Towards a Unified Model of Outdoor and Indoor Spaces

Sari Haj Hussein[*] , Hua Lu, Torben Bach Pedersen
Department of Computer Science, Aalborg University, Denmark
{sari, luhua, tbp}@cs.aau.dk

ABSTRACT

Geographic information systems traditionally dealt with only outdoor spaces. In recent years, indoor spatial information systems have started to attract attention partly due to the increasing use of receptor devices (e.g., RFID readers or wireless sensor networks) in both outdoor and indoor spaces. Applications that employ these devices are expected to span uniformly and supply seamless functionality in both outdoor and indoor spaces. What makes this impossible is the current absence of a unified account of these two types of spaces both in terms of modeling and reasoning about the models. This paper presents a unified model of outdoor and indoor spaces and receptor deployments in these spaces. The model is expressive, flexible, and invariant to the segmentation of a space plan, and the receptor deployment policy. It is focused on partially constrained outdoor and indoor motion, and it aims at underlying the construction of future, powerful reasoning applications.

Categories and Subject Descriptors

G.2.2 [**Graph Theory**]: Graph labeling; H.2.8 [**Database Applications**]: Spatial databases and GIS

General Terms

Algorithms, Design, Theory

Keywords

Outdoor space, indoor space, model, RFID, moving objects, spatio-temporal databases

1. INTRODUCTION

Ubiquitous receptor devices such as RFID readers, wireless sensor networks (WSNs), and motion detectors are increasingly deployed in outdoor and indoor spaces (OI-spaces) [8] to enable new classes of applications that enhance our ambient awareness about the physical world. A myriad of examples exist, of which we mention supply chain and product lifecycle management, asset and personnel tracking, environmental monitoring, and intelligent buildings. In order to support these emerging applications, so-called receptor-based systems [4] are being built with a focus on managing and analyzing the data collected by receptors. In most of these systems, outdoor and indoor motion is partially constrained, primarily due to the presence of obstacles in outdoor spaces (O-spaces) and floor plans in indoor spaces (I-spaces).

A common assumption made in geographic information systems is that geographic spaces under consideration are O-spaces. As a matter of fact, a considerable portion of our lives is spent indoors - what increases the size and complexity of I-spaces. Nonetheless, indoor spatial information systems are less developed than their outdoor counterparts that have GIS at their core. The unification of these two types of spaces, both in terms of modeling and reasoning about the models, is lacked so far. A variety of applications, facilitated by receptor-based systems, need to span seamlessly both O- and I- spaces. The most fundamental of these applications is positioning, i.e., determining the location of a moving object in OI-spaces. Supporting this application and others, at various levels in OI-spaces, motivates this study which reports a unified model of OI-spaces and receptor deployments in these spaces. This model seamlessly integrates the topology and dynamics of OI-spaces. It is shown to be expressive, flexible, and invariant to the segmentation of a space plan, and the receptor deployment policy.

The remainder of this paper is organized as follows. Section 2 presents the unified model of OI-spaces. The modeling of a case study of receptor-based systems, namely an RFID readers deployment, is chosen and dealt with in Section 3. Related work is discussed in Section 4, and the paper concludes in Section 5.

2. MODELING AN OI-SPACE

This section presents a unified pseudograph model that captures two essential elements of an OI-space; the topology (i.e., the geometric properties) and the dynamics (i.e., the changes in motion). Given an OI-space plan, we proceed through four steps to identify semantic locations, connection points, moving objects, and routes. Then we construct our model, to finally show how to control its granularity and permit alternative interpretations. To illustrate our definitions, we adopt a concrete example throughout this study while emphasizing that our choice is by no means curtailing of the generality of the proposed model. Our example is the real-world baggage handling plan in Aalborg Airport. This plan comprises two essential sub-plans; the O-space and I-space plans that offer a graphical representation of baggage handling in an apron and a hall in Aalborg Airport respectively. The O-space and I-space plans are respectively shown in Figures 1 and 2. Notice in these figures that the gateways are meeting points for baggage handling that span both the hall and the apron. Notice further that the motion of baggage is partially constrained in the hall (due to the presence of conveyors) and the apron (due to the parked airplanes).

Identifying Semantic Locations. Receptor-based systems are typically not interested in the latitude and longitude of a point, neither are they interested in a location named after a specific receptor. Instead, applications are interested in the notion of a semantic location, which is a location that has a meaningful interpretation to the application. In the I-space plan shown in Figure

[*]Corresponding author.

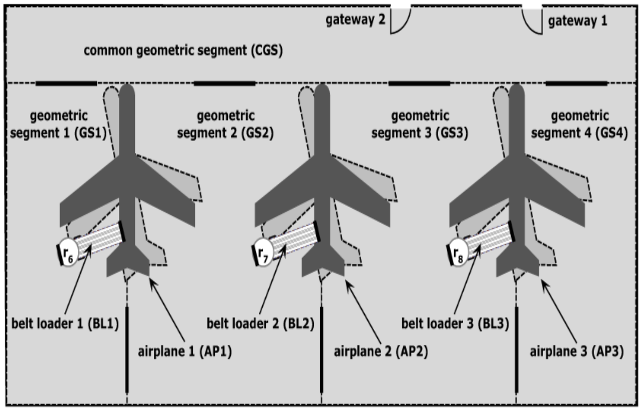


Figure 1: The O-space plan in Aalborg Airport apron

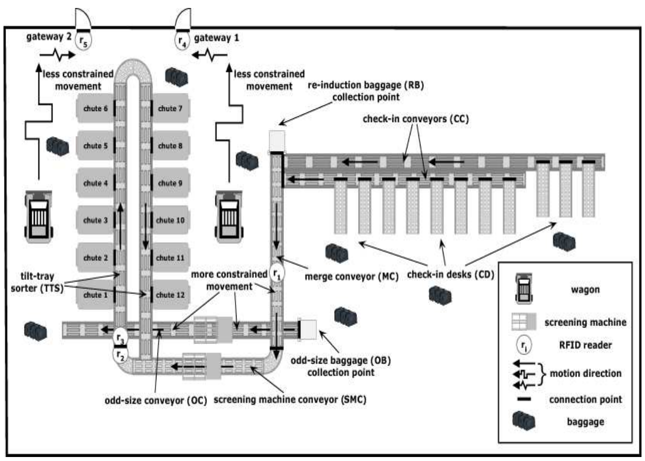


Figure 2: The I-space plan in Aalborg Airport hall

2, some meaningful semantic locations are the screening machine conveyor[1] (SMC), the tilt-tray sorter [2] (TTS), the chutes[3] (CH) that are numbered from 1 to 12, the re-induction baggage[4] (RB) and the odd-size baggage (OB) collection points. As for the O-space plan shown in Figure 1, the meaningful semantic locations are the airplanes $\mathrm{AP1}$-$\mathrm{AP3}$, the belt loaders[5] $\mathrm{BL1}$-$\mathrm{BL3}$, in addition to the geometric segments CGS, and $\mathrm{GS1}$-$\mathrm{GS4}$. Observe that the segmentation carried out of the apron surface can be done in a variety of other ways. Moreover, the geometric segments themselves need not be line segments. Indeed and in contrast to [7], they can take any geometric shape as long as they are part of the apron surface, and that satisfactory interpretations are attached to them. These geometry-friendliness and invariance to the space plan segmentation add both depth and ample expressiveness to our modeling of O-spaces.

[1]A machine that performs X-ray screening of baggage as a security measure against weapon infiltration.

[2]A high-speed, continuous-loop sortation conveyor used to sort baggage to chutes.

[3]A narrow, steep slope from which baggage is loaded into wagons that ultimately transport the baggage to airplanes.

[4]A point at which baggage that underwent a manual security check and found safe is re-inducted into the baggage handling system.

[5]A vehicle with a movable belt for loading/unloading baggage into/from an airplane.

Identifying Connection Points. A connection point is simply an actual (movable/immovable) or virtual structure at which two or more semantic locations meet one another. The connection points are shown as bold line segments in Figures 1 and 2. We note that in reality the connection points between CD and CC are actual movable shutters. The two connection points between CH and CGS are the physical gateways 1 and 2. However, the connection point between SMC and TTS is virtual. Speaking of the notation of connection points, we differentiate between a single connection point between n semantic locations l_1,l_2,...,l_n (that we denote as $l_1|l_2|\ldots|l_n$), and n connection points between two semantic locations l_1 and l_2 (that we denote as $(l_1|l_2)_1$, $(l_1|l_2)_2$,...,$(l_1|l_2)_n$). In both cases, we do not mind the order in which the location symbols are listed. As a special case, a connection point can be referred to using a given name. For instance, the connection point $(\mathrm{CH}|\mathrm{CGS})_1$ is named $\mathrm{gateway}_1$. The identification of semantic locations and their connection points completes our grasp of the topology of an OI-space.

Identifying Moving Objects. Receptor-based systems need to realize meaningful moving objects, not transponders such as RFID tags, or transducers such as motes, and motion detectors. A moving object is a living/nonliving mobile entity, to which a transponder/transducer is affixed, and whose motion reflection is crucial to the application. In the OI-space plans shown in Figures 1 and 2, moving objects are bags to which RFID tags are attached, and the RFID-based application is concerned with the identification and location of these bags. The RFID tags used in this example are passive, that is they do not have any power supply.

Identifying Routes. A route is a particular way moving objects follow (or are carried over) between semantic locations. Revisiting Figures 1 and 2, a baggage route is; $\mathrm{CD} \rightarrow \mathrm{CC} \rightarrow \mathrm{MC} \rightarrow \mathrm{SMC} \rightarrow \mathrm{TTS}$ (repeatedly in general) $\rightarrow \mathrm{CH} \rightarrow \mathrm{CGS} \rightarrow \mathrm{GS1} \rightarrow \mathrm{BL1} \rightarrow \mathrm{AP1}$. For convenience, we cut up routes into binary sub-routes, each of which constitutes an ordered pair, such as $(\mathrm{CD}, \mathrm{CC})$ in the baggage handling example. The identification of moving objects and routes completes our grasp of the dynamics of an OI-space.

Constructing the OI-Space Pseudograph. Let $\mathcal{W}_l$, $\mathcal{W}_c$, $\mathcal{W}_o$, and $\mathcal{W}_m$ be the sets of semantic locations, connection points, moving objects, and binary sub-routes. Given that both sets $\mathcal{W}_l$ and $\mathcal{W}_m$ are finite and assuming that $\mathcal{W}_l$ is further nonempty, we use a directed graph $\mathcal{D}_{oi\text{-}space} = (\mathcal{W}_l, \mathcal{W}_m, c)$ to model an OI-space [1] adding $\mathcal{W}_o$ as an explanatory symbol on its pictorial drawing. The sets $\mathcal{W}_l$ and $\mathcal{W}_m$ are respectively called the vertex and edge sets. The mapping $c : \mathcal{W}_m \rightarrow \mathcal{P}(\mathcal{W}_c)$ assigns labels to the edges in $\mathcal{D}_{oi\text{-}space}$ where $\mathcal{P}(\mathcal{W}_c)$ is the power set of $\mathcal{W}_c$. The direction of an edge in $\mathcal{D}_{oi\text{-}space}$ indicates the order of the corresponding binary sub-route. We allow $\mathcal{D}_{oi\text{-}space}$ to include looping edges whose head and tail coincide (such as (l_1, l_1)) and edges with the same end-vertices (such as (l_1, l_2) and (l_2, l_1)); however, we do not allow multiple edges with the same tail and head (such as (l_1, l_2) twice). Multiple edges are avoided because there is no point in modeling the same binary sub-routes multiple times. The imposed restrictions characterize $\mathcal{D}_{oi\text{-}space}$ as a labeled directed pseudograph without multiple edges. Figure 3 shows the OI-space pseudograph of the OI-space plans shown earlier in Figures 1 and 2.

Modeling Granularity and Alternative Interpretations. The OI-space model we built is sufficiently flexible to enable us to control the granularity or the extent to which we capture the

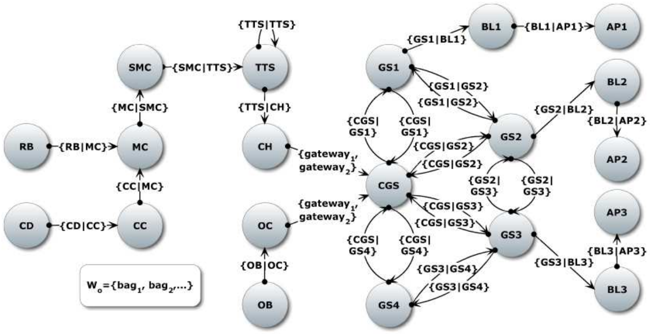
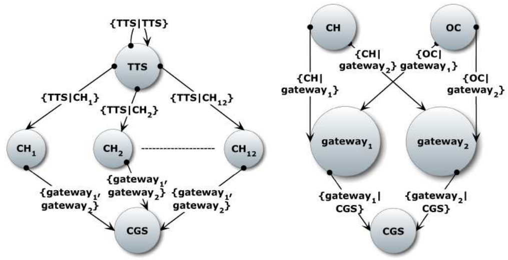


Figure 3: The OI-space pseudograph of the OI-space plans shown in Figures 1 and 2

details of the physical world. Our model can be made finer using the essential operations of splitting a vertex and subdividing an edge, whereas it can be made coarser using the opposite operations of set- and path- contractions [1]. Consider for example the OI-space pseudograph shown in Figure 3. If we are interested in including more details about the chutes, we split the vertex CH into 12 vertices, and subdivide the edge $(\mathrm{TTS}, \mathrm{CH})$ into 12 edges to obtain the sub-pseudograph shown in Figure 4a. The flexibility of our model goes beyond granularity control to enable us to interpret a connection point as a semantic location, which could be beneficial to various reasoning scenarios. Returning to the OI-space pseudograph shown in Figure 3, we may wish to think of the gateways 1 and 2 as semantic locations and this is possible. We simply convert them into vertices and assume virtual connection points between them and the surrounding semantic locations. The sub-pseudograph in Figure 4b illustrates the outcome.



(a) (b)

Figure 4: Figure (a) shows how we can increase the fineness of the pseudograph in Figure 3; and Figure (b) shows alternative interpretation of the gateways in Figure 3 too.

3. MODELING RFID READERS DEPLOYMENT

As a case study on receptor-based systems, we address the modeling of an RFID readers deployment in an OI-space. Modeling the deployments of WSNs and motion detectors in OI-spaces should not differ from that. In fact, several schemes for integrating the RFID technology into WSNs are being used [2]. A possible RFID readers deployment for our running baggage handling example is shown in Figures 1 and 2. To model this deployment, we transform $\mathcal{D}_{oi\text{-}space}$, we constructed in Section 2, by modifying the edge labels and introducing labels into vertices. Let $\mathcal{W}_l$, $\mathcal{W}_c$, $\mathcal{W}_o$, and $\mathcal{W}_m$ be as annotated in Section 2. We drop $\mathcal{W}_c$ from the RFID modeling, and add the set $\mathcal{W}_r$ of RFID readers in the deployment instead. Additionally, we drop the mapping $c : \mathcal{W}_m \to \mathcal{P}(\mathcal{W}_c)$ adding instead two new mappings $c_l : \mathcal{W}_l \to \mathcal{P}(\mathcal{W}_r)$ and $c_m : \mathcal{W}_m \to \mathcal{P}(\mathcal{W}_r) \cup \mathcal{P}(\mathcal{W}_r \cdot \mathcal{W}_r)$ for labeling the vertices and edges respectively. These nearly effortless adjustments transform $\mathcal{D}_{oi\text{-}space}$ into $\mathcal{D}_{rfid} = (\mathcal{W}_l, \mathcal{W}_m, c_l, c_m)$ with $\mathcal{W}_o$ similarly added as an explanatory symbol on $\mathcal{D}_{rfid}$'s pictorial drawing. $\mathcal{D}_{rfid}$ is characterized as a labeled and vertex-labeled directed pseudograph without multiple edges. The assignment of c_l and c_m labels is controlled by the readers positioning with respect to the semantic locations and their connection points as specified in the following guidelines:

Algorithm 1 Constructing the RFID readers deployment pseudograph

Input: An OI-space pseudograph $\mathcal{D}_{oi\text{-}space} = (\mathcal{W}_l, \mathcal{W}_m, c)$ where $c : \mathcal{W}_m \to \mathcal{P}(\mathcal{W}_c)$, and the set $\mathcal{W}_r$ of RFID readers in a possible deployment.
Output: The RFID readers deployment pseudograph $\mathcal{D}_{rfid} = (\mathcal{W}_l, \mathcal{W}_m, c_l, c_m)$ where $c_l : \mathcal{W}_l \to \mathcal{P}(\mathcal{W}_r)$ and $c_m : \mathcal{W}_m \to \mathcal{P}(\mathcal{W}_r) \cup \mathcal{P}(\mathcal{W}_r \cdot \mathcal{W}_r)$.
// Stage 1. Copying stage.
copy $\mathcal{W}_l$ from $\mathcal{D}_{oi\text{-}space}$ to $\mathcal{D}_{rfid}$
copy $\mathcal{W}_m$ from $\mathcal{D}_{oi\text{-}space}$ to $\mathcal{D}_{rfid}$
// Stage 2. Initialization stage.
for each $l \in \mathcal{W}_l$ **do**
  $c_l(l) = \emptyset$
for each $m \in \mathcal{W}_m$ **do**
  $c_m(m) = \emptyset$
// Stage 3. Vertex labeling stage.
for each $l \in \mathcal{W}_l$ **do**
  for each $r \in \mathcal{W}_r$ **do**
    if r is positioned in l away from any connection point **then** ▷ G1
      $c_l(l) = c_l(l) \cup \{r\}$
      $\mathcal{W}_r = \mathcal{W}_r \backslash \{r\}$
// Stage 4. Edge labeling stage.
for each $cp = l_1|l_2|\ldots|l_n \in \mathcal{W}_c : l_1, l_2, \ldots, l_n \in \mathcal{W}_l$ **do**
  for each $r, r' \in \mathcal{W}_r$ **do**
    if r is positioned at cp **then** ▷ G2
      for each $m = (l_i, l_j) \in \mathcal{W}_m : i, j \in [1, n]$ **do**
        $c_m(m) = c_m(m) \cup \{r\}$
    if r, r' are adjacently positioned at cp **then** ▷ G3
      for each $m = (l_i, l_j) \in \mathcal{W}_m : i, j \in [1, n]$ **do**
        if r reads before r' when moving from l_i to l_j across cp **then**
          $c_m(m) = c_m(m) \cup \{(r, r')\}$
        else
          $c_m(m) = c_m(m) \cup \{(r', r)\}$

G1. If a reader is positioned inside a semantic location away from any connection point, then add this reader to the label set of this semantic location.

G2. If a reader is positioned at a connection point between semantic locations, then add this reader to the label set of the edges connecting these locations.

G3. If two readers are adjacently positioned at a connection point between semantic locations, then add these two readers as an ordered pair to the label set of the edges connecting these locations.

Observe the generality and completeness of $\mathrm{G2}$ and $\mathrm{G3}$ in that they permit the handling of a single connection point between any number of semantic locations, and any number of connection points between two semantic locations. The reader can easily verify this fact. Another important thing to notice in $\mathrm{G3}$ is that labeling an edge via an ordered pair enables the capturing of the motion direction across the connection point by merely looking at the RFID readings sequence. One final thing we accentuate in $\mathrm{G3}$ is that it permits and equally handles joint (overlapping/nested) and disjoint reading zones begotten by adjacent positioning of two readers.

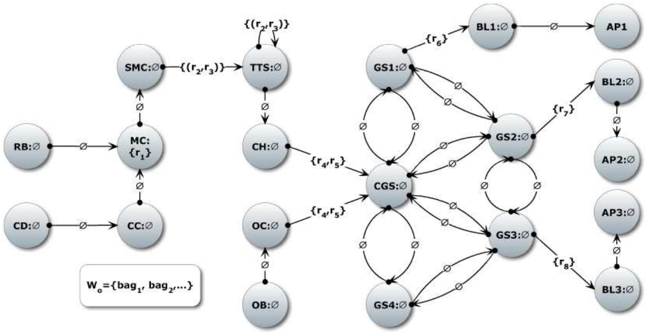


Figure 5: The RFID readers deployment pseudograph of the OI-space pseudograph shown in Figure 3

Let us return to Figures 1 and 2 and experiment with c_l and c_m assignments. The reader r_1 is positioned inside MC away from any connection point. Therefore r_1 is added to the label set of MC i.e., $r_1 \in c_l(\mathrm{MC})$. On the other hand, r_4 is positioned at $\mathrm{gateway}_1$ which leads to adding r_4 to the label sets of $(\mathrm{CH}, \mathrm{CGS})$ and $(\mathrm{OC}, \mathrm{CGS})$ i.e., $r_4 \in c_m(\mathrm{CH}, \mathrm{CGS})$ and $r_4 \in c_m(\mathrm{OC}, \mathrm{CGS})$. Finally, r_2 and r_3 are adjacently positioned at $\mathrm{SMC}|\mathrm{TTS}$, and r_2 reads before r_3 when moving from SMC to TTS across $\mathrm{SMC}|\mathrm{TTS}$. Thus, $(r_2, r_3) \in c_m(\mathrm{SMC}, \mathrm{TTS})$.

Figure 5 shows the RFID readers deployment pseudograph of the OI-space pseudograph shown in Figure 3. A generic algorithm for constructing the RFID readers deployment pseudograph is given in Algorithm 1. Algorithm 1 is divided into four stages. In stage 1, all the vertices and edges are copied verbatim from $\mathcal{D}_{oi\text{-}space}$ to $\mathcal{D}_{rfid}$. The mappings c_l and c_m are initialized in stage 2 by assigning $\emptyset$ to the labels of vertices and edges. In stage 3, labels are assigned to all the vertices following the reasoning prescribe in $\mathrm{G1}$. Finally, $\mathrm{G2}$ and $\mathrm{G3}$ are used to assign labels to all the edges in stage 4. Notice how we preserve the efficiency of Algorithm 1 in stage 3 by removing the readers that were successfully processed by $\mathrm{G1}$ from $\mathcal{W}_r$. This removal is justified since we really do not expect a reader to be positioned inside more than one semantic location, neither do we expect it to be simultaneously positioned inside a semantic location and at a connection point. However, we do not do the same in stage 4 since it is possible for more than one binary sub-route to have shared elements in their labels (refer to Figure 3).

4. RELATED WORK

Although it falls into several categories, related work has by far focused on the modeling of indoor spaces. An integrated indoor model [3] covers different information dimensions of indoor models including thematic, geometric, and routing-related information. It is based on classifying indoor objects and structures while taking geometry, appearance, and semantics into account. A lattice-based location model for indoor navigation [5] is capable of preserving semantic relationships and distances, e.g., the nearest neighbor relationship among indoor entities. A distance-aware indoor space model [6] accompanies a set of indoor distance computation algorithms and an indexing framework in order to enable the processing of indoor distance-aware queries over indoor spatial objects. Our work distinguishes itself from those aforementioned by capturing both O- and I-spaces in a unified model.

5. CONCLUSIONS

We propose a unified model of OI-spaces that is expressive, flexible, and invariant to the segmentation of a space plan, and the receptor deployment policy. The model is focused on partially constrained outdoor and indoor motion common in receptor-based systems. Adopting RFID as an example receptor technology, and given an arbitrary RFID readers deployment, we perform a nearly effortless transformation of our OI-space model into an RFID readers deployment model. The transformation is based on a set of coherent guidelines that enjoy enough generality and completeness. In particular, these guidelines are functional under various set-ups of connections between semantic locations, and under (dis)joint reading zones of adjacently positioned readers. Furthermore, these guidelines are capable of capturing the motion direction across connection points. The two models presented in this paper not only underpin tracking applications, but also a number of powerful reasoning applications whose investigation is left as future work.

6. ACKNOWLEDGMENTS

This work was supported by the BagTrack project sponsored by the Danish National Advanced Technology Foundation under grant 010-2011-1.

7. REFERENCES

[1] J. Bang-Jensen and G. Gutin. *Digraphs : theory, algorithms, and applications*. Springer, 2. ed. edition, 2009.

[2] K. Finkenzeller and D. Müller. *RFID handbook*. Wiley, 3rd ed. edition, 2010.

[3] B. Hagedorn, M. Trapp, T. Glander, and J. Döllner. Towards an indoor level-of-detail model for route visualization. In *MDM*, 2009.

[4] S. Jeffery, G. Alonso, M. Franklin, W. Hong, and J. Widom. A pipelined framework for online cleaning of sensor data streams. In *ICDE*, 2006.

[5] D. Li and D. L. Lee. A lattice-based semantic location model for indoor navigation. In *MDM*, 2008.

[6] H. Lu, X. Cao, and C. S. Jensen. A foundation for efficient indoor distance-aware query processing. In *ICDE*, 2012.

[7] L. Speičys, C. S. Jensen, and A. Kligys. Computational data modeling for network-constrained moving objects. In *ACM GIS*, 2003.

[8] M. Worboys. Modeling indoor space. In *ISA*, 2011.