MODELING SPATIAL SCENES IN DISASTER DOMAIN ONTOLOGIES

C. Lucas [a]*, S. Werder [b]

[a] Institute of Photogrammetry and Remote Sensing (IPF), Universität Karlsruhe (TH), Kaiserstraße 12, 76128 Karlsruhe, Germany – christian.lucas@ipf.uni-karlsruhe.de
[b] Institute of Cartography and Geoinformatics (IKG), Leibniz Universität Hannover, Appelstraße 9a, 30167 Hannover, Germany – stefan.werder@ikg.uni-hannover.de

Commission IV, WG IV/8

KEY WORDS: Disaster Management, Topological Relations, Spatial Modeling, Image Understanding, Geographic Information Science

ABSTRACT:

Disasters create extremely dynamic situations which have to be handled by emergency operations centers. For fulfilling their task they rely on up-to-date information from on-site units and passer-bys. Every individual has its own mental image of the situation which is recorded for situation evaluation as free-form text messages. In order to enable further automatic reasoning processes, this mental image must be taken into account. This paper focuses on modeling the topological and neighborhood relations of disaster situations. Also the spatial reasoning process and the important aspects of the used ontology are highlighted. A short introduction to orientation and distance aspects completes the required components for modeling spatial scenes as a whole.

1. INTRODUCTION

1.1 Background Situation

In the disaster management domain it is fundamental to visualize detailed up-to-date information of the situation. Thereby a situation map is an important decision base for an emergency operations center (EOC) and provides information sharing between the management staff. The up-to-date information originates from several on-site units and passer-bys located at diverse damage sites. Normally it is recorded as free-form text messages. This variety of incoming messages has to be analyzed with respect to their visualization by one operator of the management staff. With regard to digitally distributed situation maps and in order to assist the updates, the aim of this project is to apply an automated system for simplifying and speeding up the message analysis.

In order to implement the approach of a human operator with methods of information technology, several processing steps are necessary. Firstly, sentence detection and information extraction play a crucial role for formalizing and analyzing the message content. Subsequently, a step of semantic augmentation is necessary to harmonize the content, solve semantic gaps, and provide content based spatial reasoning. The final step is to create a graphical representation of the relevant information with respect to the domain specifics.

Fundamental for processing, particularly for semantic augmentation, is a knowledge base. An ontology designed with domain specific considerations is used to provide the necessary knowledge. This includes background and context information about objects as well as the relations between them. The developed ontology, named Disaster Management Data Model (DM²), was derived from the Command and Control Information Exchange Data Model (C2IEDM), used for military interoperability in the NATO (cf. Lucas et al. 2007).

1.2 Spatial Scenes

This paper focuses on modeling spatial aspects of objects in disaster domain specific ontologies. In this context the common spatial attributes of objects are their location as well as their geometric attributes (form, size and feature alignment). These elementary attributes are traditionally provided in spatial ontologies as well as geographic information systems (GIS) and allow describing discrete objects unambiguous by their dimension and location in space.

Nevertheless, in order to support a spatial reasoning process for disaster events based on textual descriptions, a more comprehensive level of spatial information is necessary. The method of object modeling within the ontology has to be comparable with the mental model of the reporting person (Frank, 1998). A mental model represents the level of geographic perception of an average citizen, and characterizes thus the perspective view of an observer. This mental image of the situation is incomplete, represents objects which seem important to the observer and does not include detailed metrics (Barkowsky, 2002). This model contains besides discrete objects also spatial scenes with interactions of two or more spatial objects in the meaning of neighborhoods or part-of-relations. Thus a detailed information level is essential for analyzing e.g. coherences of cities, districts, damage sites, and operation areas as well as for solving ambiguities. According to that, the spatial attributes of topology, neighborhood, orientation, and distance have to be taken into account for defining spatial scenes.

2. TOPOLOGICAL RELATIONS

2.1 Domain Requirements

The initial information state of a typical situation of the disaster management domain is presented in Figure 1. The situation is composed of a fire event and the respective affected regions.

---

* Corresponding Author

The regions are both static a-priori defined regions with political background like cities and districts (solid lines) and dynamic regions of the emergency administration, like damage sites and operational areas (OA) (dashed lines).

The binary topological relations of the diverse regions are easy to identify for human operators. The fire is *inside* the operational area 3 which is *disjoint* to the operational area 2 and *contained by* the damage site. The damage site *intersects* district A and B and all regions are *inside* the city and so on.

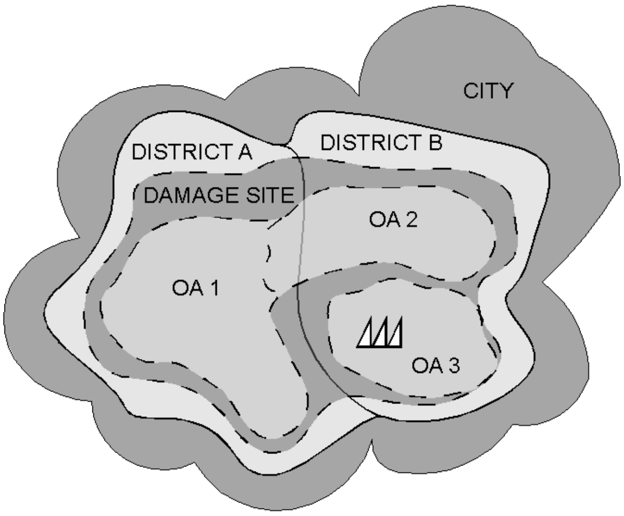

Figure 1. A fire event (ʌʌʌ) and the resulting interactions of involved administrative regions (OA - operational area)

But first of all a definition of the degree of the needed topological relations as well as the region characteristic is necessary. Based on the situation in the figure above, equation 1 defines a set Ω_R of essential topological relations in $\mathbb{R}^2$, which are adequate for representing domain specific spatial scenes.

$$\Omega_R=\{disjoint, intersect, contain, inside, equal\} \quad (1)$$

Further possible relations like *touch*[*] (OA 2 touches OA3), *cover* (damage site covers OA3) and *covered by* (inverse relation to cover) are excluded deliberately because no benefit of gaining further information was found. As a basis restriction regions have to be regular closed and without holes.

For processing, the information content of the scene in Figure 1 is also represented in a knowledge base, here the domain ontology DM². It has to be emphasized that modeling relations in such ontologies has a semantic background which is quite different from the topological one. Semantic relations are focused on entities and objects in general. So, a semantic relation is for example the part-of relationship of a fire engine and a fire brigade (a composite of engines) which does not contain topological information about the spatial situation of both. It is not possible to know at a specific point in time, if the fire engine is *contained by*, or *disjoint to* the convoy of the fire brigade. The needed information content for a correct topological representation is derivable by using background and context knowledge which is also inherent in the ontology. For example it is possible to deduce the location of a fire engine based on information of its activity. That means that an engine is located, where it extinguishes a fire. Its location is therefore independent of the location of the fire brigade.

The scene information of Figure 1 is modeled in the DM² according to the class-scheme in Figure 2. The five object classes of *fire*, *operational area*, *damage site*, *district* and *city* are obviously required. For modeling the complete semantic of this situation, the classes *context*, *building* and *address* are also necessary. Semantic modeling means here that more information is represented in the knowledge base than is inferable by the visualization solely. That way an event in general relates to an object which is affected, here a building. The relation between building and fire in the DM² is *affected by* and the inverse relation is *affects*. *Building* itself has a geographical location as well as a "semantic" location, the *address*. The relation between them is an *instance of* relationship in the ontology. That way the content given by the ontology holds much more potentially useful information for a respective reasoning process.

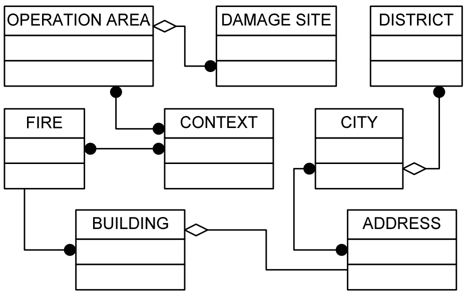

Figure 2. Part of the class scheme of the DM², in IDEF1X-notation

This kind of object modeling and reasoning is a bit more complex than a spatial query function in a GIS for relating a fire and the respective city, but it is done with respect to the systems semantic and the mental model of the staff members. This is important for adopting the reasoning process.

2.2 Topological Reasoning

Diverse methods are available for different ways of topological reasoning. They can be categorized in the three different groups of position based methods, dimension extended methods and calculus based methods. Position based methods derive the respective topological relation between regions from the position to each other. Such methods like the weighted walkthroughs model (WWM) (Cicerone and Clementini, 2003) as well as the model of ternary projective relations (TPR) (Billen and Clementini, 2004) are suitable for topological reasoning about dynamic and moving regions. More popular are dimension extended methods like the intersection model (IM) (Egenhofer and Herring, 1991) and calculus based methods like the region connection calculus (RCC) (Renz, 2002). The latter two concepts of representing a set of topological relations are quite different.

The formal categorization of topological relations by the IM is based on a comparison between the interiors δx and the boundaries x^o of objects. That way, a 4-intersection-matrix

---

[*] The touch relation is not necessary, because neighbourhood relations are defined separately.

characterizes each topological relation by a different set of empty or non-empty values. This concept is shown in equation 2 for the *contain* relation.

$$contain(x,y) \coloneqq \begin{pmatrix} x^o \cap y^o & x^o \cap \delta y \\ \delta x \cap y^o & \delta x \cap \delta y \end{pmatrix} = \begin{pmatrix} \neg\emptyset & \neg\emptyset \\ \emptyset & \emptyset \end{pmatrix} \tag{2}$$

In the 9-IM, the exterior x^c of a region is considered supplementary. Thus the topological relation is represented by a 9-intersection-matrix. But for the set of Ω_R relations *"(...) 9-intersection do not discriminate any further than the 4-intersection, they just make the terms larger*" (Hernández, 1994, p. 61). Additionally two different resolutions for representing relations in the IM exist. The so-called high resolution includes eight relations and the medium one represents the needed set of Ω_R relations.

In contrast to the IM, the RCC is based on the single axiom *connected* which implies that the regions *x* and *y* share a common point. Conditions of this axiom allow as well the definition of topological relations in two resolutions. On the one hand, the RCC9 characterizes nine possible relationships of two regions *x* and *y* and on the other hand the RCC5 explicitly the five of Ω_R. The concept of representation is shown in equation 3 again for the *contain* relation *(PP)*.

$$PP(x,y) \coloneqq P(x,y) \wedge \neg P(y,x) \tag{3}$$

where $P(x,y) \coloneqq \forall z[C(z,x) \rightarrow C(z,y)]$ (4)

$C(x,y) \coloneqq \forall x C(x,x),\ \forall x,y[C(x,y) \rightarrow C(y,x)]$ (5)

In both concepts the type of representation as well as the characteristic of the topologic relations is different. For instance a general disadvantage of the RCC is the restriction to regular closed regions for the reasoning (pointless geometry). In contrast, relations represented by the IM are also valid for the geometric primitives line and point. However, this feature of the IM is not important for the application, because relevant objects are represented by regular closed regions, due to the applications range of scale.

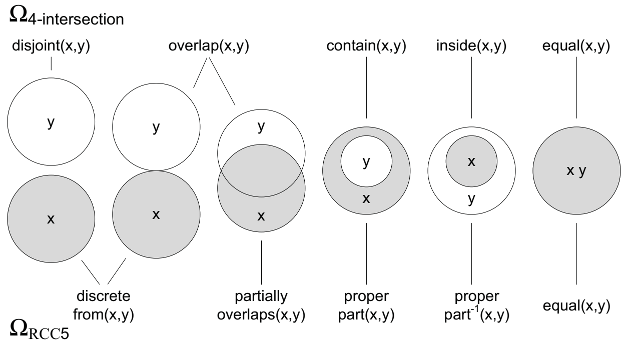

Figure 3. Characteristic of basis relations Ω in the RCC5 and the 4-intersection calculus (medium resolution)

A further aspect of both methods is the different semantic of topological relations. In contrast to the IM the RCC5 does not distinguish between the boundary and interiors of regions in its definition of the set of relations (Grigni et al. 1995). Thus the differences are between the semantic of the *disjoint* and *overlap* relations of the IM and the *discrete from* and *partially overlap* relations of the RCC5. This problem is shown in Figure 3.

For further considerations, the semantic of the Ω_R relations has to be defined with respect to the disaster management domain. The semantic defined by an operator serves as a reference because it has to be similar to human interpretation and their respective mental image. It turned out that humans do not distinguish between the interior and the boundary of a region. In Figure 1 for example the operational area 1 and 2 are disjoint and not overlapping according to human consideration.

The concept of human interpretation results in a constrained set of possible topological relations between regions. These topological constraints define the semantic of the Ω_R relations unambiguously by the equations 6 to 10. Therein x denotes the regular closed region $x = \delta x \wedge x^o$ composed by the regions interior δx and the regions boundary x^o.

$$disjoint(x,y) \coloneqq\ \delta x \cap \delta y = \emptyset \tag{6}$$
$$intersect(x,y) \coloneqq\ \delta x \cap \delta y \neq \emptyset, x \not\subseteq y, y \not\subseteq x \tag{7}$$
$$contain(x,y) \coloneqq\ y \subset x \tag{8}$$
$$inside(x,y) \coloneqq\ x \subset y \tag{9}$$
$$equal(x,y) \coloneqq\ x = y \tag{10}$$

An additional requirement of the regions respectively the relations between them, is that they have to be reflexive (eq. 11) and symmetric (eq. 12).

$$\forall x R(x,x) \tag{11}$$
$$\forall x,y[R(x,y) \rightarrow R(y,x)] \tag{12}$$

A comparison of the domain topological constraints and their respective characteristic (cf. equations 6 to 10 and , Figure 4) to the topological constraints of the IM[*] as well as the RCC5 showed that the semantic of the RCC5 is congruent with the semantic required for the domain. This aspect can be seen in figure 3 and 4.

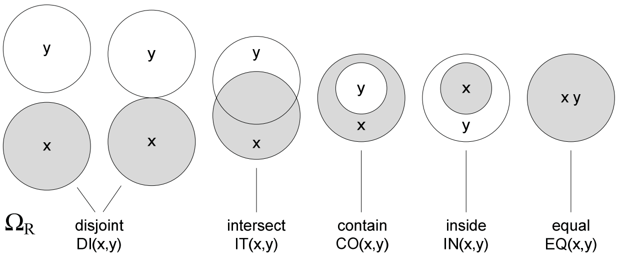

Figure 4. Characteristic of the set of Ω_R relations

Nevertheless it is also possible to define the topological relationships of the IM according to the semantic of the Ω_R relations. In contrast to the RCC the determination of the intersections in the IM is semantically correct, because the

---

[*] Topological constraints of the IM for the critical relations $disjoint(x,y) \coloneqq\ x \cap y = \emptyset$ and $overlap(x,y) \coloneqq\ x \cap y \neq \emptyset, x \not\subseteq y, y \not\subseteq x$.

intersection matrix represents always the true intersections of the interiors and boundaries of regions. That way the interpretation of the set of Ω_R relations has to be done by an algorithm of the application itself. Consequently the algorithm interprets the respective relation correctly. For example the intersection-matrix for the situation between operational area 1 and 2 is presented in equation 13.

$$R(OA1, OA2) = \begin{pmatrix} \emptyset & \emptyset \\ \emptyset & \neg\emptyset \end{pmatrix} \qquad (13)$$

The meaning of this matrix is that the intersection of the interior is empty. However, the intersection of the closure between both is non-empty. A common point on the closure is existent and the respective relation is *touch*. But the algorithm identifies this set of intersections as *disjoint*, because the intersections between the interior and the closure as well as the interiors of both are empty.

For the application in the disaster domain using the IM and an algorithm that is able to identify the set of Ω_R relations correctly has two advantages. The first one is that the IM is widely implemented in GIS and spatial databases. The second one is that this GIS component can then also be used for visualization and user feedback.

2.3 Types of Reasoning

The spatial reasoning process has to provide the needed information based on the present information state of the database as well as general and context knowledge. An example for such reasoning is the query for all operational areas which are in a damage site containing a fire (cf. Figure 1). For solving this problem two approaches are possible.

The first one is the geometric approach which is compulsory for GIS. A spatial query algorithm checks if a point location with the attribute fire is *inside* the closure of a region with the attribute damage site. The next step is to find all operational areas, which are also *inside* this damage site.

The second approach is a more elegant way of processing this question on the level of the ontology. The knowledge base contains general knowledge about the domain as well as specific knowledge about a situation. The general domain knowledge is defined a-priori by modeling the ontology accordingly (cf. chapter 2.1). For example the *part of* relation in the ontology between the two classes damage site and operational area corresponds to the topological relation *inside*. Such relations are universally valid in the whole domain. The *disjoint* relation between several operational areas as well as the *contained* relation between an operational area and an event are modeled in a similar manner (cf. Figure 5). In contrast dynamic knowledge, which is also given by the knowledgebase, is only valid for a specific situation at a specific moment. For the example the specific fire event is related to operational area 3 by the *inside* relation.

All relations which are given by the knowledge base for the situation of Figure 1, are represented in Figure 5 by solid lines. That way answering the query for all operational areas which are in the damage site of the fire is possible. The fire is *inside* operational area 3 which is also *inside* the damage site. Again all operational areas of this damage site can be provided. The advantage of this type of reasoning is that the relations are always present and do not have to be evaluated geometrically.

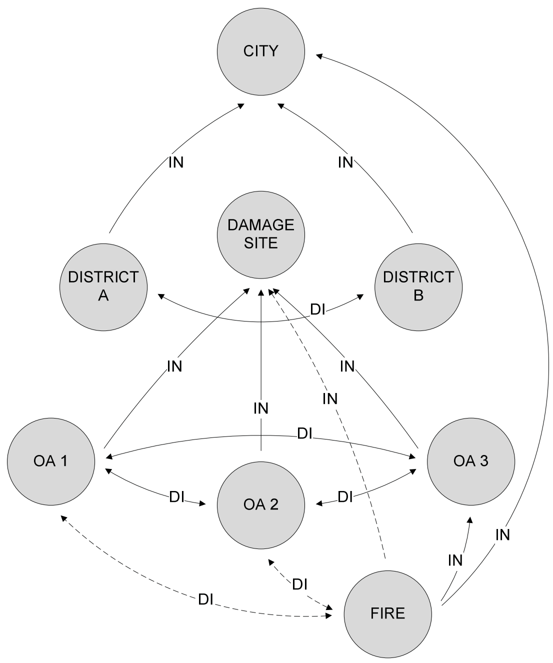

Figure 5. Ontology based inference net for topological relations of the spatial scene in Figure 1 (used shortcuts of the Ω_R cf. Figure 4)

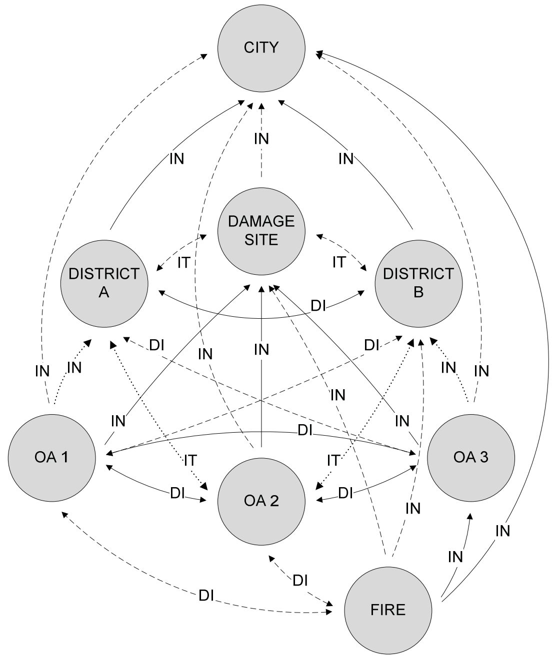

Figure 6. GIS supported inference net for the special scene of Figure 1 (used shortcuts of the Ω_R cf. Figure 4)

Another advantage of the reasoning process lies in conditions of plausible combinations of relations, so called compositions (dashed lines in Figure 5). A plausible combination is given, when the relation can be identified unambiguous. For example when the fire is *inside* the operational area 3 and operational area 3 is *inside* the damage site, then the fire is also *inside* the damage site (cf. Figure 5).

A striking disadvantage of the ontology based reasoning is the restriction of reasonable relations because the set of identifiable relations is static and predefined. As can be seen in Figure 5, direct links between the districts and the operational areas are missing. According to that, identifying the relations between both unambiguously by the compositions it is not possible. To solve this problem and to make reasoning process possible, the intersections between the regions have to be determined geometrically (dotted lines in Figure 6). After that all topological relations can be solved by the possible compositions (cf. Figure 6 with respect to clearness only an extract of all possible relations is shown).

3. NEIGHBORHOOD ASPECTS

Besides the topological relations between regions, neighborhood relations are essential for describing spatial scenes with respect to the mental model (Gold, 1992). Moreover these relations are for example important for analyzing potential risk for objects and plausibility of reports.

Neighborhoods are often geometrically defined by the Euclidean distance *di*, which generates a circumcircle around the reference object. All objects inside this circumcircle are neighbors of the reference object. This concept of defining neighborhood relations by a static distance is not very elegant and discriminates non-standard situations. Such situations are for example given by the different housing density of a region with an irregular settlement. In Figure 7, *(A,B)* as well as *(A,D)* are neighbors if the distance *di* is two units. However *(A,C)* are not neighbors, although this neighborhood is desirable. A problem arises when *di* is enlarged to three units. Then *(A,C)* are neighbors but also *(A,E),* what leads to an unsatisfactory result.

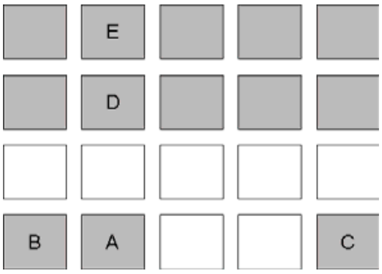

Figure 7. Example for a situation of an irregular settlement (one square represents one object (filled) as well as one length unit)

Therefore a neighborhood graph is needed which is both scale and orientation invariant and complies with the natural neighbor definition. Natural neighbors are objects which are linked by one and only one edge of a triangle. The respective generation *n* of neighborhoods is defined according to the graph theory, by the minimal number *n* of edges between them (Koch, 2007). The correct neighborhood relation with respect to the natural neighborhood for the example of Figure 7 is represented by: generation one neighbors *(A,B), (A,C)* and *(A,D),* generation two neighbors *(A,E)*. This concept is based on a triangulation defined by a set of points with a maximum of edges in between, which have a minimal length and do not cross each other. Adequate to this definitions are the minimal weight triangulation (edge remove method) as well as the Delaunay triangulation, which are quite different.

The minimal weight triangulation on the one hand starts with the complete graph between all objects. Based on this graph the shortest edge is selected and all crossing edges are removed until no edge crosses any other edge (Hlavaty and Skala, 2004). The Delaunay triangulation on the other hand is based on the so-called empty circumcircle criterion. Three points form a triangle when the circumcircle of these three points is empty (does not include other points). Both concepts of triangulation have different end functions. The minimal weight triangulation is focused on minimizing the edge lengths and the Delaunay triangulation is focused on equal edge lengths. That way the result of the Delaunay triangulation is a more ideal and homogenous meshed graph.

An example is shown in Figure 8 for a typical situation of a residential estate. The solid lines represent the respective Delaunay neighborhood graph between the objects, here buildings. This way the determination of natural neighbors of objects in terms of graph theory is ensured.

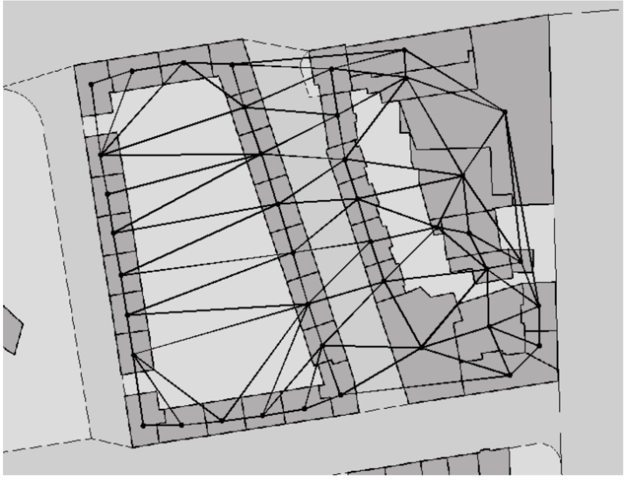

Figure 8. Delaunay triangulation between buildings based on their centre point

4. ORIENTATION AND DISTANCE ASPECTS

Modeling orientation aspects for characterizing a spatial scene is quite complex because the orientation of objects depends on the reference frame. Thus the types of reference differ as follows: *intrinsic* (orientation is given by an inherent property), *extrinsic* (external objects impose an orientation) and *deictic* (orientation is imposed by the point of view) (Hernández, 1994). According to that, the intrinsic reference is given by an inherent property of the object like the front or back side of a building. Such knowledge is a priori available and can be included in the domain ontology as a specific feature. Extrinsic and deictic references are mutable, that is why they require a reference in time, like the speakers point of view during the observation time. The basis for analyzing such references within the DM² is already given by the explicit modeling of time by tuple of object-time-location (Lucas et al., 2007). Further aspects of orientation descriptions are the canonical identifier like *in front of*, *to the right of*, or cardinal points like *north of* which also exist in free-form text reports. But solving such identifier is not task of the ontology because of the inherent given deictic references.

Distance aspects also have to be considered for characterizing spatial scenes and analyzing spatial descriptions. As a basic principle quantitative and qualitative descriptions of distance parameters have to be distinguished. Quantitative descriptions are based on units of lengths (meters) as well as units in time (minutes). According to that a quantitative description of a distance is always an isotropy. In contrast qualitative distance descriptions are terms like *quite near* or *far away*. Such descriptions are anisotropy because they depend on the observer, position, size, visibility, dominance and a lot of other features. Thus a quantitative representation of a qualitative distance can be achieved by classification with fuzzy membership functions (cf. Guesgen, 2002).

5. CONCLUSION

Information retrieval in the disaster management domain is based on verbally given descriptions of spatial scenes. Spatial scenes here are quite dynamic situations and require that topology, neighborhood, orientation as well as distance aspects are considered. For a semantically correct representation of the required general and context knowledge, complex structures are necessary, as given by ontologies.

Such ontology provides a spatial reasoning process and makes different types of reasoning possible. By modeling relations between classes, topological relations are directly inferable. To amplify this type of reasoning some additional relations have to be identified by a spatial reasoning algorithm. Therefore the intersection model (IM) and the region connection calculus (RCC) are evaluated. Both algorithms make reasoning with respect to the needed set of Ω_R topological relations possible. But using the IM algorithm seems practicable because this algorithm is already implemented in most GIS components.

For the evaluation of neighborhood relations also different methods are analyzed. The distance based definition is compared to a triangulation method, whereas the best method for representation and identification with respect to the systems requirement is the Delaunay triangulation. Based on object center points, a natural neighborhood in terms of graph theory is given by an edge of the connecting triangle.

ACKNOWLEDGEMENTS

The work of Christian Lucas has been funded by the Deutsche Forschungsgemeinschaft (DFG), project no. BA 686/16 “Abstraction of Graphically and Verbally Represented Geoinformation”.

REFERENCES

Barkowsky, T.: Mental representation and processing of geographic knowledge. Lecture Notes in Artificial Intelligence, Volume 2541, Springer, 2002.

Billen, R. and Clementini, E.: A Model for Ternary Projective Relations between Regions. Advances in Database Technology, Lecture Notes in Computer Science, Volume 2993, Springer, 2004.

Cicerone, S. and Clementini, E.: Efficient Estimation of Qualitative Topological Relations based on the Weighted Walkthroughs Model, GeoInformatica, Volume 7, pp. 211-227 , 2003.

Egenhofer, M.-J. and Herring, J.-R.: Categorizing binary topological relations between regions, lines, and points in geographic databases. Technical report, Department of Surveying Engineering, University of Maine, 1991.

Frank, A.U.: Formal models for cognition - taxonomy of spatial location description and frames of reference. Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge, pp. 293-312, 1998.

Gold, C.M.: The Meaning of ”Neighbour”. Theories and Methods of Spatio-Temporal Reasoning in Geographic Space, Volume 639, pp. 220-235, 1992.

Guesgen, H.-W.: Reasoning About Distance Based on Fuzzy Sets. Applied Intelligence, Volume 17/3, Kluwer Academic Publ., Boston, pp. 265-270, 2002.

Grigni, M., Papadias, D. and Papadimitriou. C,: Topological inference. In IJCAI-95, pp. 901-906, 1995.

Hlavaty, T. and Skala, V.: Combinatories and Triangulations. Computational Science and Its Applications, Lecture Notes in Computer Science, Volume 3045, Springer, pp. 81-89, 2002.

Hernández, D.: Qualitative Representation of Spatial Knowledge. Volume, Lecture Notes in Artificial Intelligence, Volume 804, Springer, 1994.

Koch, A.: Semantische Integration von zweidimensionalen GIS-Daten und Digitalen Geländemodellen. Dissertation, Verlag der Bayerischen Akademie der Wissenschaften, 2007.

Lucas, C., Werder, S. and Bähr, H.-P.: Information Mining for Disaster Management. International Archives of Photogrammetry, Remote Sensing and Spatial Information Science, Volume 36, Part 3, pp. 75-80, 2007.

Renz, J.: Qualitative Spatial Reasoning with Topological Information. Lecture Notes in Artificial Intelligence, Volume 2293, Springer, 2002.