. Orientation of Street Segments in Street Network. The Oriented Point Relation Algebra (OPRA) of Moratz et al. (2005) is used for the formal representation of the relative orientations of street segments with respect to each other. The primitive entities are oriented points. In sketch maps these are junctions with the orientation given by the connected street seg-
Figure 5. Qualitative constraint network for the topology of street segments. The visualization includes only connected street segments. All other street segments are related via xxxx.

Figure 6. The eight possible relative positions $b^{bc}$ in OPRA_{16}.

ment: for example, junction $b$ with the orientation towards $c$ is written as $b^{bc}$. The relations can be represented at variable granularities. Klippel and Montello (2007) distinguish eight different turn directions, which seem to be suitable in a schematized visualization. For the metric maps, a further simplification to only four directions might be useful.\textsuperscript{7} OPRA_{16} (Lücke et al., 2011) is applied here, because it can represent Klippel’s eight directions, but can be aggregated to four relations as well: The plane around a junction is partitioned into 16 planar and 16 linear sectors (Figure 6). We define eight possible relative positions by the following mapping of sectors

\textsuperscript{7}We are aware of the fact, that these angles were suggested for navigation in street networks. Investigations to what extent these angles are applicable also to street networks in survey maps are ongoing.
to relations:

- Front (f) → \{62, 63, 0, 1, 2\}
- Half left (hl) → \{3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13\}
- Left (l) → \{14, 15, 16, 17, 18\}
- Sharp left (sl) → \{19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29\}
- Back → \{30, 31, 32, 33, 34\}
- Sharp right (sr) → \{35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45\}
- Right (r) → \{46, 47, 48, 49, 50\}
- Half right (hr) → \{51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61\}

For two junctions \(a\) with the orientation \(ab\) and \(b\) with the orientation \(bc\), an OPRA relation is distinguished by the position \(j\) of \(a\) with respect to \(b\), and the position \(i\) of \(b\) with respect to \(a\) written as \(a^{ab} <_i^j b^{bc}\). In the sketch map, oriented junction \(a\) has the following relation to oriented junction \(b\): \(a^{ab} <_{\text{back}} b^{bc}\), which means \(b\) is to the front of \(a\) and \(a\) is to the back of \(b\). The relation between a pair of oriented junctions gives their relative locations based on their intrinsic orientation particularly distinguishing whether one is on the left or on the right side of the other. But capturing the relative orientation of an outgoing street segment requires relative orientations with respect to both preceding and succeeding segments. Figure 7 shows the resulting QCN.

**Figure 7.** QCN for orientation of street segments for junction \(b\) and all locally related junctions \(a\), \(d\), and \(f\). For the sake of readability, we do not visualize all relations, but only junction \(b\) with respect to the oriented junctions \(a\), \(c\), and \(f\) with an orientation towards \(b\).
4.2.3. Orientation of Landmarks with Respect to Street Segments. We apply the ternary LR Calculus (Scivos & Nebel, 2004), an enhanced and refined version of the FlipFlop Calculus (Ligozat, 1993) to represent orientation information of landmarks with respect to street segments qualitatively. The proposed model deals with point-type entities. Because the footprint of landmarks is captured by polygons, we approximate landmarks by the centroid of their footprints. The street segments defined by their start and end points are used as reference objects to extract the orientation information.

For configurations with $A \neq B$, the LR calculus distinguishes qualitative relations such as left, right, inside, front, back, start, and end. It introduces the relations $dou$ ($A = B \neq C$) and $tri$ ($A = B = C$) as additional relations. The orientation relation of an object using LR is represented as $A, B(relLR)C$.

As explained at the beginning of this section, we consider only orientation information of landmarks nearby the reference street segment. The obtained orientation information of landmarks with respect to street segments is represented as $r(a, b : l_1)$, where relation $r$ represents orientation information of landmark $l_1$ with respect to street segment $ab$. Similarly, we use ternary operations (Zimmermann & Freksa, 1996) to infer qualitative knowledge based on previously obtained qualitative information. Figure 8 shows the resulting QCN.

4.2.4. Order of Landmarks and Street Segments Along Route. We apply a coarse version of the Interval Algebra (IA) by Allen (1983) to represent ordering information of landmarks and street segments along a specific route in the street network. A route is a set of connected street segments. We
considered the ordering relations of these street segments and landmarks nearby the route. The interval algebra analyzes the temporal relations of intervals along the time line and distinguishes thirteen relations: before (\(<\))\), overlaps (\(\cup\)), meets (\(\cap\)) during (\(\cap\)), equal (\(=\)) starts (\(s\)), finishes (\(f\)), and the inverse relations after (\(>\)), \(oi\), \(di\), \(si\), and \(fi\). Figure 9 illustrates how intervals are determined. Following the cognitive analysis, we coarsened the relations and distinguish only three relations: before (which include IA relations \(<\) and \(m\)), after (which include IA relations \(>\) and \(mi\)), and overlap (which include IA relations \(o\) \(d\) \(s\) \(f\) and their inverse \(oi\) \(di\) \(si\) \(fi\)).

When following a route, we traverse one street segment after another and pass by landmarks one after another. The route is interpreted as time line. Each street segment is interpreted as closed interval on the time line defined by its start and end junction. Each landmark is also interpreted as closed interval on the time line: The dotted lines perpendicular to the route illustrate the procedure to project the interval of a landmark onto the route. Landmarks might also start before or end after the route.

In our running example, the route with the maximum landmarks on it is \(efbcd\). Figure 9 visualizes the intervals for landmarks and their relations to the street segment intervals on the route. For example, the interval describing the landmark \(l_2\) is during the street segment \(bc\), but before the interval describing landmark \(l_3\). We visually represent the relations of all time intervals on the route and list some of the relations formally below using the coarsened version of Allen’s IA.

**Figure 9.** Ordering of street segments and landmarks along route using coarse relations of Allen’s IA.
4.2.5. Order of Landmarks and Street Segments Around Junction. We use the Cyclic Interval Algebra (CIA) suggested by Osmani (2004) to extract the ordering information of street segments and landmarks (as extended objects) around a junction. This representation accounts for the spatial and angular extensions of landmarks. The Cyclic Interval Algebra expresses relations of intervals (called c-intervals) on a circle using slightly modified IA relations. Due to the circular nature of the timeline, the IA relations before and after are merged into a single relation called disjoint from (ppi). Like IA, CIA distinguishes the relations overlaps (o), starts (s), during (d), finishes (f), meets (m), their inverse relations, and the relation equals (eq). CIA also includes four additional relations accounting for the cyclic nature of the embedding space: moi (m and oi), ooi (o and oi), mmi (m and mi), omi (o and mi).

Junctions serve as reference points and form the center of the oriented circle in CIA. We consider only connected street segments and their nearby landmarks. A meaningful representation contains at least three intervals, e.g., two street segments and one landmark around one junction. The c-intervals of the landmarks and the angle between two street segments are their projections onto a (unit) circle around the junction. The c-intervals are defined as closed intervals on a real circle.

Figure 10 shows the c-intervals corresponding to landmarks and street segments around a junction b with its surrounding landmarks l₁ to l₄ and surrounding street segments ab, bf, and bc. The street network is represented as intervals in-between two street segments, i.e., street segment ab and street segment bc are represented via the c-interval sₑₑₐ on a real unit circle between ab and bc. In our running example, the interval describing landmark

![Figure 10](image_url)
4.2.6. Topology of City Blocks. City blocks in the sketch map are stored as polygons and their topological relations are interpreted as relations in circular string based topological model (Li & Liu, 2010). Using this representation, the atomic topological relation between two convex regions can be uniquely represented as a circular string. The circular strings \( \{(e), (u), (v), (x), (y)\} \) represent the atomic topological relations disconnect (DC), nontangential proper part and its inverse (NTPP, NTPP-i), and two refine subrelations (x and y) for the externally connect of RCC (Randell et al., 1992). Similarly, the combinations of strings represent partially-overlap (PO), tangential proper part and its inverse (TPP, TPP-i) of RCC-8. The string-based topological model provides a complete classification for topological relations between regions. The refine subrelations for EC distinguish the topological relations between regions which are externally connected by lines or points. Thus, we can distinguish city blocks connected by street segments or junctions (which we cannot with RCC-8).

In frehand sketches, the city blocks are mixed (concave and convex) regions surrounded by street segments. For qualitative representation of concave city blocks, we use a procedure of decomposing the concave city block into a set of triangles, known as triangulation (Eberly, 2002). In triangulation, concave polygon of \( n \) vertices is decomposed into \( n-2 \) triangles with the help of the ear-clipping algorithm (further details in Jan et al., 2014).

City blocks are delineated by street segments. It is worth noting at this point that although the street network defines the topology of city blocks, these two structures are not equivalent to each other, because some street segments are not part of the city block topology.

By their definition, a city block is constituted by a connected region and no two city blocks can overlap. The adjacency between city blocks are represented using an adjacency matrix (Theobald, 2001). Each boundary street segment in the sketch map corresponds to a value of 1 in the intersections of the rows and columns of the matrix for the city blocks which it borders (Figure 11). The adjacency matrix is important for both alignment and determination of city blocks when city blocks are aggregated. When comparing sketch maps, it is common to encounter aggregated city blocks due to their incompleteness. Consequently, two externally connected regions can only be aggregated if their intersection is not a single point.

4.2.7. Topology of City Blocks and Landmarks. The topological constraints on landmarks and city blocks together allow us to partially constrain the possible locations of landmarks. Although city blocks are not overlapping, a landmark may overlap several city blocks. In addition, the distinction between
overlapping and disjoint borders becomes less important when landmarks are involved. This is because sketchers are in general not precise about the relations involving landmarks boundaries. Therefore RCC-5 is used to represent the relations among landmarks. RCC-5 has five basic relations such as DC, O, PP, PPi, and EQ.

4.3. Step 3a: Alignment within Sketch Aspects

The qualitative representations of a sketch map and those of a metric map are matched pairwise based on the calculi over which they are defined. We assume that we are given a set of sketched objects $O = \{o_1, o_2, \ldots, o_{|S|}\}$, a set of metric map objects $O' = \{o'_1, o'_2, \ldots, o'_{|M|}\}$, and for each of the sets of objects, $O$ say, a set of qualitative constraint networks $Q(O) = \{(N_c(O), R_{N_c}(O))\}, c \in C$. Here $C$ is the set of qualitative spatial calculi used in the representations, $N_c(O) \subseteq O$ are the objects in $O$ for which relations from the calculus $c \in C$ have been specified and $R_{N_c}(O)$ are the $c$ relations among objects in $N_c(O)$.

A match $m \subseteq O \times O'$ is a set of object pairs $\{(o_i, o'_j), \ldots\}$ such that no two of them contain the same object from either of the two maps. That is, objects are matched uniquely. The matching itself is done by successively adding a pair of objects to an existing match. Starting at the empty match a pair of objects, one from the sketch map and one from the metric map, are selected and added to the match. At each point several pairs may be selected creating several extensions to the current match. As per our definition of match, a pair is added if and only if none of the objects in that pair is already matched with another object in the current match.

The foregoing discussion entails a search space with a binomial shape. The space is most dense around the region containing matches $m$ with $|m| = (|O|+|O'|)/2$. To explore this space the Tabu metaheuristic search strategy of Glover (1989) is used. The main important aspect of tabu search is its effective use of memory (based on tabu attributes of solutions) to drive the search into

![Figure 11. Qualitative constraint network of the topological relations between city blocks (string-based relations) and landmark-city blocks (RCC-5).](image-url)
areas that are more likely to generate high quality solutions (Chipofya et al., 2013).

In our case quality is determined by the number of correctly matched objects. The correctness of the match is based on the admissibility criteria introduced in Wallgrün et al. (2010). In that work a match \( m \) is admissible if (i) For every pair of objects \( o_i \) and \( o_j \) of \( O \) that are matched with objects \( o'_{k} \) and \( o'_{l} \) of \( O' \), respectively, in the match \( m \), the constraint holding between \( o_i \) and \( o_j \) is compatible with the constraint between \( o'_{k} \) and \( o'_{l} \) in terms of a nonempty intersection, and (ii) replacing the original relations with these intersections still yields two consistent sets of constraints.

The search algorithm is driven by an evaluation function \( f(m) \) equal to the size of \( m \) and a heuristic \( h(m) = f(m) + g(m) \) combines the evaluation of \( m \) with an estimate of its extensibility into a new solution \( m' \) with \( f(m) < f(m') \). \( g(m) \) is computed in the same manner as was done in Wallgrün et al. (2010).

The algorithm executes until a solution is found or a number of iterations as determined during its invocation have elapsed. This number can be set to a very high value such as 100,000 if a complete solution is sought provided symmetries are small and isolated.

4.4. Step 3b: Alignment across Sketch Aspects

Given that the maps being matched are represented on multiple dimensions, the above matching procedure can be optimized further by relating the different dimensions during each iteration. This relationship is established in terms of restrictions on the allowed combinations of spatial constraints. For each pair of representational languages a compatibility table specifies the acceptable combinations of constraints expressed in them. For example, given three mutually adjacent street segments, they cannot all be part of the external boundary of the same city block. This restriction implies that the search should not explore paths going beyond or towards configurations that violate it.

5. EXEMPLARY EVALUATION OF SketchMapia

We propose a three-step alignment approach: After the segmentation and object recognition (step 1), we propose qualitative representations of reliable sketch aspects to compute qualitative constraint networks (step 2), which are used for alignment (step 3). As the focus of this article is on step 2, the evaluation addresses only this step. We apply the segmentation and object recognition to three sketch maps and evaluate the qualitative representations proposed earlier for the seven sketch aspects proposed earlier. A more extensive evaluation of step 2 for a larger number of sketch maps can be found in
Step 3, which is briefly described here, cannot be evaluated at the current state of the project, thus its current state is described.

We use three sketch maps for the evaluation. Each sketch map covers an area of approximately 1 km$^2$. The sketch maps are generated by three different people. All sketchers were familiar with the area, because their student dormitory and the university building are located within the study area. For our evaluation, we consider all depicted spatial objects in sketch maps and the corresponding spatial objects from the metric map.

### 5.1. Result of Step 1: Element Extraction

Figure 12 shows the result of step 1: three sketch maps after segmentation and structural recognition of objects. We annotated the sketch maps by labeling the landmarks and the street network with its street segments and nodes. Figure 13 shows the metric map of the corresponding area.

![Figure 12. Three sketch maps and their segmentations used for the evaluation.](image-url)
5.2. Evaluation of Step 2: Qualitative Representation

In the following we evaluate step 2, the qualitative representations proposed earlier. We extract qualitative information in the form of QCNs from the geometric information from the sketch and the metric map. For the qualification we use the qualitative spatial reasoner SparQ (Wolter, 2009) in combination with manual analysis for those spatial representations not supported by SparQ and compute the qualitative information from the quantitative representation of sketch and metric maps. Next, the obtained QCNs of the sketch maps are compared with QCN derived from the metric map to determine the degree to which the information is identical. If the representations proposed above are suitable, the QCNs of both maps should be identical to a high degree.

To align sketch and metric maps we identify possible pairing of nodes from one QCN with those in the other QCN. Finding possible pairs of nodes requires the correct correspondence between the spatial entities depicted in sketch maps and entities in metric maps. In this part of the evaluation, the hypothesis of matching elements is generated based on a visual analysis, where we consider each depicted spatial object from sketch map and identify their corresponding objects in the metric map.

Note that the sketch maps show information at an aggregated level, in particular the street network is highly aggregated. For this evaluation, we aggregate the information in the metric map manually (after our participants completed drawing the sketch map, we asked them to indicate the corresponding street segment for every sketched street segment, thus we got
information on how streets were aggregated). The automatic aggregation is another complex problem which is subject to future work.

5.2.1. Topology of Street Segments in Street Network. Above we proposed DRA\textsubscript{7} to capture the topology of street segments at a global level. The qualitative constraints from sketch maps and the metric map are tabularized to align and compare topological relations of street segments in the street network. The qualitative constraints derived using DRA\textsubscript{7} has an accuracy rate of 98.2\%, i.e., almost all connected street segments (with manual aggregation) are depicted correctly in the sketch maps. Thus, the proposed formalization is highly reliable for alignment (Table 1). We compared our approach to other representations such as DRA\textsubscript{24} and DRA\textsubscript{69} (Moratz et al., 2000). Note that DRA\textsubscript{24} and DRA\textsubscript{69} convey also orientation information. The accuracy rate was 91.6\% for both DRA\textsubscript{24} and DRA\textsubscript{69}.

5.2.2. Orientation of Street Segments in Street Network. We propose OPRA\textsubscript{16} to capture the orientation of street segments at a local level. The qualitative constraints from sketch maps and the metric map are tabularized to align and compare orientation relations of street segments in the street network. We used the eight sectors proposed by Klippel and Montello (2007) for turn directions to evaluate the orientation relations within OPRA\textsubscript{16}. Our evaluation indicates that we find only four relations in sketch maps (left, right, front and back), but metric maps show a higher variability in angles (Table 2). Our test area was the city center of Muenster, a European city with many curved streets in the center. We found many half left/right and sharp left/right streets in the metric map. Using all eight sectors, the mean accuracy is only 71.2\%.

Thus, the distinction in eight sectors seems to be unsuitable for alignment of sketch maps. However, if only four relations are distinguished and half left, sharp left and left are aggregated to left (for the right side analogously), the accuracy rate increases: The qualitative constraints for OPRA\textsubscript{16} with four relations derived have an accuracy rate of 98.9\% (Table 3). The aggregation seems to be more plausible for schematized street networks in sketch maps. As mentioned before, the empirical evaluation of these angles is still ongoing.

<p>| Table 1. Errors and accuracy in connectivity of street segments in the street network using DRA\textsubscript{7} |</p>
<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>111</td>
<td>2</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>45</td>
<td>0</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>109</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>88</td>
<td>2</td>
</tr>
</tbody>
</table>
On an aggregated level with only four relations, two errors are found for \( n_{10} \) to \( n_9 \) and \( n_{17} \).

5.2.3. Orientation of Landmarks with Respect to Street Segments. We proposed the \( LR \) calculus to capture orientation information of landmarks with respect to street segment at local level. The metric map contains footprints of many houses. In the comparison we considered only those which are captured by the sketch map as well. The qualify operation is applied to both data sets to obtain the QCNs, which are tabularized afterwards. The overall evaluation shows that the proposed representation provides 99.0% correct orientation relations (Table 4). Thus, the proposed representation is highly suitable for alignment of sketch and metric maps. We compare these results to the QCN obtained from the Single Cross Calculus (SCC) (Freksa, 1992). The accuracy

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>130</td>
<td>2</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>47</td>
<td>0</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>111</td>
<td>2</td>
</tr>
<tr>
<td>Average</td>
<td>96</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 4. Accuracy of orientation information of landmarks with respect to street segments using LR calculus

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>26</td>
<td>0</td>
</tr>
</tbody>
</table>

A rate drop to 89.9%. We exclude the Double Cross Calculus (DCC) (Freksa, 1992) in the evaluation as it is not closed under composition and permutation and there exists no finite refinement of the base relations with such a closure property (Scivos & Nebel, 2004).

5.2.4. Order of Landmarks and Street Segments Along Route. We use the coarsened version of Allen’s Interval Algebra in order to extract linear ordering of landmarks and street segments along the route at a local level. In a sketch map, the footprints of landmarks are approximated by polygons and routes are represented as sequence of junctions. For the ordering information, we consider start and end points of landmarks and sequence of street segments along the route as intervals. For our analysis, we select the route in sketch maps that contains the maximum number of landmarks. We interpret a route as time line and traverse one street segment after another. We extract qualitative ordering information in the form of QCNs for both street segments and landmarks that pass by one after another (Table 5). The accuracy rate for the coarse IA was 98.4% for the longest route (Table 6).

Table 5. Excerpt of the comparison table of ordering constraints of landmarks and street segments along a route for sketch map 1

<table>
<thead>
<tr>
<th>MM</th>
<th>SM1</th>
<th>n1-n2</th>
<th>n2-n3</th>
<th>n3-n4</th>
<th>n4-n5</th>
<th>n5-n6</th>
<th>n6-n7</th>
<th>n7-n8</th>
<th>n8-n9</th>
<th>n9-n10</th>
<th>n10-n11</th>
<th>n11-n12</th>
<th>LM74</th>
<th>a10</th>
<th>h9</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1-n2</td>
<td>o</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>o</td>
<td>&lt;</td>
<td>&lt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n2-n3</td>
<td>&gt;</td>
<td>&gt;</td>
<td>o</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>o</td>
<td>o</td>
<td>&lt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n3-n4</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td></td>
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<tr>
<td>n4-n5</td>
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<td>&gt;</td>
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<td>&gt;</td>
<td>&lt;</td>
<td>&gt;</td>
<td>&lt;</td>
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<tr>
<td>n5-n6</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
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<td>&gt;</td>
<td>&gt;</td>
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<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n6-n7</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
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<tr>
<td>n7-n8</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
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<td>&gt;</td>
<td>&gt;</td>
<td>&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One error exists with respect to the position of landmark b9 and street segment n4-n5.
Alignment of Sketch and Metric Maps

Table 6. Accuracy of ordering information along a route using coarse IA relations

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>592</td>
<td>9</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>91</td>
<td>3</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>169</td>
<td>0</td>
</tr>
<tr>
<td>Average</td>
<td>284</td>
<td>4</td>
</tr>
</tbody>
</table>

5.2.5. Order of Landmarks and Street Segments Round Junction. For the evaluation of landmarks and street segments around junctions we used the CIA representation. The evaluation was done on the two junctions with the most landmarks in each sketch map. The qualitative constraints derived have an accuracy rate of 97.2% (Table 7). Thus, the proposed formalization is highly reliable for alignment.

5.2.6. Topology City Blocks. We proposed the string based topological model to capture the topology of city blocks at a global level. The qualitative constraints from sketch maps and the metric map are tabularized to align and compare topological relations of city blocks (Table 8). The qualitative constraints derived have an accuracy rate of 99.25% (Table 9), i.e., the topological relations were almost always depicted correctly (at an aggregated level). Thus, the proposed formalization is highly reliable for alignment.

5.2.7. Topology City Blocks and Landmarks. We proposed RCC-5 to capture the topology of landmarks with respect to city blocks at a global level. The qualitative constraints from sketch maps and the metric map are tabularized to align and compare topologic relations of landmarks and city blocks. The qualitative constraints derived have an accuracy rate of 100.0% (Table 10), i.e., the topological relations were always depicted correctly. Thus, the proposed formalization is highly reliable for alignment.

Table 7. Accuracy of cyclic ordering information around junctions using CIA

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>113</td>
<td>2</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>89</td>
<td>4</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>Average</td>
<td>100</td>
<td>2.7</td>
</tr>
</tbody>
</table>
5.3. Current State of Step 3: Alignment

The evaluation in the preceding section demonstrates what sketch aspects are reliable and how many constraints are produced. For the alignment, we need sketch aspects with high accuracy and high information value as well. Thus, the alignment starts with matching identifiable landmarks. Based on these match hypotheses, the algorithm continues to align the street segments, city blocks and other landmarks based on topology, connectivity, and relative orientation.

### Table 9. Accuracy of topological information among city blocks

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>169</td>
<td>1 99.41%</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>49</td>
<td>0 100.0%</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>121</td>
<td>2 98.35%</td>
</tr>
<tr>
<td>Average</td>
<td>113</td>
<td>1 99.25%</td>
</tr>
</tbody>
</table>

### Table 10. Accuracy of topological information of landmarks and city blocks

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Errors</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch map 1</td>
<td>209</td>
<td>0 100.0%</td>
</tr>
<tr>
<td>Sketch map 2</td>
<td>36</td>
<td>0 100.0%</td>
</tr>
<tr>
<td>Sketch map 3</td>
<td>100</td>
<td>0 100.0%</td>
</tr>
<tr>
<td>Average</td>
<td>115</td>
<td>0 100.0%</td>
</tr>
</tbody>
</table>
6. CONCLUSION AND FUTURE WORK

Sketch maps represent the physical environment in a highly schematized and distorted way. In this article, we describe a qualitative approach to align spatial objects and spatial relations in sketch maps with metric maps. Based on empirical studies, we identify qualitative aspects that are typically not affected by, thus are reliable aspects for alignment. These sketch aspects address the topology, orientation, and ordering information of street segments, junctions, landmarks, and city blocks. We apply existing qualitative representations to formalize these aspects in qualitative constraint networks. We develop a procedure to compare QCNs obtained from both sketch maps and corresponding metric maps to evaluate their level of accordance. A reliable alignment is supported across different sketch aspects. That is, two sketched objects correspond to each other in different QCNs. The evaluation shows that the selected representations are highly suitable for comparing sketch maps to metric maps.

This article addresses many different aspects of sketch map alignment. Due to the complexity of this highly interdisciplinary research, several problems still remain unsolved. Next steps of our research will address the following topics:

- Aggregation and generalization of information are important characteristics of human knowledge. But sketch maps are incomplete, because humans focus on relevant information. Thus, the alignment algorithm needs to be able to match aggregated sketched objects to a set of nonaggregated objects in the metric map automatically. None of the approaches mentioned earlier addresses this problem. For the purpose of testing the effectiveness and reliability of our framework, we manually conducted this alignment in our evaluation. The automatic solution is currently under development.

- The sketch aspects all contribute equally to the alignment. We neither did investigate dominance and dependency of these aspects, nor did we account for redundancy in the information. Future work needs to investigate whether some sketch aspects are primary, and others can be used for the refinement of the alignment. Furthermore, we intend to investigate qualitative representations combining two sketch aspects such as orientation and connectivity as proposed in (Chipofya, 2012).

- In accordance with findings in realms of psychology and behavioral geography, we claim that sketch maps do not have global reference systems. At least from a theoretical standpoint, global reasoning on ordering and orientation information does not make sense. We will investigate the notion of global versus local in sketch maps and test the positive and negative effects of reasoning on the alignment.

- To test the robustness of our approach, we will investigate a wider range of sketch maps using our approach. So far, we have tested the approach only on sketch maps of urban areas containing numerous landmarks and rather
small street networks. The corresponding metric maps were determined manually.

- The empirical studies on distortions and schematizations, thus also the alignment procedure focus only on survey sketch maps of urban areas. Future research investigates route sketch maps and sketch maps on different scales to investigate differences in alignment is needed.

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