Closing the gap between indoor and outdoor space

A study of navigation and evacuation applications in complex three-dimensional built environments

Ann Vanclooster

The research reported in this dissertation was conducted at the CartoGIS Research Unit, Department of Geography, Faculty of Sciences, Ghent University.

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Faculty of Sciences
Department of Geography

CLOSING THE GAP BETWEEN INDOOR AND OUTDOOR SPACE

A study of navigation and evacuation applications in complex three-dimensional built environments

Dissertation submitted in accordance with the requirements for the degree of Doctor of Sciences: Geomatics and Surveying

INTEGRATIE VAN INDOOR EN OUTDOOR RUIMTEN

Onderzoek naar navigatie- en evacuatietoepassingen in complexe drie-dimensionale omgevingen

Proefschrift aangeboden tot het behalen van de graad van Doctor in de Wetenschappen: Geomatica en Landmeetkunde

ANN VANCLOOSTER

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Department of Geography, Ghent University

Prof. dr. Veerle Fack (promotor)
Department of Applied Mathematics and Computer Science, Ghent University

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PREFACE

When pursuing a PhD, a typical question that you always encounter is: What is your PhD now actually about? I always dreaded having to answer this as I was for a long time quite unsure about my PhD and my future as a researcher. However, that all changed during my research stay in Seoul, Korea in January 2011. At the time, I had all sorts of questions wandering around in my brain: 'What should I do with my research? How to proceed? Will I be able to come up with something interesting? …' At some point, my boyfriend asked me: 'What is it that you actually like about your PhD-topic?' My answer came, quite surprisingly to me, as sudden and swift as the wind. 'Navigation is like traveling to me. Having the opportunity to expand someone's travel experience, guiding them in a world they would like to discover, but are unsure about.' In that one moment, I realized I could finish this PhD, because I was still passionate about the topic. Now, a couple of years later, the result is here. How small and insignificant it may look on the outside, it encompasses much more than I ever could have imagined.

Along the way, I have bumped into my fair share of obstacles, disappointments and difficulties. Years of doubt, tears, frustration but also enjoyment, pride and happiness. A rollercoaster of emotions that would be turned upside down even more when I got sick. But now, at the end of the road, I think I have an answer to the question of what it is that my PhD is about: improving the navigation experiences of people. People, that is what it is all about in the end. And I have had the pleasure to have worked with several very interesting, accomplished and sincere ones.

First of all, this PhD started and ended thanks to the eternal support of my supervisor, Prof. Philippe De Maeyer. As many times as his work, meetings or other commitments kept him from actually asking about your research itself; whenever I needed some guidance, help or just some support, I knew I could rely on him. He was the one leading me into the PhD, he was the one allowing me to go abroad and the one, insisting on continuing when I felt like quitting. Thank you Philippe!

Next to my main supervisor, I had the pleasure of being guided in this PhD by Prof. Nico Van de Weghe and Prof. Veerle Fack. Over the past 5 years, I have come to know them both as encouraging and friendly people on which I could always rely on for interesting discussions, thorough reading and

sincere commenting on my work. Thank you both for your time and dedication.

During my PhD, I also had the opportunity to meet and work with several fellow researchers. First of all, I sincerely would like to thank Prof. Jiyeong Lee for allowing me to work in an incredible new environment in Seoul and for improving my understanding of indoor space concepts. Secondly, I would like to thank Tijs, Kristien and Pepijn for the comments and ideas on my research. Kristien, I also really enjoyed my time teaching the programming course with you.

Our department would not be the same without the administrative support of Helga Vermeulen. Not only does she cover all ins and outs of paperwork, I could always rely on her for some much needed advice, or just a chat. I would also explicitly like to thank Nathalie Van Nuffel for dealing with the administrative difficulties when I got sick. Thank you both for taking away that extra burden at the time.

Doing research can often be a lonely task. Luckily, the many colleagues made my day-to-day office life quite enjoyable and worthwhile. Some of them even became good friends. I especially want to thank my office colleagues: Ruben for being your funny and reliable personality that gave my first working year so much joy and pleasure. Soetkin and Rasha, thank you for being there for me; listening to my complaints, sorrows, giving me a hug whenever I needed it. You have meant such a great support to me in pursuing and finishing this PhD, but also in being a great friend. I look forward to attending your defense soon!

I was also very lucky to be surrounded by much support from friends and family. This really helped me to set aside the worries about finishing an article, or distracting me from frustrating ‘I am not making enough progress’-days. I cannot express to you all how important these moments were to not become PhD-insane. Special thanks go to my fellow geography-LMK friends, aka ‘the girls’ (Anneleen, Eveline, Evelyne and Katrien); my childhood friend Anke; my tea-game night friend Joni and my fellow PhDer Coen (one day we will write our article together ☺).

A special word of thanks is dedicated to my parents, brother and sister-in-law. Over the past few years, we have had our misunderstandings and discussions, but I always knew you wanted the best for me. Thank you for always being there, believing in me and letting me grow into my own person.

A special thank you to my brother Bart for making the cover design, and for giving me the joy to becoming an aunt to Kamiel and Kobe. I have also been blessed with becoming part of a new family on the other side of the world. We might not see each other very frequently, but it has always been a pleasure visiting and hanging out with you all. You have opened my eyes to the American hospitality and freedom of mind.

In true PhD-preface writing tradition, this last paragraph is dedicated to the person that I have become so close to these last four years. I didn't know you when I started this PhD. Unexpectedly; I bumped into your 'arrogant' personality in Stockholm. We fell in love and tried to see each other whenever and wherever, all over the world. One year ago, you decided to come and live with me here in Belgium. Thank you Seann, for taking the risk in committing to a relationship with me, to giving up your trip around the world, and to settling in a new country and learning a new language for me. I am so grateful for all the love, encouragements, support, laughter and joy you have given me so far. I am especially blessed that you stuck by my side when I got sick, and for all the effort in reading and re-reading this dissertation. I am really looking forward to the rest of our life together, wherever that may end up being.

Thank you!

Ann

‘Success is not final, failure is not fatal:
it is the courage to continue that counts.’

Winston Churchill

1

INTRODUCTION

1.1 REFERENCE CONTEXT

'Product search in supermarkets will soon become a lot simpler given the Indoor GPS. This smartphone-based application guides customers through supermarkets providing them with the most efficient route, based on their shopping list' (translated from De Morgen, 2014). Although stated as an evolution still being in its infancy, this newspaper article, published February 17 2014, highlights the potential of providing Location-Based Services (LBS) to indoor environments. This also demonstrates a current trend in geospatial research, which emerged in line with two major evolutions over the past years: (i) the proliferation of current-day mobile phones leading to a huge increase in big data; (ii) privatization of public spaces (Mitchell, 2011).

LBS have been on the radar for quite some time, providing information services in a variety of outdoor contexts (e.g. health, advertisement, gaming, and transportation). Their main characteristic is using location data to provide information and services to users. The advent of the Global Positioning System (GPS) and the availability of chip-size receivers allowed for the equipment of many nodes with the knowledge of (outdoor) location (Kolodziej & Hjelm, 2006). As location data has become increasingly available, a typical and necessary follow-up question is: What is around here and how do I get there? That is where navigational applications come into play.

The past several years have slowly witnessed a shift in attention from outdoor to indoor LBS. The potential of location-aware indoor applications were first realized in the early 1990's and explored in conjunction with research on ubiquitous computing (Kolodziej & Hjelm, 2006). Over the past decade, significant advancements have taken place in indoor positioning developments and more recent an increasing commercial interest in indoor mapping (e.g. Google Maps Indoor), serving as a first step in opening indoor environments (Figure 1-1).

This is not surprising given the fact that as humans, we spend by far the most of our time in indoor environments (Jenkins et al., 1992). A large commercial potential of possible consumers is currently being ignored as millions of square meters of indoor space and urban areas are out of reach of GPS. Indeed, the main backbone of the LBS market is formed by consumer-facing and local applications (Kolodziej & Hjelm, 2006). Additionally, population growth and concomitant city expansion have exerted more and more pressure on urban space. Recent years have not only witnessed horizontal urbanized spreading, but also many vertical building developments. These are triggered by a pinching deficit in land availability, constructions of iconic single-phase mega-projects and enforced rules from governments revitalizing residential inner-city areas (Abel, 2010; Hwang, 2006; Wilson, 2010). The three-dimensional vertical city was born and with it, the requirement of dealing with the corresponding complexities of multi-level building structures. Additionally, evolutions in three-dimensional modeling (Becker et al., 2009) combined with the rapid progress in spatial information services and computing technology (Li & Lee, 2010) have put indoor geospatial research on the map.

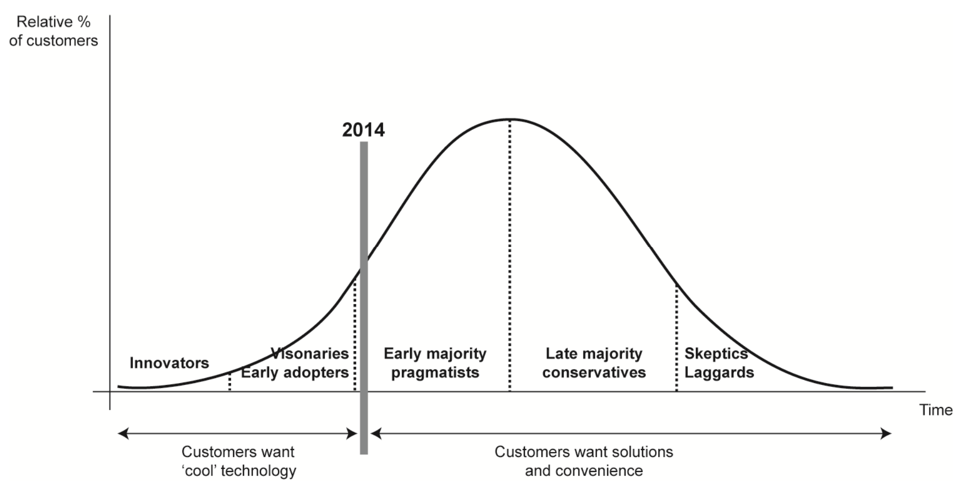

Figure 1-1 Indoor LBS market adoption (based on Lacroix, 2013)

At this point, indoor LBS have not yet reached their tipping point (Figure 1-1), leaving ample room for scientific research. This dissertation focuses on a specific segment of the indoor LBS market; namely, navigation and evacuation scenarios. In particular, it examines the current modeling and analytical support for indoor applications. The end goal of this research is to present valuable insights on the current status of indoor navigation and evacuation applications, and to improve analytical and algorithmic support for indoor spatial environments by relying on similar outdoor methodologies and bringing them to the indoor context.

In the following paragraphs, first a general background on navigation and evacuation (Section 1.1.1) is given with afterwards a delineation of indoor and outdoor space concepts (Section 1.1.2). Finally, Section 1.2 identifies the specific motivation and research aims and translates them into several research questions that are answered within this dissertation.

1.1.1 Defining navigation, wayfinding and related concepts

1.1.1.1 Navigation versus wayfinding

As long as people need to decide where to go and how to get there, navigation will remain one of the fundamental behavioral problems for human cognition (Montello, 2005). Behavioral and cognitive sciences have already widely studied navigation processes (e.g. Golledge, 1999). Navigation is thereby defined as the coordinated and goal-directed movement through the environment by organisms or intelligent machines (Montello, 2005). It involves both planning and execution of movement. The main tools for navigation are the user's cognitive abilities (to perceive, remember and reason in space and time) and his motor abilities (to use his cognitive input to execute movement).

According to Darken and Peterson (2002) and Montello (2005), navigation is a complex negotiation process between locomotion and wayfinding elements. Locomotion is thereby defined as the movement of one's body around an environment, coordinated specifically to the local surroundings, using current sensory information. The various modes of locomotion can affect the way with which certain information is acquired and processed. For example, while driving a car, people remember other details of the environment compared to walking the same path, partly because of a different line of sight and speed (Goldin & Thorndyke, 1982). Wayfinding, on the other hand, is defined as the purposive, directed and motivated process of determining and following a route between origin and destination, supported by a cognitive map of the environment (Montello, 2005). It requires answers to three questions: Where am I with respect to my environment? Where do I want to go? How do I get there? (Akerman & Karrow, 2007). The eventually followed route is a result from implementing an a priori defined travel plan which encapsulates a chosen strategy for path selection (Golledge, 1999).

There is much confusion about the exact definition of navigation and its relation to wayfinding. Nagel et al. (2010) define (what they call) navigation by its three interacting components: (i) determination of the current location of object or subject (i.e. localization); (ii) determination of the best path from current location to destination; (iii) guidance along the path, including the monitoring of the difference between current position and path (i.e. tracking), and enforcement of appropriate actions to minimize this difference. This aligns with Montello's view (2005) on wayfinding and not on navigation. In the rest of this dissertation, wayfinding and navigation are used intermittently, but we always refer to the aspect of path guidance or routing (Figure 1-2).

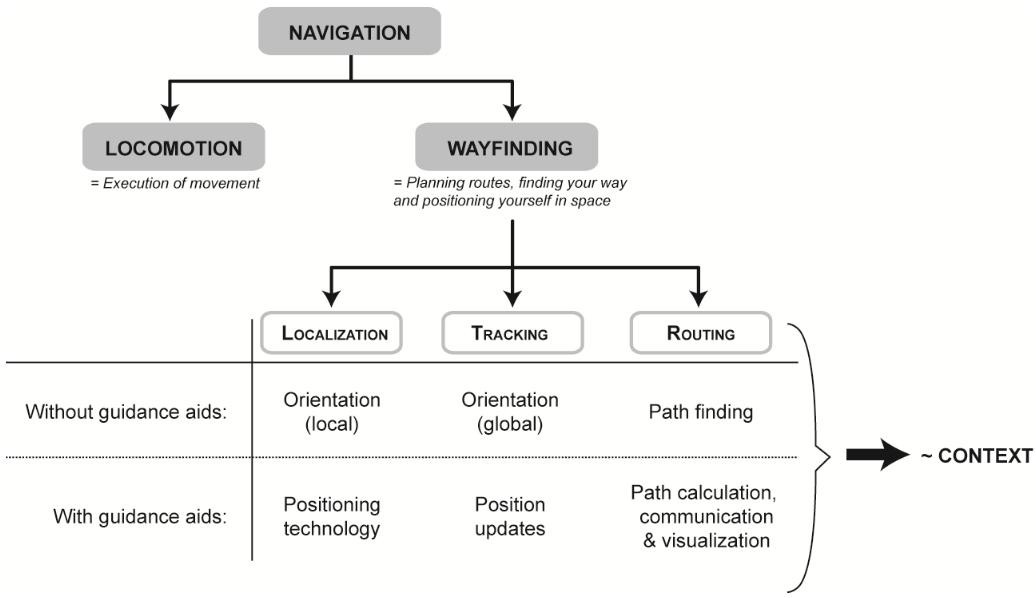

Figure 1-2 Definition of navigation and wayfinding

Several attempts have been made to model navigation and its relationship with spatial information acquisition and spatial knowledge generation. However, most of these models are specifically linked to one type of environment, or they do not capture the intricacies of the entire task (Darken & Peterson, 2002). Generally, they consist of a series of hierarchically staged processes that unfold sequentially and iteratively during wayfinding. The main processes are recognized as (i) cognitive-mapping, (ii) decision-making and (iii) decision-execution (Figure 1-3) (e.g. Passini, 1984).

First, cognitive-mapping[1] is a process of acquiring, forming, and maintaining spatial information and spatial knowledge (Chen & Stanney, 1999). Lynch (1960) suggested that cognitive maps are constantly developed and updated during wayfinding tasks. The spatial information available within cognitive maps is the product of both sensory information and of memory of past experience. Lynch (1960) reasoned that cognitive maps primarily function as orientation aids and that people generally orient themselves using only five different elements, which are universal across urban systems: landmarks, routes, nodes, districts and edges. This work still presents the most compelling, environment-independent answer of spatial information elements useful for navigation (Chen & Stanney, 1999; Darken & Peterson, 2002).

Second, in the decision-making process, individuals plan actions and structure them into an overall wayfinding plan based on their cognitive map. Wayfinding plans can be used to connect the internal information processing to actual behavior (Gärling et al., 1983). These travel plans are often revised, as such providing learning experiences that can alter the user's cognitive map.

In the third process, decision-execution, individuals transfer decisions into physical behavioral actions. This step is often forgotten in wayfinding models, but it ties immediately back to the locomotion aspect of navigation and the reason why cognitive maps and wayfinding plans are required.

These three steps are repeated several times in a recurring loop, until the target destination is reached, thereby ending the wayfinding process (Figure 1-3). During movement, individuals continue to retrieve stimuli from the environment to confirm that they are moving in the right direction. Through this interaction the user acquires an improved cognitive representation of the environment (Gaisbauer & Frank, 2008). His cognitive map will be updated with the newest information. Afterwards, the previously defined planned

[1] The Nobel Prize for Medicine 2014 has been awarded to research focused on understanding how cognitive maps get created in the brain and how they make it possible to gain internal positioning and orientation.
http://www.nobelprize.org/nobel_prizes/medicine/laureates/2014/press.html

actions are assessed against the updated cognitive map, possibly leading to adjustments of travel plans and eventually further locomotion. As such, planning and task execution are not serial events but rather intertwined in the context of the situation (Darken & Peterson, 2002).

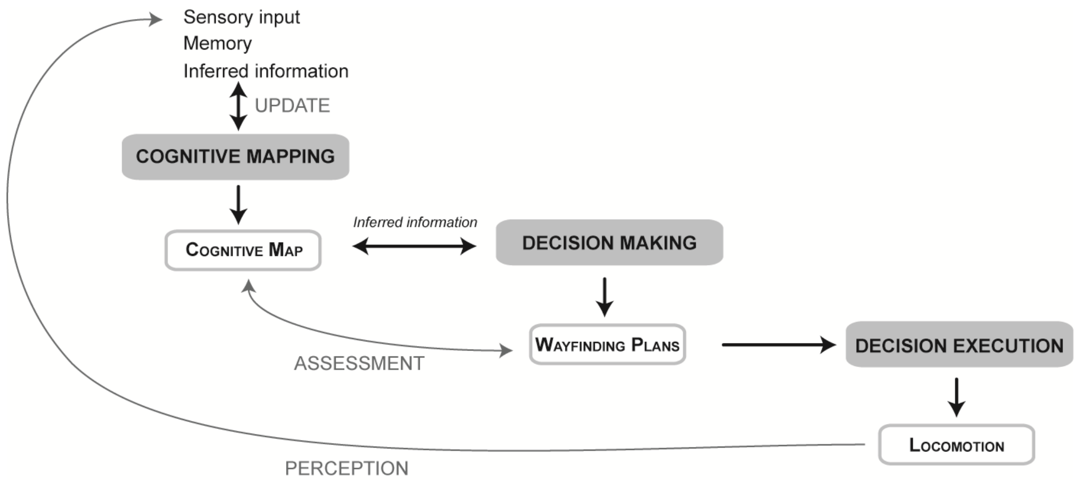

Figure 1-3 Navigation and wayfinding processes

Since not all users necessarily command a sufficient cognitive map for successful wayfinding, wayfinding processes can be guided by external aids (Golledge, 1999). Tools for guidance can be found everywhere nowadays: from regular paper maps to car navigation systems; from spoken route instructions to evacuation and You-Are-Here floor plans. These tools can alleviate certain problem areas of the wayfinding process. For example, tools that display an individual's current position and orientation result in an easier cognitive-mapping process. Guidance aids that also show the surrounding environment with additional routing tools make that the user only has to execute movement, without necessarily even creating a personal cognitive map and wayfinding plans. As such, there may be a trade-off between reaching a destination and the acquisition of spatial knowledge when navigational tools are used (Chen & Stanney, 1999).

As such, the minimum requirements for guidance tools for wayfinding applications can be summarized as (based on Nagel et al., 2010):

- support of different and multiple localization methods and infrastructures;
- appropriate (for the application level) and accurate topographic representation of space in a spatial reference system;
- support of multiple navigation contexts.

1.1.1.2 Context

Context is a key word in navigation and wayfinding processes. Afyouni et al. (2012, p.85) define context as 'any information that is gathered and can be used to enrich knowledge about the user's state, his physical surroundings and capabilities of his device'. Context varies with the application, the users and the environment, as well as the interactions and relations between each of these. It encompasses both (i) the context of use being the user (i.e. his experiences with space and cognitive abilities), the environment (i.e. type, mode of locomotion, timing) and their mutual interactions; and (ii) the context of execution, being the behavior of the information system (Afyouni et al., 2012). In the rest of this dissertation, whenever context is mentioned, it refers to the context of use.

Navigation and wayfinding highly depend on context, whether it is in a guided or unguided setting. Both user and environmental context variables influence the cognitive-mapping process and the decision-making process (Chen & Stanney, 1999) (Figure 1-4).

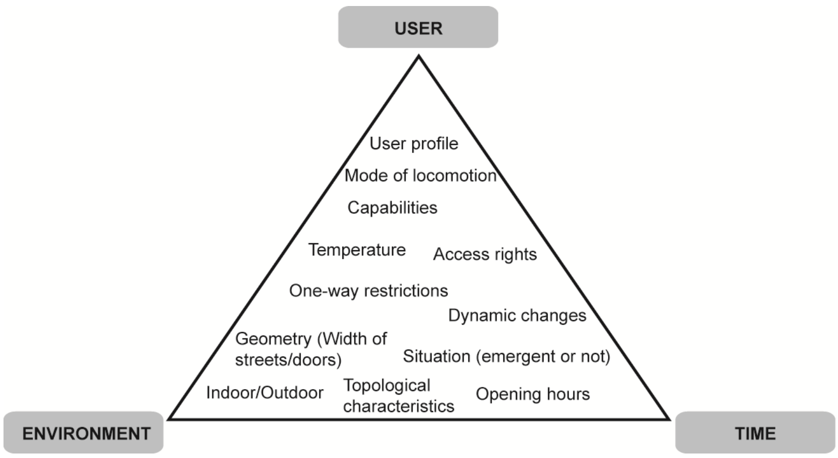

Figure 1-4 Context defining variables for navigation applications

Forming an internal cognitive map does not result in a veracious representation of space (Carlson et al., 2010). The type of space greatly affects this representation, typically with prioritization of certain objects, a simplification of the entire space and a personal organization of the separate elements. Additionally, individual factors such as experience, search strategies, ability differences, and motivation can all have an impact on the wayfinding process in some way (Goldin & Thorndyke, 1982). Indeed, not all users possess a similar level in terms of ability, strategy selection or experience at the same time (Carlson et al., 2010). For example, previous experience may increase individuals' environmental familiarity and improve their search skill. Different environment-encoding strategies may also result in different spatial cues collected and used by individuals (Chen & Stanney, 1999). Wayfinding research is still deciding upon the exact relationships between these context variables and wayfinding effectiveness.

Guidance aids will require flexible data structures to deal with all variables that make up the possible context situations (Nagel et al., 2010). Each of the variables involved directly influences the partitioning of space into navigable and non-navigable areas. Navigable space is thereby defined as an area where a certain user can move from a certain location at a certain time. Delineation of navigable spaces allows determination of possible paths given the context. The set of variables defining context of navigation can also change dynamically (by the location of the user, situational changes or time changes). Navigation guidance tools should therefore also support these dynamic aspects (Nagel et al., 2010).

1.1.1.3 Wayfinding strategies, wayfinding effectiveness and their relation to context variables

Different wayfinding strategies may be adopted depending on the availability of collectable information and an individual's personal wayfinding style (Chen & Stanney, 1999). Thus, the type of spatial information available to the wayfinder is influential in determining the adopted wayfinding strategy (Hölscher et al., 2011).

Each wayfinding strategy is observed by particular spatial knowledge representations and reasoning processes (Carlson et al., 2010). The most famous model of spatial knowledge representation is still the Landmark, Route, Survey (LRS) model by Siegel & White (1975). This model addresses both the different types of spatial knowledge as well as their creation process. It also directly fits in with the possible elements of urban environments, identified by Lynch (1960). The LRS-model identifies three consecutive stages in mental map creation. First, landmarks are extracted as salient, static cues in the environment. Next, route knowledge develops as landmarks, modeled as nodes, are connected by paths, modeled by edges. Finally, survey knowledge emerges as the graph becomes more and more complete and forms a viewpoint-independent representation of the spatial relations that enables reasoning about relative orientation and distance. The result of the integration of these three types of spatial knowledge (landmark, route and survey) forms a cognitive map.

In the past two decades, considerable research has concluded that all three levels of spatial knowledge can benefit people in performing wayfinding tasks (Goldin & Thorndyke, 1982). Route knowledge is most useful when navigating between two locations. On the other hand, in an unfamiliar environment, when route knowledge is not available, survey knowledge is the only information that users can rely on to assist them in finding their intended destination. Lawton (1996) concludes that people's wayfinding strategies gradually evolve from route-based to survey-based strategies. The development of each type of spatial knowledge within the LRS-model also likely occurs in parallel, with some information as survey knowledge, while others are stored as route knowledge (Hölscher et al., 2006).

Several wayfinding strategies, which support route choices, have been built on top of this spatial knowledge representation model, both in indoor and outdoor environments. In the route strategy, the urban environment is conceptualized as a network graph. A route-planning strategy identifies possible connections from start to destination using topological knowledge about connectivity relations between edges and nodes (Lawton, 1996; Hölscher et al., 2011). The indoor equivalent is defined as central-point strategy where users stick as much as possible to the main locations within a building (Hölscher et al., 2006). In contrast, direction-based strategies rely on information about the angular difference between the direction to the final destination, and the individual segments branching off at each intersection. This aligns with the least-angle strategy defined by Dalton (2003) where people try to minimize their global deviation from the direction of their destination, and at the same time attempt to conserve linearity throughout decisions at individual junctions. This wayfinding strategy is a predominantly visual process that is supported by awareness of the relative location of landmarks to each other (Hölscher et al., 2011). It has the advantage that when deviated from a specific route, one can mentally access a set of fixed reference points to reestablish his position within the environment (Lawton, 1996). Indoors, this strategy is translated into first choosing routes that head towards the horizontal position of the destination point as directly as possible, and then changing levels afterwards (Hölscher et al., 2006). A third wayfinding strategy works more hierarchically in a fine-to-coarse planning approach based on a cognitive segmentation into regions guiding navigation decisions. This model builds upon Colle and Reid's model (1998) stating that survey knowledge can be acquired quickly for local regions and slowly for remote regions. This translates for outdoor settings into the region-based strategies of Wiener et al. (2004), and indoors to a floor strategy where users move first to the correct floor before spreading out in the horizontal direction (floors are identified as the predominant hierarchical aspect of a building) (Hölscher et al., 2006). This strategy reduces the complexity of planning and navigation by first entering the target region before starting fine-tuned search (Hölscher et al., 2011).

Hölscher et al. (2006) discovered that the two main factors determining the choice of a wayfinding strategy are task and wayfinding instructions, rather than familiarity, gender or individual preferences. Lawton (1996) discovered that the main wayfinding strategies are universal across space concepts. However, the wayfinding approach itself and the concomitant guidance support differs according to the specific wayfinding context (Akerman & Karrow, 2007) (Section 1.1.2.2).

1.1.1.4 Evacuation

Evacuation applications are commonly related to navigation as they require movement to a safer place. As a research topic, evacuation has already been thoroughly studied in psychology, mathematics, engineering, architecture and geo-information science (Pu & Zlatanova, 2005). Commonly, four different phases constitute emergency management: mitigation, preparedness, response and recovery (Zlatanova & Holweg, 2004). In this dissertation, the focus lies on emergency response, which traditionally concentrates on the immediate and urgent aspects of an incident. Furthermore, our field of view is limited to evacuations in the built environments, not to natural environments.

In emergency response and ensuing evacuations, time is the most critical factor. Figure 1-5 describes the user's cognitive framework during emergency response, which is quite similar to the wayfinding model presented in Figure 1-3. However, time plays a more important role and the sensory input is somewhat different. Emergency situations can be characterised by a cause, a location and an extent. Following an emergency, often cues are initiated in order to inform the users of the situation. Upon receiving and recognizing these cues, the user starts his cue validation process to come up with a cognitive map of the current situation, also based on previous memory and sensory information. This map is then used to make an action plan before movement (also referred to as pre-movement times). Finally, the decision is executed through movement to a safer place. From then on, the recurring loop of perceiving cues, updating the cognitive map and assessing the previously made plans with the new situation continues until an exit or other safe place is reached. The emergency situation is dynamically changing, so at any time in the process, cues related to the emergency itself, progress in the evacuation of people, obstacles, etc. can influence wayfinding plans.

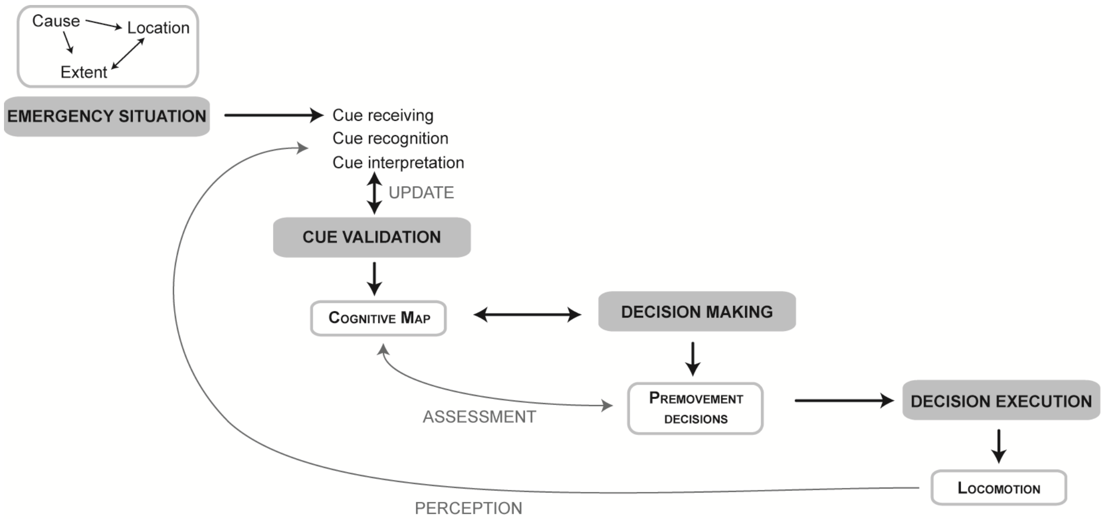

Figure 1-5 Crisis management scheme (based on Cepolina, 2005)

Since the 1980's with the modeling of emergency egress in fires, research on evacuation and emergency situations has increasingly grown (Gwynne et al., 1999). Models are mainly divided in two categories: those that only consider human movement (i.e. macroscopic models) and those that attempt to link movement with behavior (i.e. microscopic models). Many of these models consider various aspects of relevance to emergencies, being behavioral modeling, space layout structure, movement interaction and hazard influence (e.g. Gwynne et al., 1999; Hamacher & Tjandra, 2001; Santos & Aguirre, 2004; Kuligowski & Peacock, 2005).

In all models, evacuation times are recorded. The Required Safe Evacuation Time (RSET) of a building is defined as the time needed for the last person in the building to leave (Cepolina, 2005). In any evacuation scenario, the RSET is defined by two major elements: pre-movement time, and movement time. Pre-movement times mainly consist of the detection of, and the response to, an emergency situation. Given that they depend on parameters such as the type and extent of the emergency situation, the number and the quality of detectors and the warning system in the building (Kuiper, 2001), pre-movement times are hard to predict or measure (Gwynne et al., 2003). That is why evacuation models often only deal with the actual movement from the position at the beginning of the hazard to a safe place, as such neglecting the pre-movement time.

The actual movement of occupants to an exit is determined by both user and environmental context parameters (Figure 1-4). However, due to the inherent differences between evacuation and navigation, the interpretation of user and environmental parameters can differ greatly. Additionally, many other parameters, specific to dealing with the emergency context, need to be involved in the process. For example, related to the environment, damage status, toxicity status and traffic capacities can be of importance during evacuations (Lee & Zlatanova, 2008). With respect to user context, mostly those factors which influence people's speed are focused upon (e.g. population density, age, disability, gender …) (Lee & Zlatanova, 2008). Much research also considers human interaction under stress, cueing and other human behavioral characteristics. It is often not explained how these factors relate to each other nor how they can be calculated (Gwynne, et al., 1999; Kuligowski, 2008).

1.1.2 Space concepts: indoor and outdoor

Previously, it was discussed that wayfinding processes and the concomitant guidance support differ according to the specific wayfinding context. One of the largest influencing parameters is the environment, which encompasses both indoor and outdoor space.

1.1.2.1 Indoor versus outdoor space definition and characteristics

Indoor space can be defined as 'a space within one or multiple buildings consisting of architectural components' (OGC, 2014, p.12). It is not necessarily covered by a roof, and for example an inner court or veranda can belong to an indoor space. Outdoor space covers the remaining environmental areas.

Several authors (Li, 2008; Walton & Worboys, 2009; Giudice et al., 2010; Worboys, 2011) have tried to identify the structural differences between indoor and outdoor space. First, an obvious distinction in scale level can be detected when moving from outdoor (macro-scale) to indoor space (micro-scale) (Li, 2008). Outdoor space is considered large scale with objects ranging from small to large scale dimensions. Indoor environments often contain smaller objects in a smaller scaled setting (Walton & Worboys, 2009). As such, the scale level of indoor environments is limited to vista scale while outdoor space objects exist on an environmental or geographic scale level. Second, the spaces themselves are considerably distinct in structure, constraints and usage. Outdoor environments are commonly described as continuous with no constraints, while the perception of buildings is strongly influenced by the architectural enclosures (Li, 2008; Walton & Worboys, 2009). This is linked to differences in the origin of space. Outdoor spaces are frequently considered as non-built space with irregular features, while indoor buildings are manmade constructions consisting of rectilinear surfaces (Walton & Worboys, 2009). However, urban and city environments are manmade environments often consisting of many linear structures with obstructions as well. Third, the degree of mobility is more restricted in indoor environments - specifically, to pedestrian access - while in outdoor space various modes of locomotion (e.g. plane, train, car...) are supported (see also Section 1.1.2.3).

1.1.2.2 Effect of space division on cognitive wayfinding

The above structural differences between indoor and outdoor environments define the chosen wayfinding approach, and as such also the complexities and difficulties of users' wayfinding experiences. The reason for this is that relevant stimuli must be present for a wayfinding strategy to be selected. The wayfinder has to be sufficiently experienced with these stimuli (or similar ones) to understand and interpret them correctly, in order to become part of the wayfinder's cognitive map (Hölscher et al., 2011). Indoor and outdoor environments mostly differ in their availability of stimuli; hence affect wayfinding choices, effectiveness and success.

The exact influence of the difference between indoor and outdoor environments on a user's wayfinding experience is at this point not yet entirely known. However, three factors have already been investigated and determined to influence the complexity of wayfinding in a given environment: spatial structure, the created cognitive map, and the strategies and spatial abilities of the individual user (Carlson et al., 2010). While all three factors contribute, it should be noted that the third factor, the strategies of the individual user, is the only one that differs independent of the environment. In fact, since user strategies are linked to individual and personal characteristics, not all users are at the same level in terms of ability, strategy selection, or experience (Carlson et al., 2010). Due to this, we feel that it is not feasible to compare indoor/outdoor on this factor at this time.

However, the other two variables - spatial structure and created cognitive map - do vary when dealing with indoor versus outdoor space. Hölscher et al. (2006) define such specific elements of the spatial structure as visual access, the degree of architectural differentiation, the use of signs, and general spatial plan configuration. Indoor environments often have many discontinuities that clutter them and are totally covered spaces, which is perceived as a fragmented, enclosed and clustered environment (Richter et al., 2011). However, a typical perceptive image of indoor spaces simplifies the indoor environment with regularization of distances, angles and structure both within and across floors. Users also assume that the organization of a given floor extends to all floors. If this is not the case, one witnesses considerable difficulty with the correct execution of wayfinding tasks (Carlson et al., 2010). In contrast, outdoor urban environments have a mostly wider view with no covering, which is sensed as uncluttered and ordered, even in dense city environments. In cities with small, curved streets, the perception is more like indoor spaces where the visual understanding is hindered and more broken line of sights occur. Buildings are also nested environments that require a coherence across local and global levels. Additional problems indoor occur due to a general lack of visibility and three-dimensional floor level changes, which make it harder to maintain a general orientation with respect to the outside environment (Carlson et al, 2010). In contrast, in outdoor space, orientation is often much easier with a general global orientation facilitated by notable landmarks and local orientation supported by wider views.

Apart from the building structure, configurational objects also differ in indoor and outdoor spaces. When building a cognitive map of the environment, typically a prioritization of certain features and objects occurs within a user's brain. The objects that are detected, i.e. landmarks, are salient, stationary, distinct objects that are uniquely identifiable with reference to their immediate environment (Millonig & Scherchtner, 2007). In outdoor environments, a reasonable amount of research regarding the characteristics of landmarks and their influence on pedestrian navigation has been established (e.g. Sorrows & Hirtle, 1999; Millonig & Scherchtner, 2007; Caduff & Timpf, 2008). However, indoor spaces deal with more universal designs, less signs, less visibility - impeding large objects to stand out, and less architectural diversity. These aspects all hinder a clear and obvious detection and presence of indoor landmarks. As such, future research on what constitutes a good indoor landmark is highly necessary.

The above aspects are at the foundation of why wayfinding tasks in multi-level buildings have often proven to result in a higher risk of both disorientation and getting lost-episodes. As such, building occupants are faced with a deficient perspective on the building structure, which influences their movement behavior (Hölscher, et al., 2006). These more complex cognitive challenges indoors, induced by structural differences stress the importance of developing appropriate guidance support for wayfinding in indoor environments.

1.1.2.3 Mode of locomotion

With respect to navigational applications, one of the most important differences between indoor and outdoor is the type of navigating agents (Yang & Worboys, 2011). Examples of outdoor locomotion range from public transport, cars, and planes to pedestrian movement; while indoor movement is more restricted to pedestrian navigation (and in extension robotic movement). In this dissertation, we decided to solely focus on pedestrian navigation.

In theory, pedestrian navigation systems hold similar demands for route planning as car navigation systems do; i.e. guide user from starting point to destination (Popa, 2012). However, a pedestrian's movement occurs under different terms and conditions than the way cars reach their destination. As such, the interpretation and specification of routes to the pedestrian context calls for many adaptations, in addition to the adjustments already required due to the differences in space concepts discussed in previous sections. These new elements include:

- Degrees of freedom: Pedestrians can roam freely between the interior boundaries of buildings. They possess greater freedom in movement as they can walk in any direction and have access to places where vehicles are excluded (Millonig & Schechtner, 2007). Also, locomotion in indoor space is less regulated than in street traffic (Richter et al., 2011). Cars are often bound to their predefined network structure and more formal restrictions like one-way streets and speed limitations (Stoffel et al., 2007;

Popa, 2012). Additionally, cars are dealing with a fixed orientation with only forward or backwards movement (Bogdahn & Coors, 2009). This implies that only a minimal set of instructions is required for navigation.

- Data requirements: Most databases and common available data sources only include the accessible parts of road networks for vehicles. With pedestrians not being tied to those, other data sources will have to be opened up (Elias, 2007; Popa, 2012).
- Seamless movement: Pedestrians also have access to both indoor and outdoor environments, requiring route guidance in both. This seamless movement of pedestrians from indoor to outdoor has to be supported in the developed navigational models and route finding applications. This requires availability of both indoor and outdoor data, technological support in indoor environments and a communal space model.
- Environmental factors: Car drivers control their own environment and are provided with a constant level of comfort (protection against climate impacts, dust, pollution, noise, etc.), while pedestrians are exposed to a great variety of environmental impacts. (Millonig & Schechtner, 2007). This can influence the priority in route choice with pedestrians preferring indoor and underground paths over outdoor sections.

As can be seen, pedestrian navigation has to deal with a variety of unique situations, from restricted travel on outdoor walkways or in underground structures, to open pedestrian access on squares, and even covering multiple dimensions within multi-level building complexes.

1.1.2.4 Implications of space division for navigation guidance tools

Given the actual differences between spaces and their effect on user's wayfinding experiences, it seems only logical that navigation guidance tools would be developed. Basic concepts, data models and standards of spatial information should thereby be redefined to meet the requirements of the applications in their specific spatial environment (OGC, 2014). In outdoor environments, a mature basis for navigational applications exists with car navigation systems that have been widely developed over the last decade. Their evolution started during the 60's by the development of the Global Positioning System. Over the last 50 years, augmentations, additional next-generation satellites, upgrades, and similar systems developed by other countries have increased accuracy, coverage and robustness considerably for both civil and military users (Kaplan & Hegarty, 2006). For car navigation, GPS meant the stimulus for a worldwide overtaking of the routing world from ordinary paper maps. Additionally, a more efficient and abundant data collection using mobile mapping technology and improvements in modeling and data storage (e.g. GDF standard – see Chapter 6 for more information) made it possible to fulfill the requirements of outdoor navigational systems.

On the other hand, the adaptation of navigational systems to the indoor environment is still quite problematic on several levels. Technologically, positioning technology currently remains one of the major issues holding back navigation applications for indoor environments. Several solutions have been proposed over time, beginning with the extension of outdoor GPS to indoor space (Worboys, 2011). Furthermore, a large array of new sensors for indoor positioning has been developed and is continuously being improved (Figure 1-6) (Kolodziej & Hjelm, 2006). There are many requirements for those localization technologies: reliability, speed, safety, availability, cost .... (Mautz, 2012), with the main question in this context being what level of accuracy and coverage is required to support navigation and evacuation indoors.

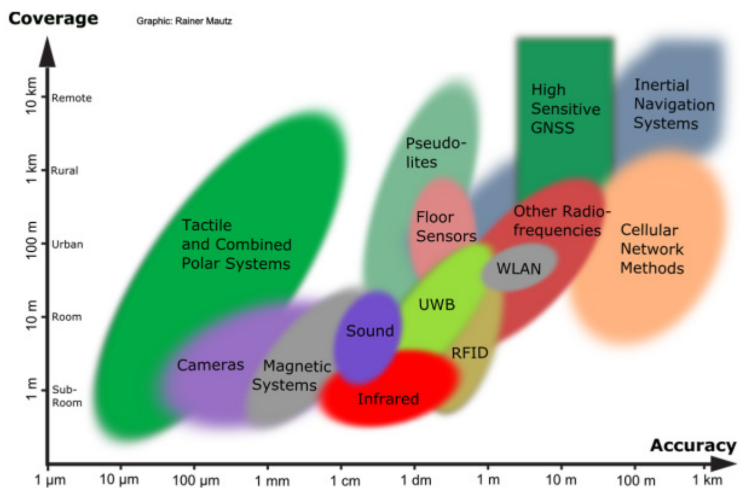

Figure 1-6 Overview of indoor positioning technologies (Mautz, 2012)

In addition to technological problems, spatial reference systems for indoor spatial localization are currently based on outdoor ones. Indoor systems often only have a local absolute or relative coordinate system, and outdoor geocoding technologies are not applicable indoors (Lee, 2009). The focus indoors is also less on exact absolute positioning but rather on the connectivity and topology of the spatial structure due to the cluttered and fragmented spatial structure (Walton & Worboys, 2009). Spatial orientation indoors is also hampered by less visibility, less orientation clues and environmental information due to the fragmentized space (Stoffel et al., 2007; Giudice et al., 2010). Landmarks may have a similar functionality across space concepts, but for indoor navigation, a larger reliance is based on local landmarks due to those visibility restrictions (Yang & Worboys, 2011).

A third issue is that the actual structural and cognitive differences of both spaces lie at the core of the large variety of existing models between indoor and outdoor space. The change in scale from outdoor to indoor space manifests through dimensional differences in the developed models: common outdoor models are 2D or 2.5D while indoor models are either 2D blueprints or complex 3D models (Walton & Worboys, 2009). Also, although connections (in terms of networks) are available in both space concepts (e.g. roads and railway structures outdoor, and corridors indoor), their relationship with the surrounding space is completely different. Indoor three-dimensional networks might look structurally similar to their 2D counterpart, with attributes attached to the vertical edges, but networks embedded in the two-dimensional plane do not support the 3D topological relationships that characterize indoor networks (Stoffel et al., 2007; Thill et al., 2011). Outdoor networks are also used for physically connecting places, while indoor sections form a functional part of the entire space and are contained within this space (Walton & Worboys, 2009; Yang & Worboys, 2011). With regard to the cognitive modeling of spaces, indoor spaces are more perceived as symbolic cellular and non-Euclidean constraint spaces, rather than purely geometric (OGC, 2014). This is also the reason for the development of many symbolic models with indoor positioning through abstract symbols (Becker & Dürr, 2005). The variety in indoor objects places a high demand on appropriate semantic models, where semantics can be used to provide classification and to identify a cell (OGC, 2014). The properties of a semantically identified cell have an impact on the indoor network connectivity, and can act as a navigation constraint in the model.

Because of these structural and cognitive different perceptions of space and their implications on data, models and algorithms, the question arises as to whether available outdoor models and algorithms for routing are sufficient to be directly adopted into indoor navigational applications.

1.2 Rationale and synopsis

1.2.1 Research objective and questions

Over the past decade, research around navigation and evacuation in the built environment has undergone a new impetus as a result of various developments in LBS, information technologies and new building developments. These evolutions have lead to a renewed focus on developing and improving navigation and evacuation applications.

Navigation is essential to any environment that demands movement across large spaces, even though it rarely forms the primary task (Darken & Peterson, 2002). Both navigation and evacuation are complex tasks located at the edge of multiple research domains, from cognition and psychology to geospatial and architectural analysis. In this dissertation, the focus is on the geospatial domain and more specifically on navigation (and evacuation) guidance tools. While outdoor car navigation implementations are quite well-developed and mature, indoor navigation applications are just starting to be opened up. Indoor implementations thereby have to specifically deal with several structural and cognitive aspects that are not yet covered within traditional outdoor guidance aids (Section 1.1.2.2). This is why our main motivation for our research aims at examining the support for multiple navigation and evacuation contexts by focusing on the models, algorithms and analyses required as part of the routing aspect of guidance support systems (Figure 1-2).

From a theoretical point of view, one could assume that routing in indoor environments is quite similar to their outdoor counterparts. However, from a cognitive point of view, path finding and calculation within buildings and underground structures are highly different than routing on a road network (e.g. Section 1.1.2). In navigation guidance applications, networks are mostly employed as underlying model of space and delineate the navigable space to solve path-finding problems. While outdoor road networks are quite common, in building and underground structures, networks might not constitute an appropriate modeling formalism as the strategies used for navigation are highly different from those on road networks. Additionally, in outdoor environments, car drivers are mostly interested in shortest or fastest paths, while pedestrians might prefer easier-to-follow (Duckham & Kulik, 2003) or reliable routes (Haque et al., 2007). Furthermore, within buildings, physical and psychological properties of the user are of more importance (disability, claustrophobia ...). This often more complex context indoors has to shine through in the variables and algorithms for indoor navigation guidance. The evacuation context adds even more constraints to the wayfinding process. All these aspects contribute to a growing need to consider navigation and evacuation aspects in indoor environments in greater detail, with specific attention to models and analytical support. As such, the main research objective in this dissertation is defined as:

> **Study and improve models, analyses and algorithms for navigation and evacuation scenarios in indoor spaces by linking them to similar outdoor concepts.**

With this research objective, apart from a focus on indoor navigation and evacuation applications, we draw upon the vast knowledge available around outdoor applications and will use this when developing and improving equivalent indoor implementations. This obviously means that the structural and cognitive context differences that exist between indoor and outdoor environments will come into play and have to be taken into account. It will be interesting to examine how the choice of environment affects models, algorithms and analyses of navigation guidance implementations.

An additional advantage of relying on outdoor methodologies and applying them to indoor space is a future integration of indoor and outdoor environments for navigational applications. Indeed, evacuations and routing both affect and are affected by their immediate and more extended environment. Limiting navigation and evacuation applications to either the micro indoor built environments or macro urban or regional scale outdoor, restricts analysis to one scale level and one dimension type. Additionally, it does not coincide with the complexity of the real world (e.g. finding optimal routes between two rooms may require micro and macro routing analysis). In order to support this need, this dissertation will take a first step towards examining whether integration of indoor and outdoor spaces is feasible for pedestrian navigation applications, by examining whether outdoor implementations can be easily extended into indoor environments.

From this general research objective, five more-specific research questions (RQ) were derived. Note that when the terminology wayfinding or navigation is used, we refer specifically to the route planning aspect of navigational applications.

- **RQ 1: What is the current state-of-the-art on the integration of indoor and outdoor environments for pedestrian navigation?**

  In this first research question, we aim to list and compare the current approaches in integrating indoor and outdoor environments in a combined pedestrian navigation approach. Both theoretical as well as practical developments will be evaluated in order to understand the current status of combined navigation applications and to grasp the challenges still to be dealt with in navigational research. Additionally, it will allow us to improve our understanding of the specific environmental parameters that influence navigation in either indoor or outdoor space.

- **RQ 2: What is the current state-of-the-art of indoor navigation and evacuation research in terms of models, algorithms and analyses?**

  The widespread availability of outdoor navigation systems (mostly car navigation) points to the existence of accurate support of routing guidance aids within outdoor environments. The real challenge now lies in the indoor aspect of space and its developments over the past decade with respect to indoor models, algorithms and analyses. Apart from research focusing on indoor navigation, an investigation of indoor evacuation research will also be considered as evacuation and navigation are quite closely related concepts (Section 1.1.1.4).

- **RQ 3: Can analytical procedures from outdoor space be directly applied to indoor spaces?**

  It is widely acknowledged that indoor environments lack a significant analytical backbone support system. As such, in this research question, we focus on analyzing indoor spaces by investigating the available tools. More specifically, we examine if and how existing analytical features from outdoor space can be applied in an indoor context. In doing so, it can also provide analytical functions that work in both space concepts.

- **RQ 4: Can cognitive outdoor navigation algorithms be directly extended to guide unfamiliar users in indoor spaces?**

  A similar question as RQ3 is proposed here, but this time applied to path guidance algorithms. Cognitive outdoor algorithms are found more useful in aiding unfamiliar users in outdoor environments as they are closer connected to the cognitive idea of wayfinding and joining wayfinding strategies. In indoor space, even more difficulties have been identified that complicate wayfinding endeavors (Section 1.1.2.2). As such, with this research question, we aim at investigating whether those outdoor cognitive algorithms can be applied to indoor space and in the future support integrated indoor-outdoor navigation using unified path algorithms.

- **RQ 5: Do the different indoor space models have any noticeable effect on the operation and on the results of navigation guidance algorithms?**

  This research question aims at focusing on a specific item of relevance in the discussion of extending guidance algorithm: the relationship between models of space and the application of algorithms. Are the operations and results of algorithms applied to various models of the same environment similarly accurate and trustworthy? If not, can a space-model independent concept be developed to still support navigation in indoor (and later on combined indoor-outdoor) environments? A better understanding of this intricate relationship can result in newly developed methodologies and models supporting the integration of indoor and outdoor environments.

RQ1 and RQ2 aim at giving an overview of the current and past developments of pedestrian navigation and evacuation research in indoor and combined indoor-outdoor environments. RQ3 and RQ4 focus on the application of outdoor concepts to indoor spaces to examine whether a single one-on-one translation is possible between both space concepts, and they will reveal whether new developments are required for indoor space analyses in the future. RQ5 is more integrative as it ties back to the results of RQ3 and RQ4 on the possibilities of applying outdoor algorithms and analyses to indoor space concepts. At the same time, RQ5 is also more specific than previous research questions, as it solely focuses on the relationship between models of space and analyses using these models.

1.2.2 OUTLINE OF THE DISSERTATION

The various research questions described above are discussed and analyzed throughout the rest of this dissertation. There is no one-on-one relationship between the stated research questions and the chapters themselves, as several chapters contribute to answering various research questions. This is also partly due to the fact that this dissertation is drawn up from the collection of several research articles, each written from a specific research angle. With the formulation of the five research questions, all chapters are connected into a broader framework. Figure 1-7 illustrates this broader structure of research and the links between the individual chapters and the research questions. Chapters 2 through 7 correspond to papers published or submitted for publication in international peer-reviewed journals and books.

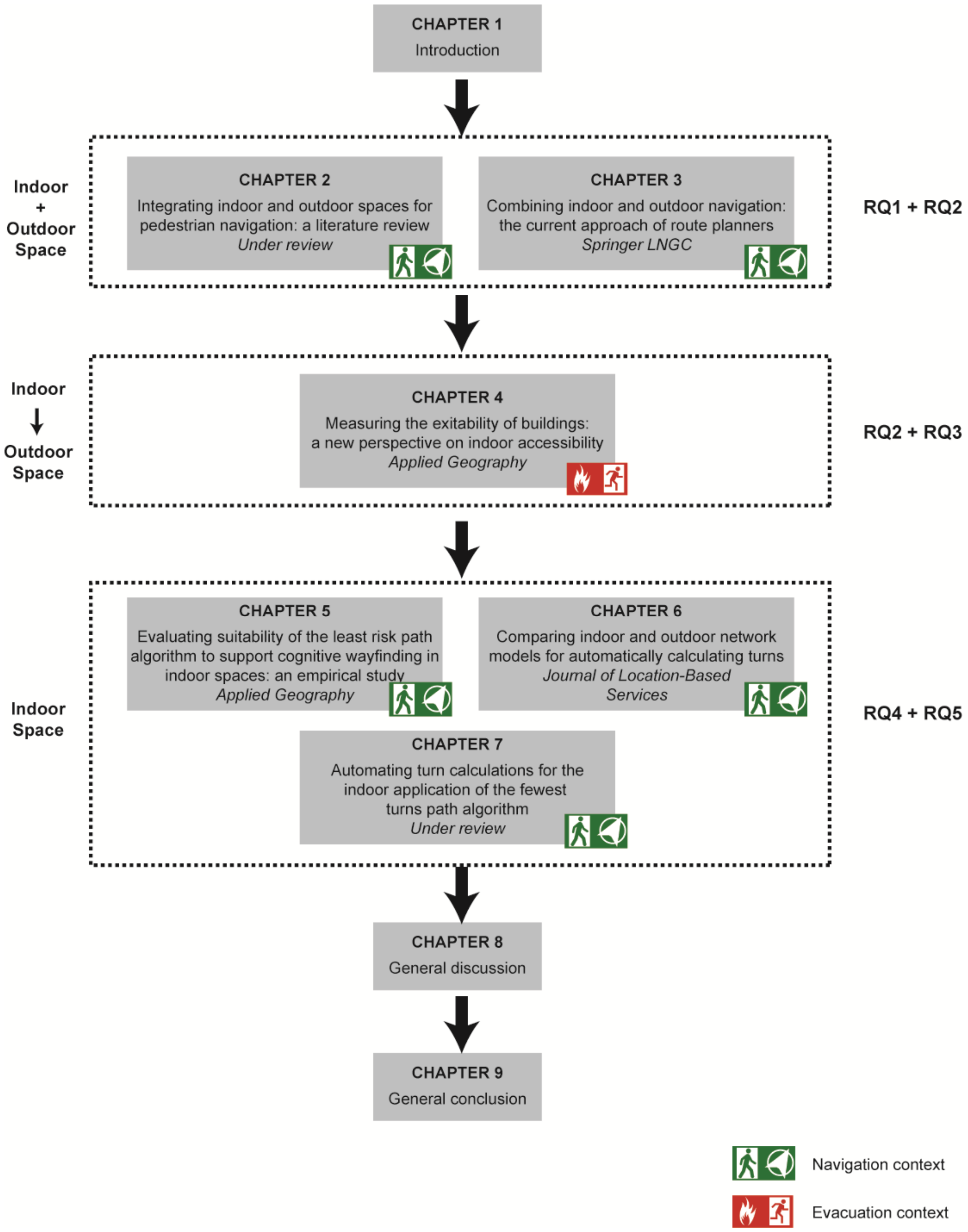

Figure 1-7 Dissertation outline

Chapters 2 and 3 provide a general review on pedestrian navigation applications in indoor and combined indoor-outdoor environments. Their scale-level is combined indoor and outdoor space. Both chapters will allow us to give an answer on RQ1 and RQ2 as they sketch the context of current navigational research.

Chapter 2: This chapter – submitted for publication to *Transactions in GIS* (Vanclooster et al., 2014c) – investigates on a theoretical level the current integration of indoor and outdoor environments for pedestrian navigation. It begins from the definition of navigation as presented in Section 1.1.1.1, and focuses on models of space, required input data, algorithms and context support. The analysis serves in evaluating the current state of integration and where, theoretically, more work is required to close the gap between indoor and outdoor space research. It will also help identify the specific achievements and problems within indoor navigation research.

Chapter 3: Besides the theoretical review in Chapter 2, Chapter 3 focuses more on the application side of Location-Based Services that facilitate integration of indoor and outdoor environments for navigation purposes. Practically, seven route planners were compared in the way they handle dealing with both space concepts. As such, the previously theoretical aspects of indoor-outdoor space integration in navigation can be linked to current practices. The results of this study were published in Vanclooster et al. (2012a) as part of the Springer book series *Lecture Notes in Geoinformation and Cartography*.

The next three chapters, Chapters 4 through 7, have a common focus of optimizing space-time decisions for movement within indoor environments.

Chapter 4: The main question behind this chapter is: How easy is it to get from the indoors to the outdoors by reaching a building exit? This study – published in *Applied Geography* (Vanclooster et al., 2012b) – is triggered by the lack of analytical support for indoor spaces. We also focused on evacuation scenarios as a special application of navigation. The article starts of by comparing the different modeling situations for evacuation in the built environment, which allowed us to answer RQ2. Afterwards, it tries to apply the common outdoor analytical concept of accessibility in an indoor environment under emergency conditions, in accordance to RQ3. The proposed analytical tool is then used to evaluate structural differences within a building in terms of evacuation support.

Finally, Chapters 5 through 7 focus solely on the indoor navigation context and its algorithms to guide unfamiliar users through the built environment.

Chapter 5: Indoor environments tend to be more difficult to navigate compared to outdoor spaces, for several reasons, discussed in Section 1.1.2.2. An algorithm that aims at minimizing the risk of getting lost- i.e. the least risk path algorithm (Grum, 2005) - could therefore prove very valuable in aiding unfamiliar users through space. As such, in Vanclooster et al. (2014a) – published in *Applied Geography* – this algorithm is extended from outdoor to indoor space. The aim was to examine whether algorithms developed for outdoor space need to be adjusted to the specificities of indoor space, and how, and relates to RQ4.

Chapter 6: A second algorithm of interest for improving wayfinding in indoor spaces is the simplest path algorithm (Duckham & Kulik, 2003), minimizing route instruction complexity, by taking into account both the number of turns along a path as well as the various intersection types. In this paper (Vanclooster et al., 2014d – published in the *Journal of Location-Based Services)*, several indoor and outdoor network options were evaluated on their suitability for automatically calculating turns. It also highlights the relationship between the calculation of the number of turns and its influence on the generation of accurate indoor route instructions.

Chapter 7: Extending the findings of Chapter 6, Vanclooster et al. (2014b) – submitted to the *International Journal of Geographic Information Science* – presents a new procedure for automatically calculating turns based on the specificities of indoor spatial structures and human cognitive perception of turns. The procedure does not rely on any kind of indoor network model and is applied in the implementation of the indoor fewest turns path algorithm (RQ4). It can serve as a basis to develop and implement the indoor simplest path algorithm.

1.2.3 OUT OF SCOPE

One can never investigate all aspects involved in a certain research study. Based on the initial definition of navigation, we decided to only focus on part of the routing aspect, namely the description and improvement of the routing model and routing algorithms. However, all items (i.e. localization, orientation, tracking, visualization and verbalization of routes...) are required for successful navigation.

The technological aspects and progress in positioning technologies has already been referred to in Section 1.1.2.4. Indoor positioning and localization gained a surge of interest with developments in WiFi, Bluetooth, RFID and many experimental setups. They are here out of scope as we assume that indoor positioning is ubiquitously available at a certain level of accuracy, enough for the navigation or evacuation application at hand.

Additionally, the cognitive and psychological effects of providing certain routes to users are not investigated. As mentioned, the geospatial aspect of navigational models, data and analyses is of focus here. This also implies that visualization and verbalization aspects of routes to users will not be touched upon.

Last but not least, combined indoor-outdoor navigation often consists of multimodal connections. While we recognize that a user's journey often includes multiple aspects of locomotion, and as such requires more complex planning, in this research only the pedestrian aspect of navigation has been considered.

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2

INTEGRATING INDOOR AND OUTDOOR SPACES FOR PEDESTRIAN NAVIGATION GUIDANCE: A REVIEW

Modified from: VANCLOOSTER, A., VAN DE WEGHE, N. & DE MAEYER, P. 2014. Integrating indoor and outdoor spaces for pedestrian navigation: a review. (Submitted to Transactions in GIS).

ABSTRACT

In light of the many improvements within indoor navigation applications, 3D urban modeling, and Location-Based Services, this paper provides a timely review of the state-of-the-art on integrating pedestrian navigation developments. Pedestrian navigation applications form the ultimate example of the need for combined indoor-outdoor geospatial research as people move seamlessly between buildings and surrounding areas. This paper specifically focuses on how current developments integrate these two diverse space concepts and as such deal with the individual specificities within the framework of available models, data requirements, algorithmic and context support. From this review, a detailed research agenda is distilled on the next required lines of research.

2.1 INTRODUCTION

While outdoor environments are commonly investigated with several geospatial analyses (Ban & Ahlqvist, 2009), indoor environments have only recently become an indispensable part of current geospatial research (Worboys, 2011). This might sound surprising, given the fact that humans spend most of their time indoors (Jenkins et al., 1992). However, new possibilities for developing comprehensive 3D geo-models (Lee & Zlatanova, 2008) only emerged quite recently, together with an improved ability to perform 3D analyses on semantic, topologic and geometric levels (Li, 2008). Additionally, the enormous commercial potential of possible consumers held within indoor environments has increasingly been recognized with a growing development of indoor Location-Based Services (Kolodziej & Hjelm, 2006). These evolutions heralded a new step in geospatial research, concerning the integration of indoor and outdoor (IO) environments (Huang & Gartner, 2010).

Navigation forms the ultimate example of the need for combined indoor-outdoor research. Indeed, humans do not distinguish between outdoor and indoor spaces in their navigation endeavors. This seamless movement between both space concepts has to come to light again in the navigation guidance aids, which aim at supporting user's wayfinding tasks. Many questions thus arise: are the navigation principles from outdoor space comparable to those of indoor environments? Do the existing theories of car navigation fit the requirements of pedestrian navigation? Which models currently support integrated IO navigation? These questions push the necessity for a thorough review on the matter. In previous reviews, the three-dimensionality of the micro-scale environment served multiple times as study subject, either focusing on the available models (Lee & Zlatanova, 2008), the topological analyses in 3D (Zlatanova et al., 2004; Ellul & Haklay, 2006) or 3D geo-database research (Breunig & Zlatanova, 2011). Although all aspects within those reviews play an important part in representing, analyzing and querying for navigation; none of these reviews focused on navigation as core application. Furthermore, several authors have studied the various models available for indoor navigation (Becker & Dürr, 2005; Afyouni et al., 2012) and the technological aspects of indoor navigation (e.g. Liu et al., 2007; Huang & Gartner, 2010). Although useful, in this review we specifically aim at examining the various theoretical approaches of integrating indoor and outdoor environments in navigation guidance aids to support seamless navigation.

In Section 2.2 of this paper, pedestrian navigation is defined and situated within a framework of both indoor and outdoor space, and differences in mode of locomotion. Section 2.3 describes the selection criteria used in choosing the relevant studies, while Section 2.4 discusses the various theoretical developments found in these studies. In Section 2.5, a discussion on the overall current state-of-the-art forms the base for defining a future research agenda in the field of pedestrian navigation.

2.2 DEFINING PEDESTRIAN NAVIGATION IN INTEGRATED INDOOR-OUTDOOR SPACES

2.2.1 NAVIGATION AND ITS REQUIREMENTS

Navigation, whether indoor or outdoor, can be defined as a two-way process consisting of (i) a purposive, directed and motivated decision on the exact path (i.e. wayfinding) and (ii) the movement along that path from start to destination (i.e. locomotion) (Montello, 2005). During wayfinding, a combination of localization, tracking and routing aspects interact with each other in order to define a possible route or continuation of a route (Nagel et al., 2010). Navigation guidance aids can help wayfinding processes in the sense that they effectuate improving the user's cognitive map so that appropriate and founded wayfinding decisions can be made (Golledge, 1999). This is especially helpful for users who are unfamiliar with the environment. It requires fulfilling the components of localization, tracking and routing and each of their specific requirements (Table 2-1, based on Becker & Dürr (2005) and Nagel et al. (2010)).

	LOCALIZATION	TRACKING	ROUTE GUIDANCE
DEFINITION	Determination of an absolute position in space of the user with respect to its environment	Following the positional changes of the user in its environment	Calculation, communication and visualization of a queried navigation path from start to destination
REQUIRE-MENTS	- Technology for absolute positioning - Model of space - Link between position and space model	- Technology for continuously updating the user's position - Geocoding - Visualization of positional changes - Orientation	- User-adopted model of space (topology, semantics, geometry) - Common vocabulary for querying and communication - Visualization & communication platform - Path calculation methodology

Table 2-1 Requirements for the various components of navigation

Over the years, navigational applications have increasingly conquered the world with online mapping services, car navigation systems and ubiquitous smartphone distribution (Gartner et al., 2009). Lately, more and more Location-Based Services and mobile applications play a crucial role in a vast number of lives as these help positioning, wayfinding and sharing of information. Smart environments will be the future, and navigation is a crucial part as it simplifies wayfinding.

The requirements of outdoor navigational systems have been gradually fulfilled over the years due to the development of the Global Positioning System, a more efficient and abundant data collection and improvements in standardizing models and data storage (e.g. Geographic Data Files ISO standard) (Lorenz et al., 2006). Indoor navigation has so far proven more challenging, but the last decade showed significant progress into the topic (e.g. indoor localization techniques, modeling ...). Most recently, this includes commercial interest with public data gathering for navigation support in several indoor buildings (e.g. Google Maps Indoor). Although progress in several areas is still required (e.g. more accurate indoor positioning, improved indoor route communication, context descriptions), the most important challenge lays in forming the integration of outdoor and indoor theories into a combined indoor-outdoor navigation system.

Combining the indoors and outdoors into a single navigation system should take into account three main aspects: (i) seamless positioning between indoor and outdoor technologies, (ii) route calculations integrating indoor and outdoor space, and (iii) appropriate route communication to the user providing a smooth visual switch between indoors and outdoors (Huang & Gartner, 2010). In this review, the focus is on providing route calculations through combined indoor-outdoor spaces, and the requirements this incurs such as structuring data, providing context and supporting algorithmic calculations. The communication and positioning aspects of navigation guidance are not reviewed in this paper.

2.2.2 DIFFERENCES BETWEEN CAR AND PEDESTRIAN NAVIGATION

Pedestrian navigation systems hold similar demands for route planning as car navigation systems, i.e. guide users from start point to destination (Popa, 2012). However, pedestrian's movement occurs under different terms and conditions than the way drivers reach their destination. The choice in mode of locomotion directly affects parameters in the broader context of space, eventually influencing modeling and analysis. Together, these sketch the challenges which developers of pedestrian navigation applications must deal with (Figure 2-1).

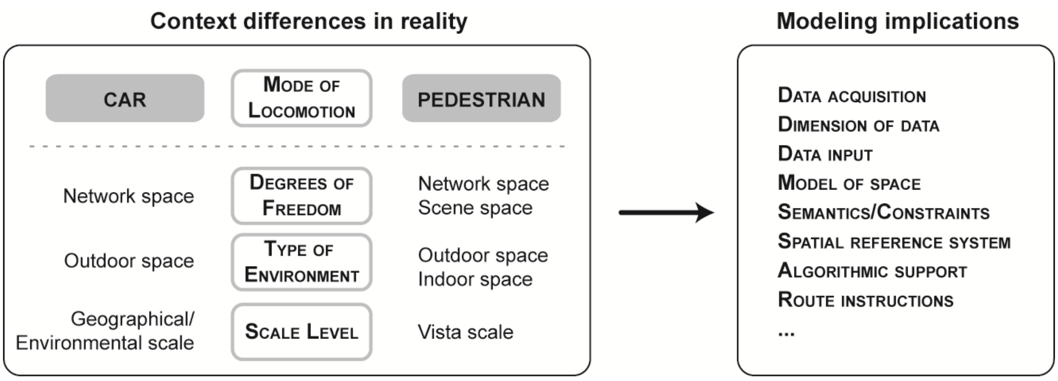

Figure 2-1 Context-dependent factors influencing navigation modeling

First, the mode of locomotion has a direct influence on the degrees of freedom available for users. Car drivers mostly move on predefined road network structures in a highly regulated manner. They are also required to deal with imposed restrictions like one-way streets, speed limitations, etc. (Millonig & Schechtner, 2007). Outdoor street networks are mostly modeled by a network structure, as movement aligns with the inherent linear connectivity structure. The direction of movement of cars is also restricted to a fixed orientation of either forward or backwards travel (Boghdahn & Coors, 2009). This minimizes the set of instructions required to guide people. Pedestrians, on the other hand, possess a greater freedom in movement; they can walk in any direction they like and have access to places where vehicles are excluded (e.g. inside buildings, pathways) (Millonig & Schechtner, 2007). Locomotion in those pedestrian areas is also less regulated than car traffic (Richter et al., 2011). Despite the fact that road networks and pedestrian networks can overlap in content, both are dissimilar in scale and details, and are incompatible for most applications (Karimi & Kasemsuppakorn, 2012). Since pedestrians walk more freely in the available space, modeling this by using the available outdoor transport networks does not necessarily reflect the available freedom (Bogdahn & Coors 2009).

Pedestrians also deal with movement in both indoor and outdoor environments, compared to restricted outdoor car movement. This influences many aspects of the modeling phase as indoor and outdoor spaces are highly different in structure, semantics and perception. For example, indoor space is volumetric and three-dimensional, while outdoor space is mostly planar with horizontal distances dominating. The one-dimensional modeling of outdoor networks is not suitable to the three-dimensional objects that constitute a building (Stoffel et al., 2007). Additionally, a different set of semantics within the data is required: indoor spaces consist of many structural building elements that can be of importance for route guidance compared to the common outdoor semantics of roads and intersections (Yang & Worboys, 2011a). Note also that the outdoor environment available to pedestrians not necessarily overlaps with that of cars, as such needing a different outdoor set of semantics. Furthermore, car drivers are provided with a constant level of comfort (protection against climate impacts, dust, pollution, noise, etc.), while pedestrians are exposed to a greater variety of environmental impacts (Millonig & Schechtner, 2007). This may have an influence on the requested guidance support and algorithms, with pedestrians preferring routes with more indoor sections avoiding the existing constraints. Finally, even though the main strategies used in wayfinding are universal across space concepts (Lawton, 1996), the wayfinding approach itself and the concomitant user support differs according to the specific wayfinding context (Akerman & Karrow, 2007).

Third, an obvious distinction in scale level can be detected between car and pedestrian use, especially when moving from outdoor (macro-scale) to indoor space (micro-scale) (Li, 2008). The scale level affects the required level of detail in the data and the coverage of data sets. For car users, while the required area of guidance is quite large (from within city boundaries to national and even international data sets), the level of detail does not necessarily have to be as high given the speed of movement and guidance instruction level. For example, this has an influence on the type and location of landmarks used in route instructions. For pedestrians, moving at a slower speed, route instructions will need to take into account specific details about the environment that can help local orientation. Spatial orientation and visibility play also a much larger role in indoor environments (Elias, 2007) due a more fragmentized space with many discontinuities (Stoffel et al., 2007; Giudice et al., 2010).

In conclusion, pedestrian navigation has to deal with a variety of situations that make it much more difficult to model when compared with outdoor navigation; from restricted travel on walkways outdoor, to openly accessible squares, to underground structures and multi-level building complexes. The seamless movement of pedestrians from indoor to outdoor has to come to light in the developed navigational models and route finding applications, without losing sight of the various dimensions, data types, data structures and models developed for each individual space concept.

2.3 SELECTION OF STUDIES

The aim of this paper is to provide an overview of the state-of-the-art of theoretical research on the integration of indoor and outdoor spaces for the facilitation of seamless navigation between them. Throughout the month July 2014, an extensive literature search was conducted on the electronic online databases Web of Knowledge (www.isiknowledge.com) and Google Scholar (www.scholar.google.com). Web of Knowledge contains links to more than 23,000 academic and scientific journals and more than 110,000 conference proceedings within scientific research in arts and humanities, sciences and social sciences. Google Scholar is a freely accessible web search engine that indexes scholarly literature across an array of disciplines. While not necessary always peer-reviewed, the use of Google Scholar was motivated by the fact that the search on Web of Knowledge database revealed little results.

The following standards were applied to the literature selection: (i) the research focuses on pedestrian navigation applications that integrate indoor and outdoor environments; (ii) The research concentrates on route guidance of pedestrian navigation, more specifically on data models, algorithmic support and context support. Reviews of neither indoor positioning technology nor visualization and communication aspects are considered; (iii) The selected studies focus on aiding all types of pedestrians, not solely aiding the visually impaired; (iv) The aim of the study is restricted to modeling the possibilities for pedestrian navigation support and does not entail predicting the exact behavior of pedestrians in combined indoor-outdoor environments. The following search key was designed to select a significant amount of articles on the topic:

pedestrian navigation –position* -technolog* -loca* -blind –impair* -robot* (1)

However, this search key resulted in very few relevant articles. As such, two additional search keys were designed: one on indoor navigation and one on outdoor navigation.

indoor navigation –position* -technolog* -loca* -blind –impair* -robot* (2)

outdoor navigation –position* -technolog* -loca* -blind –impair* -robot* (3)

The use of an asterisk in the search keys enabled the omission of articles on topics of 'positioning' or 'positions'; 'technology' or 'technological'; 'location', 'localization' or 'localized'; 'impaired' or 'impairments'; 'robots' or 'robotics'. The search of all search keys resulted in a final selection of only 36 relevant articles. These results indicate that at this point there exists a significant void in academic literature covering this research topic. Nonetheless, it is already interesting to see the current improvements and research topics related to pedestrian navigation. Indeed, Huang and Gartner (2010) acknowledged that combining indoor and outdoor navigation will be key in the next decade and the increased demand for pedestrian navigation applications forms our prime motivation for this literature review.

Table 2-2 in Appendix presents the final selection of papers and summarizes them according to the following characteristics: authors and year; study design and scale; space concept (SC); input data (ID); algorithmic support (AS); context support (CS) and a summary of key findings of each study.

2.4 Comparison of theoretical approaches

2.4.1 Space concept

In almost every article, a model of space is discussed, either with the purpose of proposing a new model, or for examining certain properties of the given context by using existing models. Note that even though the models will be subdivided according to approach, not all of them completely coincide with a single category but can contain aspects of several modeling concepts (e.g. Giudice et al., 2010; Brown et al., 2013) Figure 2-2 gives an overview of the most common space concepts, subdivided per scale level.

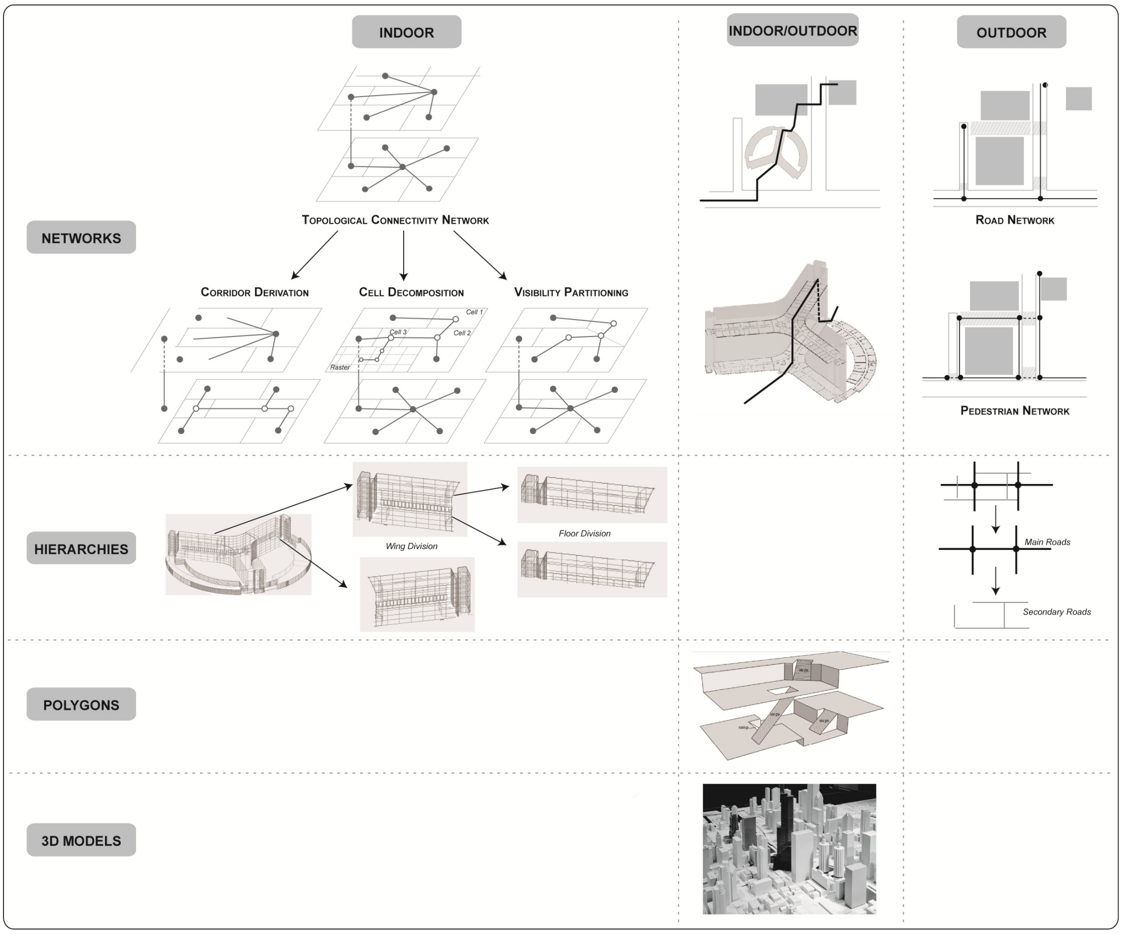

Figure 2-2 Overview of the several models for pedestrian navigation

2.4.1.1 Networks

Many authors agree on the need for a routing graph as underlying space concept to support path guidance. A graph is composed of nodes and edges, roughly describing places and their spatial interrelationships. Depending on the application field, the interpretation and definition of nodes and edges can vary considerably (see Franz et al. (2005) for a comprehensive overview of graph-based models in architecture and cognitive science).

Outdoor pedestrian network approaches

Most outdoor pedestrian network approaches still rely on the available street network for cars (Millonig & Schechtner, 2007), even though pedestrians deal with highly different context parameters (Section 2.2). Also, at present, outdoor navigation data models, such as GDF, KIWI and SDAL do not pay attention to the pedestrian transport infrastructure (Zheng et al., 2009). Karimi and Kasemsuppakorn (2012) focus as one of the only papers specifically on pedestrian navigation guidance approaches using an outdoor network. The pedestrian network is defined as a topological map containing the geometric relationship between several pedestrian path segments, i.e. any pathway that allows pedestrians to pass. Seven different types of such pedestrian path segments are suggested: sidewalk, crosswalk, footpath, building entrance, trail, pedestrian bridge, and tunnel. The vector data model, due to its ability to represent complex spatial objects using basic graphical elements (points and lines), is found suitable for representing such pedestrian outdoor networks.

Indoor pedestrian network approaches

The most elementary version of an indoor network is a 1-on-1 relation between geometrical building structure and network graph; i.e. every spatial unit is transformed into a node with the edges portraying the topological connectivity relationship between each unit (Stoffel et al., 2007; Stoffel et al., 2008; Sato et al., 2009). The Combinatorial Data Model (CDM) is a similar data model, grounded on the mathematical theory of Poincaré Duality to simplify the complex spatial relationships between 3D objects by creating a dual graph structure (Lee, 2004). This dual graph enables an efficient implementation of complex computational problems within indoor navigation systems. However, topological connectivity models still contain several shortcomings: (i) Removal of the internal building complexity (e.g. subdivisions, obstacles) within each spatial unit leading to inaccurate wayfinding guidance. (ii) Dissonance between network and actual wayfinding perception making the topological graph not necessarily suitable for visual representations of walking patterns, nor appropriate wayfinding support (Hölscher et al., 2009).

(iii) Context attribution is limited to the network which influences algorithmic support (e.g. in case of evacuation, the topological structure of the building might be altered due to blockages influencing the access to certain paths). Over time, these problems have led to several alterations to the original topological connectivity model.

(i) Corridor derivation

Corridors hold an important position within the internal building structures as they are the major connecting sections linking multiple spatial building units. Because of their typical linear structure, they can easily be represented as a sub-graph within the total building graph. The main advantage of a separate corridor derivation lies in a more realistic navigation support as people do not walk through walls, nor do they always travel first to the geometric center of a room (Meijers et al., 2005). Sato et al. (2009) introduce an indoor equivalent to outdoor networks with door openings projected on the corridor line by creating additional nodes. Lee (2004) derived a Geometric Network Model (GNM) from his CDM by applying mathematical skeletonization algorithms. Becker et al. (2009a) refine Lee's approach by suggesting a comprehensive multilayered space structure where each layer represents different contexts. Each layer is modeled by four distinct space representations: primal versus dual structures and Euclidean versus topologic representation. This is done to support the various requirements set within navigational applications. This idea is also used in IndoorGML, a recently accepted OGC standard for the exchange and representation of indoor spatial information (OGC, 2014).

Even though modeling corridors as separate linear structures allows for more accurate path calculations, it also leads to additional problems. First, the structural division of a building in corridors and non-corridors has so far always been reasonably ill-founded as it is still unclear what exactly defines a corridor. At this point, corridors are mostly manually chosen. Second, the transformation of space into a network structure has to be automatic and mathematically sound, i.e. the transformation should always result in the same topological graph structure independent of the input data. Meijers et al. (2005) recognized three methods for mapping building corridors into sub-graphs being SMAT (Straight Medial Axis Transformation), adjusting line and convex hull transformation. Although suitable, these methods are quite complex, corridor sub-graphs are still mostly drawn manually from the input data, limiting commercial and ubiquitous development. Third, the usually examined building structures for indoor navigation applications are quite structured office environments, with offices typically clustered around a main elongated corridor. However, indoor navigation applications are likely most useful for complex 3D building structures with irregular shapes and large rooms with multiple functionalities. The proposed corridor delineations are deemed impractical in those environments.

(ii) Cell decomposition

The cell decomposition approach decomposes a spatial building unit into multiple adjacent cells, each represented by a node. This method is especially relevant for modeling large irregular rooms as they can be subdivided into more realistic cells, incorporating internal obstacles and subdivisions (Lorenz et al., 2006; Sato et al., 2009). Lorenz et al. (2006) propose cell decomposition for reasons of room size, concavity or varying functionality within a large open space (e.g. an airport lounge often consists of check-in, restaurants, passport and security control areas), while Becker et al. (2009b) add specific considerations given by the navigation application (e.g. mode of locomotion, evacuation versus navigation functionality). Independent of the reasons for decomposition, cells always represent the smallest independent structural unit of an overall structure (Nagel et al., 2010). A cell decomposed representation is tied to the original topological connectivity graph by Egenhofer relations 'contain' and 'equal' (Becker et al., 2009b). Although this concept is very useful for modeling various navigation contexts and spatial structures, the main problem remains the automatic transformation between input data and cells.

At the finest level of granularity, cells can form a raster structure with a certain resolution covering every building unit (Lyardet et al., 2006; Li et al., 2010; Lin et al., 2013). This coincides with the idea of keeping modeling of indoor space as continuous as possible, in line with the less regulated space experience of pedestrian users. From these grids, a graph can be deduced to provide in algorithmic navigation support. The nodes of the graph are formed by the center of the cells (and not the rooms or vista spaces). The use of raster structures leads to less problems with automatic transformation between floors and cells. However, the granularity and extent of the grid, and thus the graph itself, depends on the requirements of the chosen indoor analyses and is still under scrutiny (Li et al., 2010; Lin et al., 2013). For example, in navigation applications the grid size is recommended to be more or less equal to the average step length of pedestrians, while in robotics research a finer resolution may be required. Additionally, efficiency and precision of algorithms depends on the size of the grid. The more detailed the grid, the more processing power, storage and calculation memory is required for appropriate path planning.

(iii) Visibility partitioning

Visibility partitioning proposes a cell decomposition of indoor environments based on visibility aspects. This idea finds its origin in Space Syntax research, with axial maps as the fewest longest lines of sight (Turner et al., 2001). Partitioning is commonly obtained by creating break lines at the concave corners, as such subdividing indoor space into several convex sub-units (Stoffel et al., 2007; Yuan & Schneider, 2010; Liu & Zlatanova, 2012). The main advantage of this method lies in the provision of graph edges that are closer connected to the actual walking pattern, making it better suited for indoor navigation support compared to the coarser connectivity graphs (Stoffel et al., 2007; Hagedorn et al., 2009; Yuan & Schneider, 2010). Additionally, it allows for the calculation of more accurate paths (Liu & Zlatanova, 2012) and it is easier to link to route instructions (Stoffel et al., 2007). However, this link with route descriptions has not yet been widely implemented, neither has the partitioning itself which is now mostly executed for each individual application.

Indoor- Outdoor pedestrian network approaches

Networks proposed for pedestrian navigation in combined indoor-outdoor environments all combine an outdoor network with a certain indoor network approach (Kwan & Lee, 2005; Arikawa et al., 2007; Elias, 2007; Lee, 2007; Jacob et al., 2009; Thill et al., 2011). As indoor space representation, the majority of authors employ a topological connectivity network transformed into a GNM (Kwan & Lee, 2005; Elias, 2007; Lee, 2007; Thill et al., 2011). In this, corridors are modeled by linear sub-graphs using SMAT transformation (Kwan & Lee, 2005; Lee, 2007; Thill et al., 2011) or Delauney triangulation (Elias, 2007). Some authors do not provide exact details on the indoor section of their pedestrian network (e.g. Arikawa et al., 2007; Jacob et al., 2009). The outdoor network is either modeled by the street network (Kwan & Lee, 2005; Elias, 2007) or by a more elaborate multimodal transportation system consisting of street networks, bus routes, walkways and bicycle paths (Arikawa et al., 2007; Lee, 2007; Jacob et al., 2009; Thill et al., 2011). The link between indoor and outdoor network space is established at building entrances and access points by modeling the direct connectivity relationship between them.

2.4.1.2 Hierarchical graphs

A hierarchization of space can be useful in combined IO navigational applications, as it allows for separate and independent searching and altering of the graph while also speeding up the calculation process by omitting certain parts of the graph (Richter et al., 2011). However, outdoor and indoor spaces deal with a different hierarchization principle: outdoors, the existing functional hierarchy of street classes and speed limits is used (Car & Frank, 1994), while indoor hierarchical graphs capture the functional subdivision within buildings (Stoffel et al., 2007; 2008) and this to support common indoor wayfinding strategies (e.g. Hölscher et al., 2009). Richter et al. (2011) extend this idea by suggesting multiple independent hierarchies based on structural, functional and organizational rules. However, there is not yet a clear understanding and foundation for the division criterion of indoor hierarchies, let alone connecting indoor and outdoor rules into a unified hierarchical graph.

A different, more cognitive type of hierarchization can be found in Walton and Worboys (2012) who propose a bigraph as abstraction for navigation in combined indoor-outdoor environments. Their model consists of a pair of constituent independent graphs sharing a common set of nodes (representing open areas) and can independently represent agents, objects, and places. The representation of place has two levels: (i) a place graph representing locality and containment relationships in a hierarchical tree and (ii) a link graph representing connectivity. Even though bigraphs model certain topologic relationships, which can aid the monitoring of agent actions and interactions with space, no geometric notions are included, making algorithmic path planning impossible without altering the original model.

2.4.1.3 Polygonal approaches

Polygonal approaches specifically avoid network structures in order to demarcate the larger degrees of freedom of pedestrians (Gaisbauer & Frank, 2008; Zheng et al., 2009). They also inherently connect indoor with outdoor by using the same data concept across spaces (Slingsby & Raper, 2008; Boghdahn & Coors, 2009; Schaap et al., 2010).

Most commonly, walkable areas are modeled by 2D polygons with clear boundaries, possibly with additional polygon classifications depending on individual restrictions and characteristics (Boghdahn & Coors, 2009; Zheng et al., 2009). The exact classification principle remains at this point subjective to personal choice and interpretation, making a more theoretically-founded reasoning required in order to expand the polygonal approach's usability and automatic creation. A more advanced polygonal model is the 2.5D geometric-semantic model of 3D space by Slingsby and Raper (2008). Their geometrical model consists of a 2.5D constraint-based surface model, in which space volumes are implicitly represented by their lower ground surfaces with embedding of both height and surface morphology constraints. The semantic model defines several feature types relevant for pedestrian navigation, as such attaching a published meaning to the polygons (e.g. spaces, barriers, portals and teleports). This combination of semantics and geometry constraints allows for a more detailed representation of pedestrian space. However, path planning is still hampered as algorithms rely on network descriptions.

That is the reason why polygonal models are often combined with a network. For example, Schaap et al. (2010) utilize Slingsby and Raper's concept (2008) for their pedestrian polygon model, combining both topology and hierarchy information. A network (also modeled by 2D polygons) is transposed on top of this model by defining 'LinkSurface' objects which prescribe how pedestrians can enter or exit single spaces, in which direction, and when. Similarly, Gaisbauer and Frank (2008) developed an outdoor pedestrian wayfinding model, consisting of decision scenes and portals overlaid by a skeleton graph for navigation. The definition of decision scenes (i.e. local vista space around decision points) and portals is tightly linked to the rules of image schemata. The use of decision scenes is also in line with the idea of Lynch (1960, p.72): 'although conceptualized as nodes in a network, decision points may represent a large spatial area that is internally structured'. An aggregation of vista space around the decision point is therefore an oversimplification of the environment, and does not represent the many choices and shortcuts that are available to pedestrians, hence the addition of a network. The main advantage is that decision points are no longer vital for navigation unless they are the start or the destination, thus becoming closer connected to the actual walking pattern of pedestrians. The main difficulties with this approach are a lack of a clear definition of decision scenes and their automation processes. Also, decision scenes alone might not be sufficient for partitioning the pedestrian's domain around decision points as sometimes pedestrians follow route segments without any decision points along their path.

2.4.1.4 3D building models (BIM/CityGML)

3D building models consist of a typical subdivision of geometry, topology and semantics, which are identified as three essential pillars of information for indoor navigation applications (Isikdag et al., 2013). Most commonly used are CityGML and BIM models, since they both contain highly detailed and semantic information on the built environment and are widely available (Isikdag et al., 2013). Many comparisons between the various building models have already been executed to evaluate their usefulness in certain applications (Isikdag & Zlatanova, 2009; Gröger & Plümer, 2012; Brown et al., 2013; Isikdag et al., 2013).

Gröger and Plümer (2012) discuss the capabilities of CityGML as city model integrating various features relevant for navigation, both of outdoor space as well as indoor environments. Semantically, several thematic modules are defined with the Building Module as most interesting in this context. Geometrically, features are modeled by the ISO GML3.1.1 standard, employing a Boundary Representation model (i.e. representing 3D objects by the description of their boundary surfaces). For topological support, a backdoor-topology is used, based on XLinks (i.e. surfaces can be shared when linked to the same boundary surface). However, for navigation applications, a graph structure will still have to be derived from the city model (Gröger & Plümer, 2012), for example by using the approach of Becker et al. (2009a). Alternatively, Hagedorn et al. (2009) present a 4 Level-of-Detail (LoD) model of indoor space that can be built upon the CityGML building module to support navigation within buildings. The various LoD's differ in thematic, geometric, topological, and visual complexity. For example, on a technical level, data size and rendering complexity varies, while on a cognitive level, they each provide different degrees of spatial awareness and navigation support. As a result, route graph and routing possibilities differ over the different LoD's, which complicates the design of a clear mathematically-sound network representation. It is also not clear how the separate edges and nodes are created within the routing module.

BIM models can also be used in geospatial applications as they provide coherent 3D indoor models (Isikdag & Zlatanova, 2009; Isikdag et al., 2013).

However, there is not a seamless information integration due to geometric and semantic differences that exist between BIM and GI models. In addition, BIMs will always contain more geometric and semantic information than what is necessary for certain geospatial applications (Lin et al., 2013). As such, Isikdag et al. (2013) present a simplified BIM model for indoor environments where all unnecessary elements are simplified or removed. Because of this, explicit connectivity and containment relationships can be deduced more easily for querying and the generation of navigational network models.

2.4.2 Input data and delineation of space concept

Data is a key element in the provision of combined indoor-outdoor pedestrian navigation systems. Several criteria in the selection and modification process of data are important in the creation of appropriate space models: (i) output requirements, (ii) data source availability and affordability, (iii) time availability, and (iv) scale of environment (based on Karimi & Kasemsuppakorn, 2012). These will be reviewed against the selection of input data and how they are manipulated into a chosen space model.

2.4.2.1 Input data source

Many authors do not comment on the exact input data source for their models (e.g. Boghdahn & Coors, 2009; Richter et al., 2011). This is not surprising given that there is not yet any specific standard model for combined IO pedestrian navigation (Section 2.4.1), complicating the provision of an all-encompassing method for data acquisition. Also, depending on the required output, different data sources can be more or less suited than others. Many developed models are also fixed to a certain specific data input (e.g. Meijers et al., 2005). That is why Becker et al. (2009a) deliberately developed their space concept in a way that any model accurately representing topographic space can be used as input data source. However, a more detailed examination of the required data for the support of pedestrian navigation applications and their incorporation into a certain space model is urgently needed (Gaisbauer & Frank, 2008). The following data sources are commonly mentioned.

Raw data acquisition

Data for navigation purposes can be gathered starting from raw measurements and 3D reconstructions using multiple data sources. An increasing amount of buildings is already documented both indoor and outdoor, but the derivation of actionable models still requires mostly manual labor and is very time consuming (Isikdag & Zlatanova, 2009). Also, the main purpose of such acquisition methods is mostly acquiring the geometrical properties of building elements without much semantic information. This does not fit the requirements for path planning. Another approach to raw data collection is collaborative mapping, which involves aggregating user-generated content, such as GPS traces (Karimi & Kasemsuppakorn, 2012). However, using GPS traces of walked pedestrian paths can pose significant challenges because accuracy is more susceptible to multipath problems and signal blockage. Also, GPS traces are limited to outdoor spaces, hampering the data acquisition indoors.

Existing 2D information

The collection of outdoor data mostly consists of using the widespread 2D road network datasets (Karimi & Kasemsuppakorn, 2012). Manual digitization by converting raster images into vector data can also yield good information on the outdoor pedestrian network; although this approach is generally only suited for field studies in small areas (Jacob et al., 2009).

Indoor data input sources commonly rely on vectorized 2D floor plans, for example by scanning paper maps (Lee, 2007; Gaisbauer & Frank, 2008; Stoffel et al., 2007; Stoffel et al., 2008; Li et al., 2010; Yuan & Schneider, 2010). Even though this produces fragmented and static information in two dimensions, it is an easily accessible and cheap data source. The indoor data will often have to be accessorized by other data sources to provide in accurate geometric and semantic information of the environment allowing further spatial analysis. Sometimes, additional manual labor is required to classify the input depending on the application (e.g. division of polygons into multiple classes) (Karimi & Kasemsuppakorn, 2012). 2D (and 3D) CAD drawings (Isikdag & Zlatanova, 2009) constitute a more detailed and semantically-rich data source. However, CAD systems are developed to model future objects at a maximum level of detail in terms of geometry and attributes, while GIS are developed to model, represent and analyze objects that already exist and this on varying levels of detail. Many problems also arise with data migration from CAD to GIS, often caused by attribution rules and a lack of topology in CAD files, coordinate system differences, various layer definitions and incomplete geometries (Isikdag & Zlatanova, 2009). Although acquiring semantics and geometry in the right format might be challenging, at least there is a basic level of semantics already available within CAD files compared to many other data sources.

Many authors use an integrated approach to align several existing 2D data sources. For example, Elias (2007) integrates road network, cadastral information and indoor floor plans to obtain an integrated indoor-outdoor network. Both Arikawa et al. (2007) and Thill et al., 2011 add information on the public transportation network to the road network. Schaap et al. (2010) create their 3D spatial data set from aerial photos and existing maps.

Existing 3D models

Isikdag et al. (2013) explicitly aim at using 3D models instead of 2D geometries as input for navigation support. Digital 3D building models such as BIM or CityGML can be extremely useful data sources as they are object-oriented, semantically-rich and up-to date models allowing queries of several building parts (Isikdag & Zlatanova, 2009). However, for use in geospatial analysis, these models have to be simplified both geometrically and semantically (Section 2.4.1.4). Also, more efficient ways of capturing and collecting spatial 3D information are required to support pedestrian routing in public transportation environments and this on a (inter)national scale (Schaap et al., 2010).

2.4.2.2 Delineation of space concept

From the chosen data input source, a certain spatial model has to be generated in order to develop the needed support for pedestrian navigation applications. Automation is important to get a universal and mathematically sound relationship between the actual environment and its space concept, facilitating a repeatable derivation (Becker et al., 2009a). However, this process can get very complicated (e.g. Lyardet et al., 2006) and often authors do not mention how this transformation is executed (e.g. Arikawa et al., 2007; Brown et al., 2013).

With regard to outdoor pedestrian path creation, Karimi and Kasemsuppakorn (2012) compared three approaches: network buffering, collaborative mapping and image processing. They discovered that the network buffering approach is the simplest and fastest method to generate outdoor pedestrian paths as it relies directly on widely available road datasets. However, all three methods have significant drawbacks, ranging from geometric and topologic inaccuracy to incomplete and highly intensive data creation. With regard to indoor network creation, manual drawing of the graph was often the only solution (Becker et al., 2009a; Lorenz et al., 2006). Recent efforts have shown possibilities of automatically deriving nodes and edges (Stoffel et al., 2008) with a more refined approach using the inherent semantics and functionalities of the input data (Meijers et al., 2005; Lee, 2007; Stoffel et al., 2007; Richter et al., 2011). Further cell decomposition (i.e. further than room transformation into nodes) has so far never been proposed automatically as it remains subject to the definition of the cells in relation to the environment. For corridor derivation, various suitable methods have been recognized (e.g. Meijers et al., 2005) but are still computationally intensive and not widely applied. Visibility modeling and derivation of axial graphs were also problematic but the method of Jiang and Liu (2010) to automatically generate axial lines in outdoor environments could be promising to apply to indoor environments. In general, derivation of network graphs in indoor environments is tightly linked to the theoretical foundation of such network structures (Becker et al., 2009b).

In the context of integrated indoor-outdoor navigation, additional problems surface, especially with the integration of multiple data sources (Elias, 2007; Jacob et al., 2009; Thill et al., 2011). First, integrating the various data sources often results in much manual work when creating a unified indoor-outdoor database. Agreements on collection, exchange and maintenance of these spatial data between all involved parties are required (Schaap et al., 2010). Second, the selection of relevant objects for the application at hand is often problematic. Sometimes too many objects are present in a single data source, requiring specific extraction rules. Sometimes the opposite exists, with not enough information on certain features (e.g. access locations to buildings are not given, street network is incomplete for all pedestrian accessible areas), requiring an integration with other sources. Third, different data sources often have varying geometric, topologic and semantic support. Extracting and combining geometries to a singular representation induces mistakes and complications (e.g. Thill et al., 2011). Conflation techniques can help integrate multiple representations of the same object (Elias, 2007), while also allowing a qualitative comparison of the data sources in terms of correctness and completeness.

2.4.3 Algorithmic support

Although it is of prime interest for guiding users, so far there is only very limited research available on developing algorithms and reasoning methods specific to combined indoor-outdoor environments. The available algorithmic support for navigation is at this point mostly restricted to shortest (Meijers et al., 2005; Elias, 2007; Jacob et al., 2009; Lin et al., 2013) or fastest path (Kwan & Lee, 2005; Arikawa et al., 2007; Lee, 2007; Thill et al., 2011) algorithms, as it is thought that once you have a network graph of the environment, there is no problem in applying the available algorithms (Lorenz et al., 2006; Becker et al., 2009a).

Defining an optimal pedestrian route is not a simple task as many differences in route choice behavior exist, varying with environmental characteristics and individual preferences (Millonig & Schechtner, 2007). As such, the proposal of the shortest route is often insufficient; most often required when the person is in a hurry. Other routes should be provided, such as safest, simplest, or most beautiful routes. Hagedorn et al. (2009) agree that by adding semantics and context to the objects, certain algorithmic searches can be improved. The importance of contextual information added to the network currently makes up most of the differences between the algorithms. For example, Arikawa et al. (2007) calculate for each request four possible 'best' routes according to shortest distance, fastest time, weather and traffic information. Lee (2007) calculates a fastest evacuation route based on traffic flow impedances. Kwan and Lee (2005) proposed a 'modified' Dijkstra (1959) algorithm adding three uncertainties that emergency responders often have to deal with (i.e. road network, entry point and route uncertainty). These can cause an extra delay on the fastest path and might require the search for a different optimal path. Many authors also adapt their model of space to visibility based networks in order to calculate more accurately the walked paths (Lyardet et al., 2006; Stoffel et al., 2007; Stoffel et al., 2008; Yuan & Schneider, 2010). Because all path calculations are made on a network graph, a connection with outdoor space is easily supported as well (Elias, 2007; Jacob et al., 2009).

2.4.4 Context support

Afyouni et al. (2012, p.85) define context as 'any information that is gathered and can be used to enrich the knowledge about the user's state, his or her physical surroundings and capabilities of the mobile device'. As such, two main concepts for context exist: (i) context of use and (ii) context of execution. The latter refers to the information system, its components and performance ability and is less relevant to this paper. Context of use refers to both the user and its personal profile as well as to the broader environmental context of navigable space influencing this user. Context-aware systems have become more and more prevalent as most previous developments in Location-Based Services merely provided a location as result of queries (Mokbel & Levandoski, 2009). Context-aware systems seek the integration of sensed and derived data in order to situate user activities and provide a more meaningful interaction with information systems (Lyardet et al., 2006). A more user- and environment-oriented interaction can indeed result in a more optimal provision of navigational routes, adapted to a specific person in a specific place at a specific time (Nagel et al., 2010).

In Section 2.4.3, it was already demonstrated that an important way to add context is through the chosen impedances in the algorithms, eventually providing more 'optimal' routes for a specific user (Millonig & Schechtner, 2007). Apart from the typical time and distance related costs, most authors add more detail by giving information on environmental context, a user profile or combinations of both. We do not have the aim of providing an exact overview of all possible parameters influencing pedestrian navigation, but merely give some examples of the most referenced types of context information within each category.

Environmental parameters refer to all object definitions and characteristics of internal and external building structures. They can be both static (e.g. room use, obstacle location, traffic capacity) as well as dynamically changing over time (e.g. speed, access restrictions, and locked doors). Kwan and Lee (2005), Lorenz et al. (2005), and Elias (2007) all rely solely on environmental context information in their models. Both Brown et al. (2013) and Isikdag et al. (2013) defined several conceptual requirements for topographic space information to facilitate 3D indoor navigation, all related to building objects, their properties and relationships. Algorithms can also be built around the characterization of certain polygons allowing different path costs depending on those classifications (Meijers et al., 2005; Boghdahn & Coors, 2009; Zheng et al., 2009). 3D models are possibly the best examples of existing models that inherently contain a lot of environmental context, in this case limited to semantic descriptions of the features. Problems exist with CityGML's LoD definitions: with increasing LoD, the semantic richness increases but also their geometric complexity (Gröger & Plümer, 2012). This could be solved by providing separate geometrical and semantic LoDs, enabling a more flexible model.

Second, different users can have different views on the same environment, with each also having different functional and organization roles that link to the specific objects in space (Richter et al., 2011). For example, a person with certain access restrictions and disabilities cannot enter a highly protected and disconnected area. These preferences are also time- and situation-dependent as physical efforts, luggage, safety, and timing of those restrictions can change dynamically. As such, conceptualization of and communication about a space largely depends on how the space is used and experienced (Stoffel et al., 2008). To model this variation, several ontologies can be developed as formal specifications of the conceptualizations of specific user groups (Richter et al., 2011).

Many authors suggest the combination of both environmental and user characteristics in their model (Lee, 2007; Slingsby & Raper, 2008; Thill et al., 2011; Walton & Worboys, 2012; Lin et al., 2013) and even leave choice in the selection of calculated routes based on pedestrian preference and context (Arikawa et al., 2007; Schaap et al., 2010). Apart from changing impedances to the graph edges themselves, Becker et al. (2009a, b) model different contexts through multiple layer construction. Context represented in those layers can be used as selection criterion as the layers are interconnected through inter-space connections.

The main challenge with adding context is the need for navigable databases that contain the required types of objects, their characteristics and relationships (May et al., 2003). The large variety in possible context-defining parameters also makes it hard to understand the exact importance of each individual parameter. Studies like those by May et al. (2003) and Millonig and Schechtner (2007) try to shed light on these pedestrian context requirements for successful navigation, in this case through a complex town-center environment. They discovered that several types of information were used by their participants, with landmarks by far being frequented the most. Additional research on pedestrians' needs for personalized navigation information is, however, highly necessary, especially in combined indoor-outdoor environments.

Due to this large diversity in contextual information, data collection, processing and storage are challenged. That is one reason that Jacob et al. (2009) only take those factors into account relevant for their campus guidance system (e.g. POI, landmarks, street names, house numbers). Also, in CityGML, semantic characterization of objects usable in pedestrian navigation is only supported in LoD4, which puts a high demand on the data acquisition and availability when modeling combined indoor-outdoor environments. Furthermore, the required context information can differ dramatically per application field (e.g. evacuation support versus a general navigation query). For example, Li et al. (2010), Richter et al. (2011) and Yang and Worboys (2011b) define impedance values depending on the nature of the phenomenon to be represented.

2.5 Discussion

This paper presented an overview of the state-of-the-art in combined indoor-outdoor pedestrian navigation research based on 36 scientific studies. Two aspects stand out in this review: first, a large variety of models, data and context parameters make up the theoretical approaches for combined indoor-outdoor pedestrian navigation, but there is not yet an agreement on an integrated concept for navigation support in indoor-outdoor environments. Second, discussing indoor spaces also means dealing explicitly with the third dimension. However, there is not currently agreement on whether this third dimension is a strict requirement for integrated pedestrian navigation applications. Both issues are discussed in this final section as we also propose a research agenda.

2.5.1 Does an integrated IO navigation model already exist?

Although providing integrated pedestrian navigation systems may sound nice in theory, our review demonstrated that indoor and outdoor research on navigation is currently still in its early days with highly different models deduced from separately acquired data, and a huge variety in context and use of space. One could question whether it is even feasible to have a single formal concept of combined indoor-outdoor structure, or if we should even strive to develop one.

With respect to the models of space, in general a choice is made between two options; namely, network and polygonal approaches. This choice touches upon the dissonance between car and pedestrian navigation (Section 2.2.2): due to pedestrian's larger degrees of freedom, they do not necessarily follow networks, but navigation applications seem to require networks to support their guidance algorithms. Networks offer the advantage of easily being extendable to indoor environments. However, in order to deal with the inherent differences between both space concepts, indoor and outdoor networks are usually individually developed and afterwards combined. The accuracy of connection between indoor and outdoor networks is thus defined by the quality of merging at connecting points. This requires a common descriptor for labeling the connections, a similar geometrical structure and a satisfying positioning accuracy. If not all connections are recognized or available, an incomplete network graph will be developed leading to sub-optimal pedestrian navigation. On the other hand, polygonal models of space have the advantage of incorporating pedestrians' flexibility in wayfinding. This improves the integration between indoor and outdoor spaces as it forms a unified space concept. However, for the actual navigational support, polygonal approaches are still enhanced by network approaches, mostly based on visibility aspects. In addition, polygons lack the semantic richness, available in networks by the attachment of a variety of attributes. Also, polygonal IO navigation approaches are currently restricted to single level buildings. An extension of walking areas to 3D indoor space will have to be considered (Slingsby & Raper, 2008; Zheng et al., 2009).

Similarly to the variation in models, a separation in available data sources can be observed between indoor and outdoor. Indoor spaces are mostly modeled by 2D floor plans, while outdoor sources range from road network data over cadastral datasets to imagery datasets. This is again linked to the specific differences when dealing with different types of environments (indoor versus outdoor) and different modes of locomotion (car versus pedestrian). Differences in data acquisition techniques, positioning methodologies, scale and granularity, and general data availability (e.g. road network datasets are commonly available worldwide, while indoor structures are only recently being opened up for commercial use) all enhance the existing separate developments in indoor and outdoor navigation applications.

Some sources do consist of an inherent combination of indoor and outdoor space, but they are not always suitable for navigation application. For example, CAD files can cover both indoor and outdoor space but are not built for geospatial analysis. CityGML recently added a LoD0 representation of the outdoor built environment with the sole purpose of supporting 2D-3D indoor-outdoor integration (Gröger & Plümer, 2012). However, when facilitating integrated IO pedestrian navigation, the data is required to be modeled in LoD4, as such putting a high demand on the outdoor modeling of space (not necessarily required and available for outdoor pedestrian modeling). Using semantically rich 3D building models has the advantage of a uniformly described geometric, topologic and semantic structure, often not available in common 2D data sources where different regulations, legal aspects and freedom of the data collector highly influence the exact information stored. On the other hand, 3D building models are often too complex with not necessarily the correct spatial relationships stored, as such requiring additional transformation and information deduction processes.

Since no single data source perfectly covers the requirements for indoor-outdoor navigation applications, integration of multiple data sources will always be necessary. This includes developing improved automation processes for deducing the required model of space and dealing with the inherent quality, accuracy and coverage differences between the data sources themselves (Elias, 2007). In this context, several questions still need to be solved: Which quality of data is required as input for IO navigation? How should the data be structured? Is first a common concept of space required in order to develop improved automation processes? Is a generic framework required that can respond to several sorts of data input, as proposed by Becker et al. (2009a, b), which is user friendly and translatable to commercial navigation systems? Additionally, data availability, updates, data processing methodologies and real-time interactivity aggravate the situation around required data input even more.

It is clear that at this stage we cannot talk of an integrated IO concept supporting seamless pedestrian navigation. Outdoor pedestrian path delineation requires developments of improved methods to define, deduce and integrate the selected features relevant for navigation. On an indoor level, a more enhanced theoretical foundation is required. At this point, IndoorGML as newly approved OGC standard is the most-developed indoor concept (OGC, 2014). Its framework for representing indoor spatial information is kept quite general, with the definition of topological and cellular space structures supporting various contexts related to navigation applications. Even here, many challenges exist. For example, IndoorGML specifically transforms environments into networks, even though polygons contain this aspect of pedestrians' freedom. A larger flexibility in the creation of such networks, founded in actual wayfinding behavior, can support a more realistic guidance. Also, it is still not decided how a division into subspaces of non-corridor open-type areas can be executed, similar to the sub-graph derivation of corridors. Finally, the multi-layered space structure as core of the standard, allows for the support of different context presentations and their interrelationships. However, it requires explicit linking with other data sources containing semantics, geometrical objects and visualization for a full navigation support. At this point, it is not made very clear how this interaction between the IndoorGML framework and other 3D standards will be effectuated. Although IndoorGML specifically focuses on indoor networks, it also provides a connection with outdoor networks by introducing an 'Anchor Node'. This connection is a key aspect for pedestrian navigation applications, and further research is required on the implications and connectivity problems related to those connection points. An important issue here is the difference in coordinate systems between the outdoor network (global reference system) and the indoor local coordinate system. The 'Anchor Node' provides the possibility for coordinate transformation but there are still issues with the accuracy of the indoor location and the importance of indoor coordinates for routing (e.g. users indoor rely mostly on semantic data).

2.5.2 Treatment of third dimension

Previously it was discussed that very few 3D data sources are nowadays employed in combined IO navigation research because outdoor pedestrian space is mostly modeled two-dimensionally. 3D data sources are currently also largely restricted to indoor navigation research. This is not surprising given the extended experience of developing 3D models for architectural purposes (Lee & Zlatanova, 2008). These developments range from purely geometric models such as IFC, CSG, voxels and TENs, partly standardized in both OGC and ISO standards, to a series of topological models, mostly as variations on the Boundary Representations with far more analytical power (Ellul & Haklay, 2006; Lee & Zlatanova, 2008). This dichotomy is in line with current models used in many geospatial applications, where depending on the need for the application, a more analytical model versus a more visual and reality-based representation of space is chosen (Breunig et al., 2011). Integration of BIM and CAD models with common GIS models demonstrates the possibility of designing one general model of the urban environment (Döllner & Hagedorn, 2008). However, this evolution is still restricted to indoor environments and specific application fields.

The main question is whether three-dimensional support is a strong requirement for pedestrian indoor-outdoor navigation applications at all. From the data and space concepts alone, it seems hard to accomplish given the variety in models, scale level, detail and data availability. Lyardet et al. (2006) also highlight that during route guidance many recalculations are required. This process would become very time- and processing power-consuming if the calculation and visualization were based on a three-dimensional model. Apart from time cost, not every user-environment supports 3D models, although this might improve in the future with higher performance computing technology. Most existing systems are based on 2D environments. A common thought is that the third dimension only seems required when moving between floors or underground sections, which can possibly be modeled by using separate maps for each floor level. For normal pedestrian navigation, this might be the case, but more advanced applications like facility management rely on knowledge of the third dimension. Additionally, it is often not clear what defines a floor level. Often, it is assumed that a complex building can perfectly be subdivided into multiple floors (Hagedorn et al., 2009). This is obviously not always the case, and already problems arise with buildings that have intermediate floor levels. This becomes even more critical when navigating across buildings and underground structures on hilly terrain. The distinction and separation into multiple floor levels as alternative for using three-dimensional data is, as such, rather controversial. Also, not using three dimensions in the modeling phase will later impede more advanced 3D analyses of combined indoor-outdoor urban environments.

2.5.3 ADDITIONAL CHALLENGES

Further research on integrating indoor and outdoor environments for pedestrian navigation is required on at least three levels.

First, algorithms are currently in combined indoor-outdoor environments restricted to Dijkstra's (1959) shortest path algorithm or modifications. Developments and research into other algorithms and analytical support has sort of stagnated as most focus is oriented towards space model developments. Extensions towards fastest, least risk paths and other could prove useful. To our knowledge, only in Chapter 5 some issues that might question the 1-on-1 application of outdoor algorithms on an indoor graph have been discussed, this mostly to more cognitive and as such more context-related algorithms. Additionally, these algorithms have to be extensively tested in a complex indoor-outdoor environment, and preferably compared with what pedestrians really require for navigation guidance. Further research is also urgently needed in mapping the relationship between the chosen network model of space and the results of the algorithms.

Second, it was demonstrated that context plays an important role in providing better-suited paths to users. Millonig and Schechtner (2007) investigated pedestrian route qualities in outdoor space, but it is unclear whether the same qualities are applicable to indoor spaces as well. Additionally, examining route characteristics of combined IO environments and their integration into context parameters is even further away. Related to this are similar requirements with respect to routing instructions. Outdoor instructions are commonly based on distances, directions and street names. However, these might not be optimal for pedestrian guidance as pedestrians deal with higher degrees of freedom and a different perception of space (Boghdahn & Coors, 2009). Future empirical research will have to unfold the complex interaction between cognitive wayfinding perception and navigation guidance aids.

Third, navigation applications are one example of combined indoor-outdoor analyses that are in need of improvement. Extensions to other applications in combined IO space are the next step in research. Both Giudice et al. (2010) and Worboys (2011) sum up several application fields that can be applied to both indoor and outdoor space situations (and should be supported by them) and possibly in a combined IO space model. What are the functionalities and the requirements that these applications hold with respect to data, structuring, methodologies, technological advancements? What are the additional challenges of integrating indoor and outdoor spaces? At this point, we find ourselves at the beginning of a new and challenging area within geospatial research where the boundaries of space slowly have started fading away.

2.6 Conclusion

Our literature review has demonstrated that integrated indoor-outdoor research in navigational applications is still mostly located at the frontiers of knowledge. The wide variety in possible models of space, together with difficulties of dealing with both indoor and outdoor environments, and with taking into account pedestrian's freer use of space, currently complicate the proposition of a unified IO space concept for navigation. Combine this with a present lack of standardized and centralized data sources for outdoor and indoor environments, and it illustrates that a consistent development of context-aware navigation systems in integrated indoor-outdoor environments is highly challenging. However, there are some interesting developments and many future possibilities in progress, from context definitions and algorithmic extensions to more data availability and an increasing awareness of pedestrians' perception during wayfinding. This will all lead to bringing outdoor and indoor spaces closer together in the realm of combined geospatial analysis.

2.7 Appendix

The table below presents the selection of articles reviewed in this chapter.

Table 2-2 Overview of the studies on combined indoor-outdoor pedestrian navigation

Author(s); Year	Study design Scale	Space concept (SC) Input (IN) Algorithmic Support (AS) Context support (CS)	Key findings
Arikawa et al., 2007	Total navigation support Indoor/Outdoor	SC: Network IN: Road network, timetable data AS: 4 possible routes based on user's preferences and context CS: Time, walking distance, travel cost	- Practical mobile phone-based navigation service (routing, visualization, localization) incorporating various modes of transportation - Extensions into more context-aware location-based services possible
Becker et al., 2009a	Model Indoor	SC: Multilayered Space Model (MLSM) IN: Any model of indoor built environment AS: Any routing support on topological dual graph CS: Attributes modeled through multiple layer construction	- Conceptual model-independent framework for indoor navigation (MLSM) - Integration of different space models into a multilayer representation, linked by an n-partite graph - Each space concept separated into primal versus dual space, and geometrical versus topological space
Becker et al., 2009b	Model Indoor	SC: N-partite graph (state-transition diagram + connectivity) AS: State-transition diagram CS: Multiple layers: selection ~logical, thematic localization considerations	- New modelling framework for indoor navigation which considers the aspects of route planning for different modes of navigation and various localization techniques. Based on MLSM - Illustration of how layers can be combined according to concrete navigation contexts to build an n-partite graph
Boghdahn & Coors, 2009	Model Indoor/Outdoor	SC: Polygonal zones AS: Shortest path (point robot collision free or channel finding algorithms) CS: Walkable, semi-walkable, non-walkable	- Pedestrian models using line graphs are too restricted - New concept for the subdivision of urban space into zones
Brown et al., 2013	Model & Requirements Indoor	SC: Conceptual model (semantics, topography, constraints) to be implemented in CityGML ADE AS: Routing algorithms on CityGML ADE CS: Hard constraints (~geometry)	- Synopsis on use cases and requirements for topographic space representation in indoor navigation applications - Evaluation of existing 3D models against those requirements - Proposal of new semantic and constraint model of topographic space in CityGML
Elias, 2007	Data acquisition & Model Indoor/Outdoor	SC: Network IN: Integration and transformation of several data sources in connected linear graph AS: Shortest path on network CS: Environmental attributes	- New approach to generate a geodatabase adapted to the specific needs of pedestrian navigation applications - Integrating several data sources and developing methods for automatically deriving the required geodata
Gaisbauer & Frank, 2008	Model Outdoor	SC: Network + polygonal zones IN: Binary image of walkable & non-walkable space	- New pedestrian wayfinding model consisting of a graph model (decision points and edges) - Free walkable space is drawn around those decision points to create decision scenes that model the higher degrees of freedom for pedestrians and thus allowing flexible navigation for unfamiliar users (~image schemata)

Author(s); Year	Study design Scale	Space concept (SC) Input (IN) Algorithmic Support (AS) Context support (CS)	Key findings
Giudice et al., 2010	Requirements Indoor/Outdoor	SC: 3 level integration: (1) formal ontological and design models; (2) data model integration; (3) interaction level	- Report on the development of a research agenda for the integration of outdoor and indoor spaces - Discussion of potential application domains and a variety of models of indoor space and unified outdoor-indoor space
Gröger & Plümer, 2012	Model Indoor/Outdoor	SC: CityGML model CS: 5 LoD with different geometrical and thematic objects	- Overview of CityGML as standard for the exchange and representation of 3D city models with its relationship to other 3D standards - Focus of CityGML is on semantic aspects of 3D city models, allowing users to employ virtual 3D city models for advanced analysis and visualization tasks (in contrast with purely geometrical/graphical models)
Hagedorn et al., 2009	Model Indoor	SC: 4 LoD model of Indoor Space with thematic, geometry (GML), routing and appearance module As: Any routing support on network CS: Data complexity, rendering, visualization, required cognitive level of navigation support	- 3D visualizations can provide a better insight into the spatial configuration and the vertical structuring of a building - Classification of indoor objects and structures taking into account geometry, semantics and appearance. - Proposal of a LoD model that supports the generation of effective indoor route visualization (as extension model to CityGML)
Isikdag & Zlatanova, 2009	Data acquisition Indoor	SC: BIM transfer into geospatial environment IN: BIM model	- SWOT analysis of implementing BIM in geospatial environments - Advantage of BIM: representation of building geometry in 3D, rich semantics - Hurdles: differences in geometric representation, use of local coordinate systems and class differences - Implementation of BIM in GI environment not seamless. BIM will always contain more information than that residing in digital city models
Isikdag et al., 2013	Model Indoor	SC: BIM oriented indoor data model (geometry ISO compliant; semantics IFC compliant) IN: BIM (IFC) model AS: Spatial and semantic related queries CS: Attributes deducted from IFC class	- Presents new BIM-oriented modeling methodology dedicated for facilitating indoor navigation by representing non-georeferenced data compliant to ISO 19107 standards - Defines three pillars of information representation for models that support indoor navigation (geometric, topologic, semantic) divided in primal and dual layer
Jacob et al., 2009	Total navigation support Indoor/Outdoor	SC: Network IN: Open Street Map, aerial photography AS: Shortest path CS: Based on necessity of application (POI, street names)	- Development of web-based campus guidance system, focused on pedestrian navigation - Routing support through shortest paths, with visual guidance through geotagged images

Author(s); Year	Study design Scale	Space concept (SC) Input (IN) Algorithmic Support (AS) Context support (CS)	Key findings
Karimi & Kasemsuppakorn, 2012	Data acquisition Outdoor	SC: Network IN: ~data acquisition method (road network, walking traces, orthoimages and LIDAR point clouds)	- Development of three new approaches and algorithms to automatically generate pedestrian networks: network buffering, collaborative mapping, image processing - Evaluation in terms of data sources, data preparation and map generation: all are viable for automatic pedestrian network map generation
Kwan & Lee, 2005	Model Indoor/Outdoor	SC: Network AS: Shortest path on network	- Potential of using 3D GIS for development of intelligent emergency response systems - Implementation of network analysis in indoor and outdoor environments
Lee, 2007	Model & Algorithm Indoor/Outdoor	SC: Network IN: Polygons per floor level AS: Evacuation route algorithm CS: 4 types of nodes (occupant characteristics, occupancy, capacity, damage, flow rate, bottleneck, impedance); 3 types of edges (occupancy, impedance)	- Represent complex internal structure of buildings at a 3D subunit level using a 3D navigable data model to analyze human behavior in emergency situations - Design of a geospatial database to manage several essential factors of emergency response - Decision support system with 3D geocoding method, 3D map matching method, indoor navigation model
Li et al., 2010	Model Indoor	SC: Cellular units +Network IN: 2D floor plans CS: Edge impedances change depending on nature of phenomenon and required spatial analysis	- Represent 2D I-space with a grid graph-based model taking into account structural and spatial properties of an indoor space and on different LoD's - Illustration of model on several types of indoor space analysis - Question of identifying appropriate modeling paradigm (continuous or discrete, graph-based) for the specific application
Lin et al., 2013	Model & Algorithm Indoor	SC: Cell-based grid + network IN: BIM (IFC) model AS: Shortest path (Fast Marching Method) CS: Walkable, non-walkable (~geometry), semantic attributes deducted from IFC class, risk level distribution	- Path planning for 3D indoor spaces with IFC model as input - Review of other path planning research associated with BIM models - Automatic extraction of geometric and semantic information from IFC to build up a map of space and find a collision-free shortest path
Liu & Zlatanova, 2012	Model Indoor	SC: Indoor Navigation Space Model IN: 3D topographic space models AS: 2 level routing: (1) rough ~connectivity; (2) fine ~visibility	- Present indoor data model (Indoor Navigation Space Model) designed to support automatic derivation of the connectivity graph of a building - It provides an extended categorization of indoor spaces based on building semantics
Lorenz et al., 2006	Model & Ontology Indoor	SC: Hybrid hierarchical graph AS: Any type of routing algorithms CS: Directional angles to doors with fuzzy sets and topological information	- Proposal of hybrid spatial model for indoor environments consisting of (1) hierarchically structured graphs, (2) cell partitioning, and (3) nodes and edges - Model can be labelled with both qualitative and quantitative information to facilitate the generation of human-understandable path instructions

Author(s); Year	Study design Scale	Space concept (SC) Input (IN) Algorithmic Support (AS) Context support (CS)	Key findings
Lyardet et al., 2006	Model & Algorithm Indoor	SC: Convex hull (2D) stored in quadtree IN: Manual creation convex hull AS: 4 variants of Dijkstra to measure most time-efficient	- Context aware indoor navigation system based on 3D world model through 2D convex hull and quadtree - Path calculation on simplified graph
May et al., 2003	Requirements Outdoor	CS: Distance, Junction, Road type, Landmarks, Street names	- Requirement study to understand information needs for pedestrians during navigation tasks - Landmarks are predominant cues, while distance and street names far less - Information is used to enable navigation decisions and enhance pedestrian's confidence
Meijers et al., 2005	Model Indoor	SC: Polygon + network IN: B-rep model AS: Shortest path on network CS: Polygon classification (persistence, existence, access-granting, types of passing), Algorithm (distance, time, labor)	- Present semantic model of interior spaces, with the aim of facilitating calculation of evacuation routes - Classification is used to build a graph, with geometry organized in DBMS - Proposition of several methods for deriving a graph from B-Rep
Millonig & Schechtner, 2007	Requirements Indoor/Outdoor	AS: Shortest path insufficient. Algorithms required tailored to pedestrian's needs CS: Topography (distance, acclivity, LoS, protection of external effects), Topological (attractiveness, facilities, safety), Complexity (number and complexity of decision points, landmarks)	- Synopsis on main dimensions of route qualities and their interaction with each other: physical, psychological and mental - Delineation of aspects influencing route choice can help in simulation models, but also in the provision of pedestrian routes adapted to pedestrian's context and preference
Richter et al., 2011	Model Indoor	SC: Hierarchical representation (no network) IN: Scene space definition defines basic building blocks CS: Ontology (user groups and tasks) defines weights in hierarchy	- Present (automatically constructed) hierarchization process that accounts for physical, functional, organizational structures and their hierarchies, relevant for different communication needs - Experiments show that differences in perspective that different user groups have on a space exist
Sato et al., 2009	Model Indoor	SC: Network	- Description of outdoor and indoor 3D routing services - Main objective is to enhance a network topology for current CityGML specification
Schaap et al., 2010	Model Indoor/Outdoor	SC: Scene space 3D model (network and hierarchical topology) IN: Aerial photos, existing 2D vector data AS: Optimal path computation CS: Traveler profile, time	- Novel 3D geo-data model of accessible pedestrian spaces in 3D to support pedestrian routing in multimodal public transport devices - 3D data model that supports finding optimal route taking into account user preferences and constraints - Definition of requirements for 3D scene space model

Author(s); Year	Study design Scale	Space concept (SC) Input (IN) Algorithmic Support (AS) Context support (CS)	Key findings
Slingsby & Raper, 2008	Model Indoor/Outdoor	SC: Polygons of navigable space in 2,5D approach (constraint-based surface model) AS: Pedestrian context specific algorithm (time, access) CS: Pedestrian user definition + Time attached to semantically defined geometric feature objects	- Overview of pedestrian navigation efforts in 3D modeling research - Implementation of prototype model of navigable spaces for IO pedestrians with different contexts
Stoffel et al., 2007	Model Indoor	SC: Hierarchical graph (containment relationship), visibility partitioning IN: Vector dataset per floor level AS: Shortest path on visibility network CS: Hard (boolean) constraints and soft (personal) constraints	- Hierarchical graph derivation for pedestrian navigation using partitioning algorithm based on visibility concept - Integration of aspects in graph modeling, symbolic models and cognitive models to handle different levels of abstractions and provide a basis for generation of route instruction
Stoffel et al., 2008	Model Indoor	SC: Hierarchical graph per floor level IN: Vector dataset per floor level AS: Shortest path on hierarchical network CS: Possible enrichment ~functions subgraph	- Hierarchical graph definition for route guidance in large public buildings, motivated by cognitive and heuristic reasons - Development of algorithm to automatically derive multi-level hierarchy
Thill et al., 2011	Model & Algorithm Indoor/Outdoor	SC: 2,5D object oriented model + Network IN: 2D floor plan, street and bus network data source, ortho-photos AS: Least effort route (minimizing travel time)	- Advocate for 3D network based urban research - Showcase of the feasibility of approach for three specific types of urban analysis (route planning, accessibility and facility location planning)
Walton & Worboys, 2012	Model Indoor/Outdoor	SC: Qualitative indoor biograph model (place graph and link graph) IN: Floor plan AS: Reasoning about space in bigraphical reactive system CS: Environmental features, agent capabilities	- Present indoor bigraph and indoor bigraph typology for the domain of indoor navigation - Flexibility in representing changes in the context and in adding missing context - Bigraphical reactive system is able to show evolution in change, and as such reason about indoor spaces and movement of people
Yang & Worboys, 2011a	Requirements Indoor/Outdoor		- Review of the similarities and differences between O-space and I-space to understand the underlying principles to make navigation seamless between both space concepts
Yang & Worboys, 2011b	Ontology Indoor/Outdoor	CS: Upper ontology as general setting, navigation task ontology related to navigation tasks, application and domain ontology related to space structure	- First steps towards ontological and formal model for navigation in IO space (4 levels of ontology) - work in progress

Author(s); Year	Study design Scale	Space concept (SC) Input (IN) Algorithmic Support (AS) Context support (CS)	Key findings
Yuan & Schneider, 2010	Model Indoor	SC: Network (visibility based) IN: 2D floor plans to cells (~no. of access points) AS: Shortest path on network CS: Accessibility rules in access points of cells	- None of the available indoor navigation models are able to automatically calculate shortest paths according to the geometric structure of indoor space (no geometry - coarse routes, ignoring architectural constraints like doors, provided routes not necessary optimal) - Proposes a model (directed path graph) that supports length-dependent optimal routing based on geometry of indoor structures
Zheng et al., 2009	Ontology Outdoor	SC: Network + polygonal zones AS: Shortest path on 2 space concept levels (network & polygons) CS: Walking area defined by access characteristics, concave-convex shape, number of islands	- Demonstrates how to handle open walking areas in pedestrian navigation applications - Characterization of walking areas into three types

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3

COMBINING INDOOR AND OUTDOOR NAVIGATION: THE CURRENT APPROACH OF ROUTE PLANNERS

Modified from: VANCLOOSTER, A. & DE MAEYER, P. 2012. Combining Indoor and Outdoor Navigation: The Current Approach of Route Planners. In: GARTNER, G. & ORTAG, F. (eds.) Advances in Location-Based Services. Berlin: Springer.

ABSTRACT

This paper studies the use of indoor infrastructures for navigation in several currently available route planners. In the context of an increasing dependence on positioning and navigation tools, a shift has taken place from solely outdoor applications to the indoor environment. Although Location-Based Services and indoor positioning techniques may have gotten increasing attention from research and commercial point of view, ubiquitous indoor navigation systems are not yet available on the market. With people moving seamlessly from indoor to outdoor, systems that integrate navigation in both will be the next challenge in navigational research. This paper contributes to this integration of the notion of indoor and outdoor space by studying its impact on route planners. A review of various case studies in multiple route planners has been carried out which reveal different aspects and requirements for the indoor-outdoor connection in wayfinding. Currently, mostly data constraints prevent the optimal use of all navigation routes. Additional problems are discovered with address matching methodologies influencing the exit choice of buildings, leading in some cases to sub-optimal routing. Recommendations are made for future enhancements based on the product-to-market implications to come to a better integration of indoor with outdoor infrastructures.

3.1 INTRODUCTION

Over the last decade, navigational tools have become more and more prevalent as a resource for reliable route planning and wayfinding. Generally, navigation requires tracking and guidance by a technical localization infrastructure, support of multiple navigation contexts (navigable and non-navigable space description based on user and environmental constraints) and an appropriate (for the application level) and accurate topographic representation of space (Nagel et al., 2010). For outdoor navigational systems, these requirements have been achieved over the years by the development of the Global Positioning System (GPS) for tracking and guidance, a more efficient and abundant data collection using mobile mapping technology and improvements in modeling and data storage (e.g. GDF standard). However, this effort has been solely centered on pure outdoor car navigation systems.

Although pedestrian navigation systems hold similar demands for route planning, their interpretation and specification to the pedestrian context calls for a specific and individual adaptation. This is induced by differences in context, environment, mode of locomotion, scale level and technology (Walton & Worboys, 2009). For example, pedestrians walk more freely in the available space. Modeling this by using the available outdoor transport networks does not completely reflect this freedom (Bogdahn & Coors, 2009). Second, pedestrians have access to both indoor and outdoor environments requiring route guidance in both. This implies availability of both indoor and outdoor data, technological support in indoor environments and a communal space model. Third, the seamless movement from pedestrians from indoor to outdoor has to come to light again in the developed navigational models and route finding applications. Fourth, a more constrained environment makes route guidance more arduous due to a change in scale level and more challenging landmark recognition. Current and future indoor and combined indoor-outdoor navigation systems should be able to implement these specific requirements.

Literature shows that over the last decade various researchers have begun developing systems based on situation awareness and smart environments using Location-Based Services (LBS) (Gartner et al., 2007; Huang et al., 2009). A recent boost in technological advancements for tracking people in indoor environments has led to increasing possibilities for the development of indoor navigational models. However, this research has focused solely on the technological aspects of indoor positioning and navigation (Mautz et al., 2010). From the multiple techniques available for indoor positioning, no standard has emerged yet because none of them fulfill all positioning requirements. Alternatively, several researchers have developed a wide variety of indoor navigational models ranging from abstract space models (Becker et al., 2009) and 3D models (Coors, 2003; Li & He, 2008) to pure network models (Jensen et al., 2009; Karas et al., 2006; Lee, 2001; Lee, 2004) and ontological models (Anagnostopoulos et al., 2005; Lyardet et al., 2008; Meijers et al., 2005). While these models might be useful in specific situations, a general framework for indoor navigation modeling has still to reach full maturity (Nagel et al., 2010). At issue is that all previously mentioned attempts remain solely applicable to indoor situations. In order to fully accommodate navigation, a connection with outdoor applications has to be made.

Most current endeavors to combine indoor with outdoor navigation are focused on tracking techniques; in particular the transition of positioning tools from indoor to outdoor environments. The majority of these efforts originated from robotic research (Pfaff et al., 2008) and navigation of the visually impaired persons (Ran et al., 2004; Scooter & Sumi, 2005). The NAVIO project (Retscher & Thienelt, 2004) is one of the few attempts focused on pedestrian indoor and outdoor navigation. It aims at developing a route modeling ontology, which provides both indoor and outdoor routing instructions by identifying and formally defining the criteria, actions and reference objects used by pedestrians in their reasoning for navigation routes (Tsetsos et al., 2007). However, the project focuses solely on location fusion (i.e. the aggregation of location information from multiple sensing elements) and user interfaces, again making the approach too narrow. In the modeling field, the most notable work is of Slingsby and Raper (2007) who model a part of the built environment with its immediate surroundings. However, their model is quite complex and not suitable for navigational applications. It is also confined to describing small scale areas. The above research overview shows that up until today no fully integrative approach for combined indoor-outdoor navigation has yet been thoroughly developed.

Apart from the theoretical research efforts, some LBS applications have already been developed as practical pedestrian navigation applications. Makkamappa (www.makkamappa.com) is a smartphone-based mapping system which can be used for GPS tracking after uploading maps and making it GPS-linked. PhotoMap (http://ifgi.uni-muenster.de/archives/photomap.html) uses a technique of photographing public maps for pedestrian outdoor navigation. Both applications are focused on outdoor pedestrian routing using continuous GPS tracking. PinWi (Löchtefeld et al., 2010) is a LBS system for pedestrian indoor navigation which uses photos of an indoor You-Are-Here-map as navigation model and dead reckoning for positioning. While this may be a worthwhile approach, it is only locally applicable and not comprehensive enough for being a general indoor routing application. It is also less accurate and disregards problems of availability and indoor-outdoor integration. With above practical implementations having their merit, they still are mainly restricted to the application goal. Before developing more models for combined routing, an evaluation has to be made of the practical implementation issues with the integration of indoor and outdoor routing.

The key purpose of this paper is to evaluate the current use of indoor infrastructures for wayfinding in common route planners. This is done to make an evaluation of the next necessary steps and current problems in indoor and combined indoor-outdoor routing applications. Route planners are one of the first applications to acknowledge the data requirements for indoor and combined indoor-outdoor navigation since they do not require the technological advancements indispensable for full navigation applications. They focus mainly on the data and the presentation of the data in a certain data model used for traditional route calculations. Their implementation of indoor navigation requirements can serve as a base for practically improving current indoor and combined indoor-outdoor routing endeavors and for bringing theory closer to practice.

In this paper, first a review has been carried out of various case studies in multiple route planners, which reveals different aspects and requirements for the appropriate indoor-outdoor connection in wayfinding. The case studies each examine a current problem in the indoor-outdoor connection by comparing the results of the most commonly used route planners. Second, results of this review and their mutual comparison are employed in the discussion to reflect on recommendations for a better future use and integration of indoor infrastructures in route planning applications.

3.2 ROUTE PLANNER REVIEW

The objective of this review is to grasp the current state-of-the-art on the integration of indoor infrastructures for navigation in common route planners. Without a proper connection of indoor with outdoor environments for navigation, route planners may calculate non-accurate and sub-optimal routes. In this review, indoor infrastructures are considered buildings with multiple entrances above and underground, underground walkways, underground shopping centers and underground transportation systems. Since the indoor built environment can only be accessed by pedestrians, only pedestrian navigation is taken into account with a possible connection to public transport options. The used route planners are common for wayfinding within the geographical area of the query. For queries in Belgium, the following route planners are used:

- Bing: www.bing.com/maps
- Google Maps: www.googlemaps.com
- Mappy: www.mappy.com
- Via Michelin: www.viamichelin.com
- RouteNet: www.routenet.com
- OpenRouteService: http://openrouteservice.org

Queries in Korea are performed with the use of Google Maps and Naver (maps.naver.com). In the different case studies, multiple aspects of the indoor-outdoor connection in routing will be investigated using various route planners. A comparison of the quality of the current route planners is assessed recording their approach of handling data.

3.2.1 INDOOR DATA AVAILABILITY

Following examples all make use of an internal network structure. However, usage is not always straightforward or optimal.

3.2.1.1 Indoor infrastructure as part of the shortest path

To test whether a route planner utilizes the indoor network structure in the shortest path calculations, a first query has been executed to navigate from Cantersteen to Ravensteinstreet in Brussels (Belgium). The optimal pedestrian and shortest path uses the Ravenstein gallery with aboveground entrances in both streets (Figure 3-1).

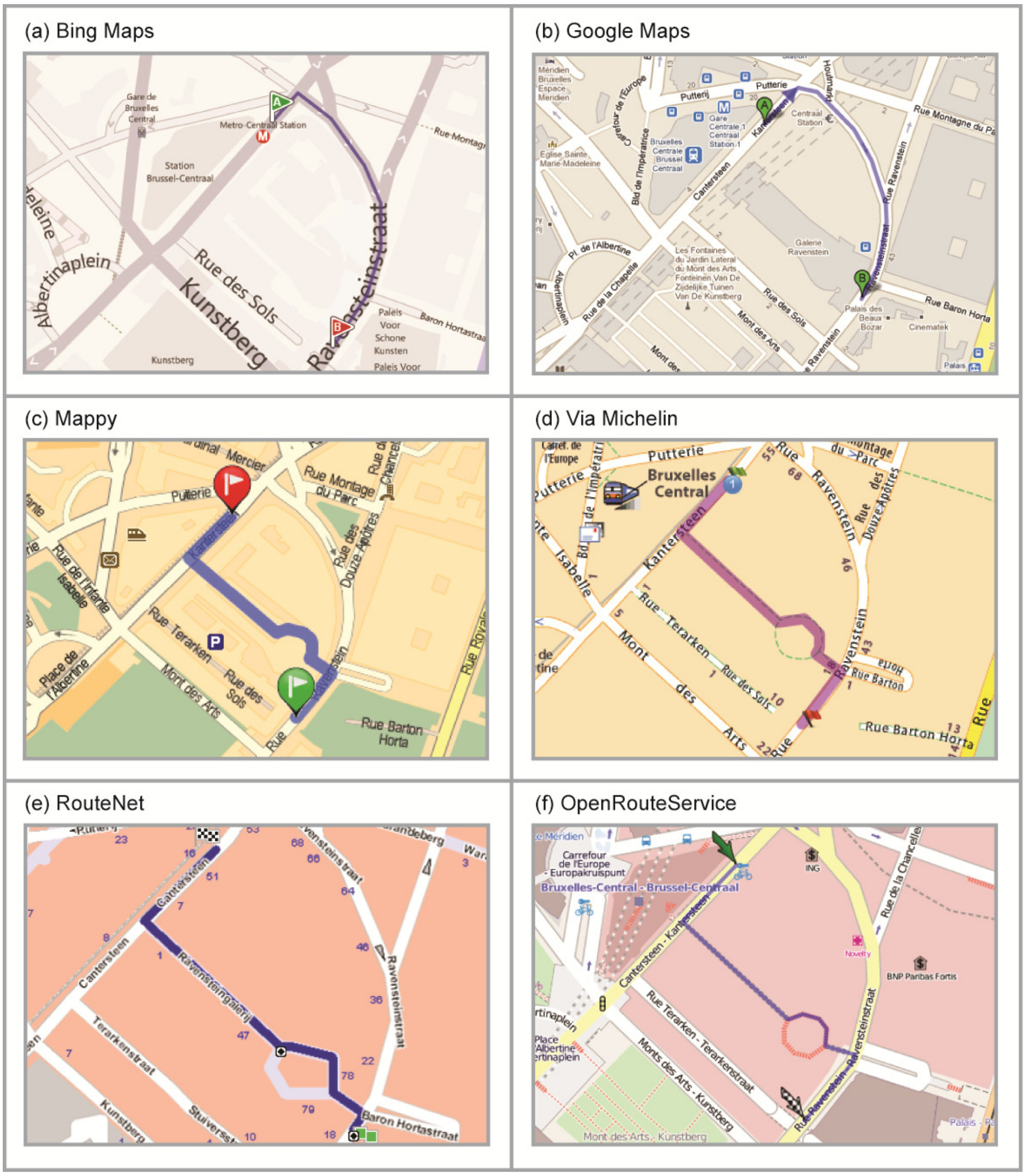

Figure 3-1 Navigation from Cantersteen to Ravensteinstreet (Brussels, Belgium)

Differences over the multiple route planners can be detected. Both Bing and Google Maps do not make use of the gallery, while Mappy, Via Michelin, RouteNet and OpenRouteService on the other hand do. It can be noted that Bing does not even recognize the gallery as part of the spatial dataset. In Google Maps, the gallery is mapped with a text label, but is not part of the vector data available for routing. The other route planners map the optimal and shortest pedestrian route between departure and destination point. This query shows that in some cases both the indoor network structure and the aboveground entrances are mapped and used in the calculation of the shortest path.

A second example studies the use of an underground structure as part of a shortest path calculation in Myondong underground shopping center (Seoul, Korea). The route planner was asked to perform a route calculation from the Lotte Department Store in Myongdong to the Ibis Hotel across the street (Figure 3-2). This street is not directly crossable by pedestrians due to heavy traffic. Instead, across the hotel entrance is an underground passage way and shopping center which leads to the other side of the road (Figure 3-3).

With this query the usability of 3D underground structures in route planners (both the location of entrance points and network usage) is tested. For this query, local data for the city center of Seoul was only available through Google Maps and Naver (a Korean route planner), while other route planners lacked detailed street network data.

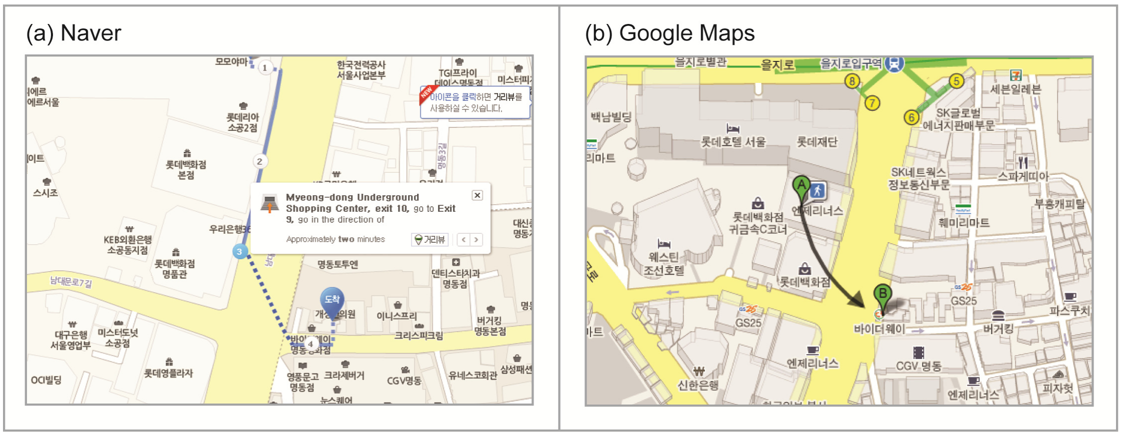

Figure 3-2 Navigation from Myongdong Lotte Department Store to Ibis Hotel (Seoul, Korea)

Figure 3-3 Street view of road in Myongdong (Source: Naver). The red arrows show the entrances of the underground passage way

This example shows that there is a huge difference in navigational instructions for both route planners. While Google Maps does not provide routing information for pedestrians in Seoul, Naver on the other hand has very detailed information of the available pedestrian roads. It recognizes the underground passage way with the corresponding entrance points and exit numbers. Consequently, the navigation instruction is described incorporating all possible details.

3.2.1.2 Availability of entrance information

Apart from checking the use of internal network structures, it is also interesting to verify the data completeness of the route planners for navigation. Interior data can be considered complete if it can solve all queries, has the appropriate interior network edges, semantic information and ability to connect the indoor with the outdoor networks via the entrance/exit points of buildings.

As is shown in Figure 3-1, Mappy, Via Michelin, RouteNet and OpenRouteService use all aboveground entrances in the calculation of the shortest path. However, the gallery also has one underground connection with the main railway station in Brussels. The following query tests the use of this underground entrance with a query from the railway station to the Ravenstein gallery. The query is executed in all six available route planners (Figure 3-4). It can be concluded that only OpenRouteService provides all the entrances to the indoor gallery, even the underground passage way. The spatial data sets of the other route planners are incomplete resulting in sub-optimal routing instructions. It has to be pointed out that the address matching (discussed in Section 3.2.2) influences the ability to calculate the routes. For the query in OpenRouteService, the start position has been manually pointed out, since this route planner does not incorporate appropriate address matching. In the Bing route planner, accurate data is lacking of the building itself (attribute is not found in the dataset), making it impossible to even calculate a route. Google Maps has the attribute information but the address is not linked to the network. Instead, the endpoint is linked to the closest available network data with respect to the central point of the gallery. Also, Google Maps links the attribute information for the Central Station to a different geographical location compared to the other route planners. Mappy and Via Michelin, on the other hand, both have network data inside the building complex. However, the underground passage way from the station to the gallery is not digitized. RouteNet maps the location of the gallery on the same position. However, despite having the internal network structure, the calculated route leads to the back entrance which is the closest to the mapped location (i.e. the location of the address).

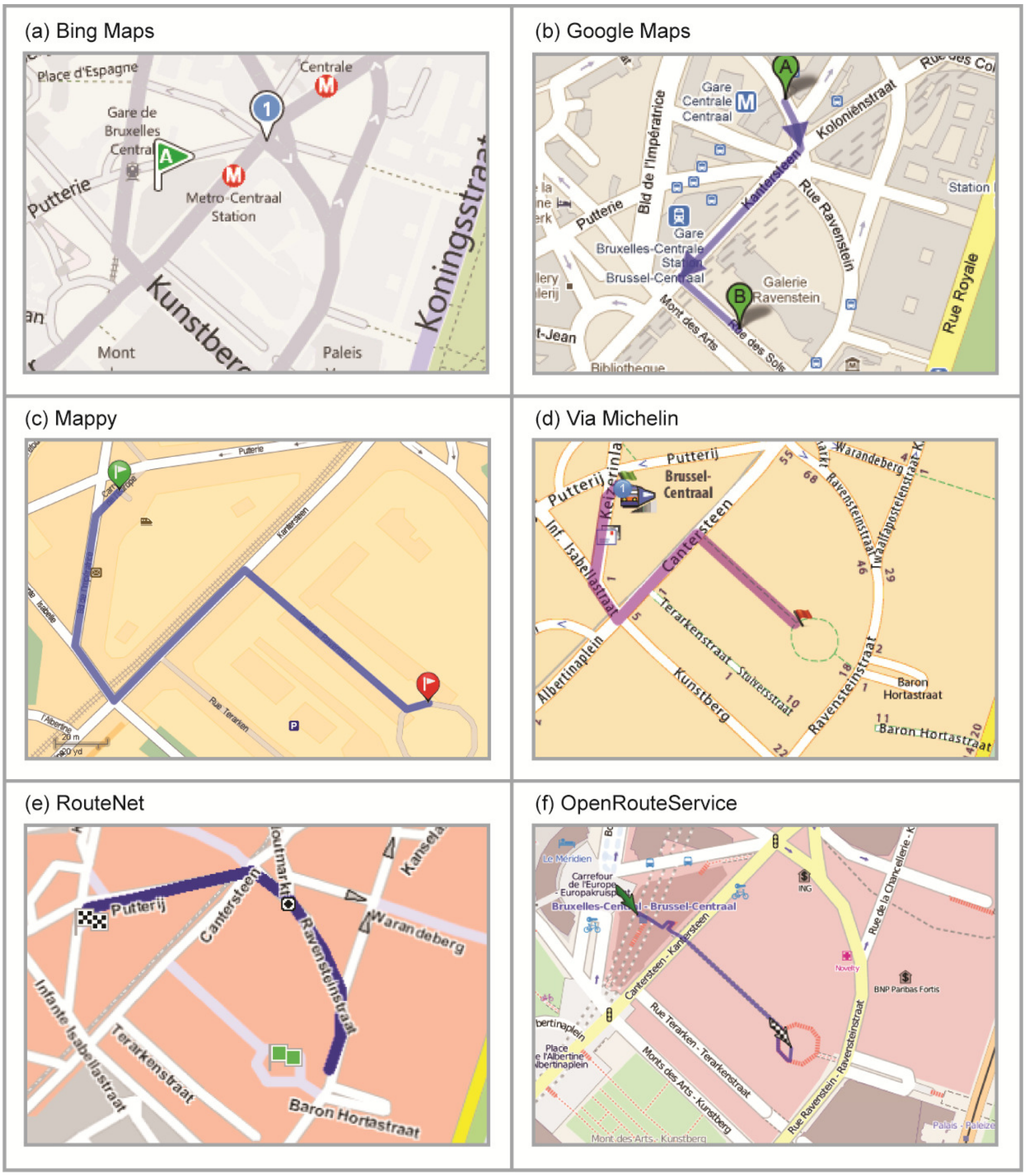

Figure 3-4 Navigation from Brussels Central Station to Ravenstein gallery

3.2.2 ADDRESS MATCHING

In the following examples the query requires appropriate linking between the users input and geographical coordinates.

3.2.2.1 Address matching within indoor infrastructures

As shown in Section 3.2.1.1, in some cases indoor network data is available. However, the availability of an indoor network is no guarantee for appropriate linking of indoor features with indoor address localization. In the following example this is tested through navigating within a certain indoor infrastructure which requires indoor addresses linked to the network structure. Note that indoor tracking methods necessary for an indoor positioning system are disregarded and as such we solely focus on the navigational instructions of route planners. This case study is again carried out in the Ravenstein gallery in Brussels. As was concluded from the example in Figure 3-4, only Mappy, Via Michelin, RouteNet and OpenRouteService were able to visualize and use the indoor network in its route calculations. Therefore only those are used in the current example (Figure 3-5).

These similar queries lead to different results over the various route planners. With the navigation instructions in the left column, both destination and departure points are situated on the same network edge which requires a linear interpolation technique for appropriate address matching. OpenRouteService completely lacks a link between addresses and spatial location. Even for outdoor environments, specific addresses in the same street are linked to one point on the network. For this query, the position of start and destination were added manually. The calculation of the shortest route makes use of the internal network. OpenRouteservice can as a consequence not be used for accurate address matching.

Figure 3-5 (left column) demonstrates that only Mappy and RouteNet are able to visualize the correct end points. However, none of them are able to actually calculate the shortest route between them. They both use a different mapping method to project the end points to the correct position on the network. Mappy maps the correct internal location, but cannot connect them through the indoor network. RouteNet searches for the closest available network edge to map the address and connects them using the outdoor network.

The second query also requires internal navigation in the same gallery, but the end point is located on a different part of the internal network. As can be seen from Figure 3-5 (right column), in this case all route planners are able to perform a correct address matching with a proper connection to the interior network. Via Michelin and RouteNet calculate the shortest path between both points, while Mappy uses a part of the network twice in its calculations resulting in a sub-optimal navigation solution.

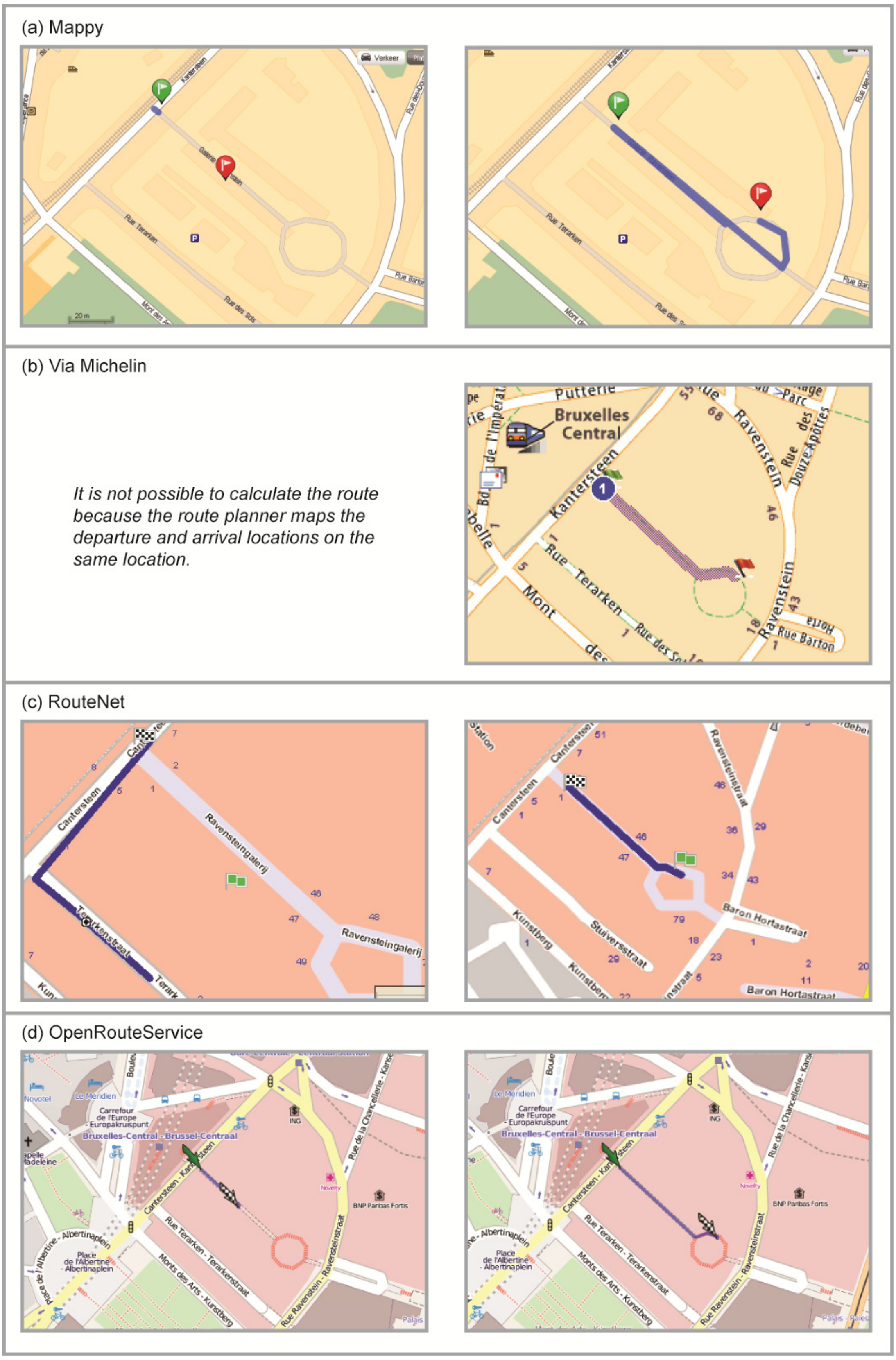

Figure 3-5 Navigation from Ravenstein gallery 2 to Ravenstein gallery 27 (left column) and from Ravenstein gallery 12 to Ravenstein gallery 60 (right column)

3.2.2.2 Address matching influences the exit choice

Another aspect of the challenges involved with the indoor-outdoor connection is the way in which exit points and address matching methods are related to each other. The next two case studies test whether route planners make use of different exit points of indoor infrastructures when calculating routes to different locations and in what way the exit choice influences the final route calculation.

This first example uses the main station in Ghent (Belgium) as starting point for two queries. The first query (Figure 3-6, left column) asks the route to the center of town, north of the station. The second query (Figure 3-6, right column) requires the route to the hospital in the south of the city. The station has two main entrances, one at the front (north side) and one at the back (south side) of the station.

From this example, it can be concluded that all five route planners only use one entrance/address point for route planning, no matter what the destination of the query is. Both Bing and Google Maps have the station located at the back entrance, making the route to the city center not optimal. Interestingly enough, in this case they even use different solutions to get to the north side of the station, due to different routing algorithms used in the calculation. For the second query, the departure points[2] with respect to the geographical location of the station remain the same over all route planners. When looking at the destination[3], the different route planners use multiple locations depending on the availability of the spatial data.

[2] OpenRouteService does not incorporate appropriate address matching capabilities. The start and end points of the queries are added manually.

[3] Via Michelin did not recognize the name 'UZ Gent' or 'Universitair Ziekenhuis Gent'. Instead the address given by the website of the hospital (De Pintelaan 185) is used as end point of the query.

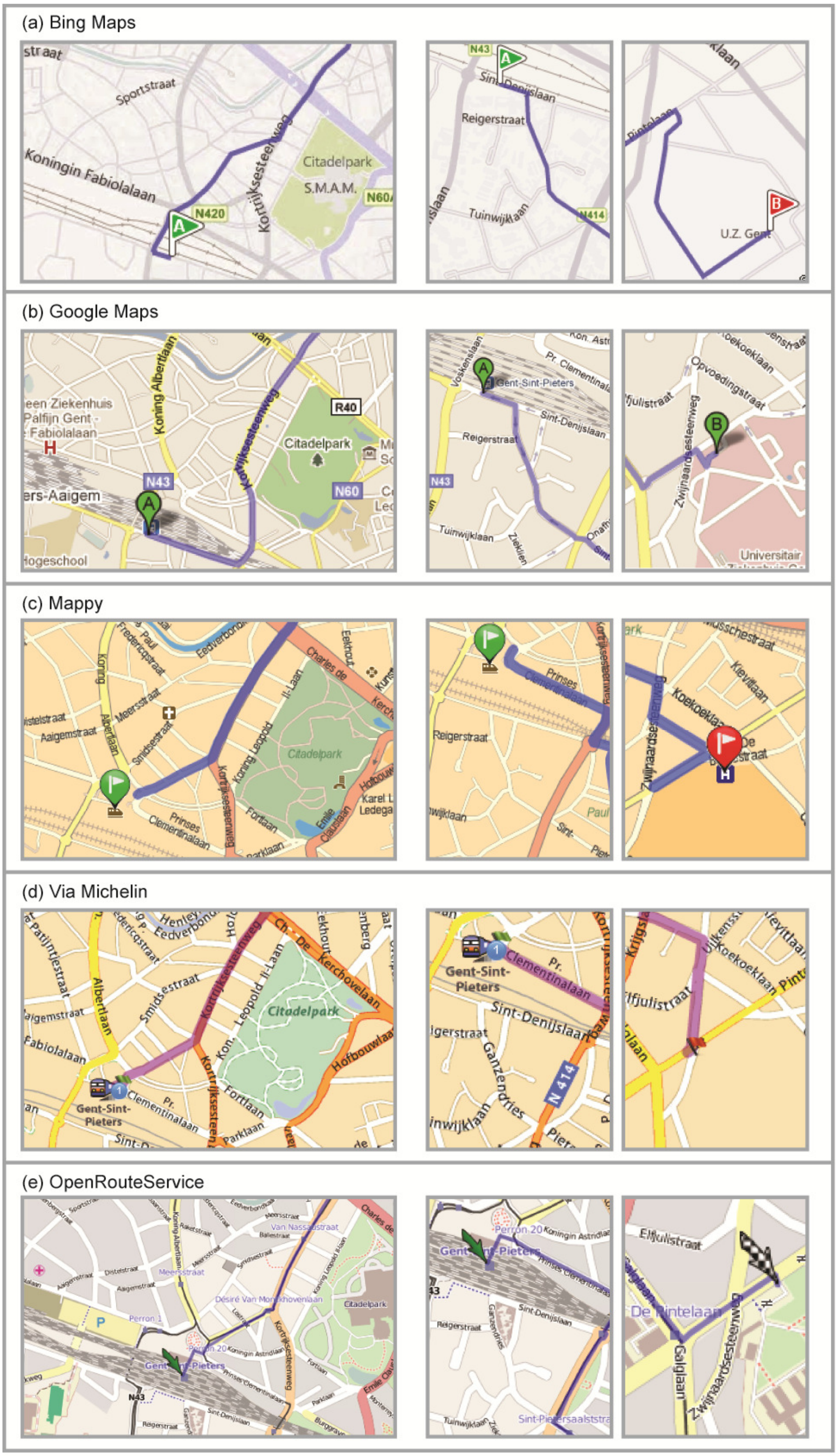

Figure 3-6 Navigation from railway station Gent-Sint-Pieters to Korenmarkt (left column) and University Hospital (center and right column)

A second case study takes place in the Waasland shopping center in Sint-Niklaas (Belgium). Although it is not so much focused on indoor networks, the results can have major importance for future indoor-outdoor connections. The query inquires about driving directions to the shopping center (Figure 3-7). The shopping center has multiple entrances and parking spaces which makes driving rather complex. One of the problems here is the question of where to park your car when you want to go to a certain shop. A certain optimization can take place which requires the connection of the several entrances, the internal building layout and the immediate outdoor environment.

Figure 3-7 Driving instructions to Waasland Shopping Center

It can be seen that the geographic location of the endpoint differs over the various route planners (Figure 3-7). The digitalization of the outdoor parking area varies from quite rough (Bing) to very detailed (Google Maps). However, none of the route planners make use of entrance point information, making a future indoor-outdoor connection at the moment rather difficult. The algorithm for linking the address information with the spatial network information differs for every application, but is of major importance for results of the route calculations.

3.2.3 MULTIMODAL ROUTING APPLICATION

One of the applications where the indoor-outdoor connection in navigation is really important is when changing mode of locomotion and this mostly related to the public transportation system. In Figure 3-8, a multimodal path using public transportation is calculated from Donuidong 30 to the University of Seoul (Seoul, Korea). The calculated route involves changes from pedestrian movement to subway and bus. The first part of the route consists of the movement from the address to the subway entrance. Both route planners make use of the same subway line.

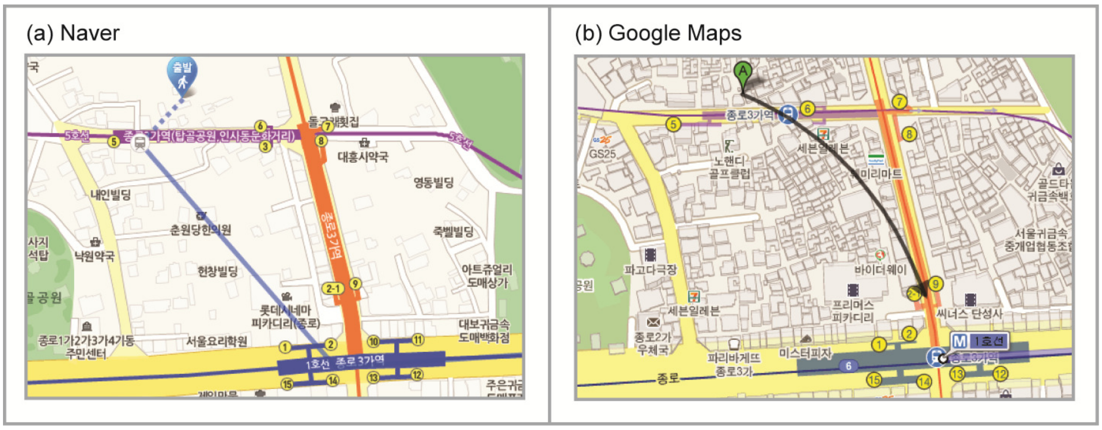

Figure 3-8 Navigation from Donuidong 30, Seoul to University of Seoul. Zoom of part 1 from Donuidong 30 to Jongno 3-ga subway line 1

With above routing navigation, we can make the following conclusion: Google Maps does not support detailed and accurate navigational instructions, only the information to go to subway line 1 with stop Jongno 3-ga. Naver on the other hand is more detailed and connects the walkway from the given address to the entrance of subway line 5 (Jongno 3-ga). The route is continued using the underground subway infrastructure until line 1 is reached. However, details from within this underground infrastructure are not provided.

With the above example, it is shown that Naver knows the available underground structures and entrances. However, the entrance choice is solely based on the shortest route aboveground. In reality, when entering the subway of Jongno 3-ga at entrance 4, the route requires descending over multiple floors and is much longer and more exhausting to walk than walking directly towards entrance 6. As is shown here, knowledge of 3D underground obstacles and structures does affect the optimal route choice but is currently not taken into account.

3.3 Discussion

In the following paragraphs, some more general conclusions with regard to the previously described case studies will be discussed. We follow the same structure of the examples given. Subsequently, some of the implications and difficulties for immediate development of indoor routing are being discussed.

3.3.1 Problems with current indoor navigation applications

From the above case studies, several conclusions can be drawn.

First, with regard to the data availability and completeness of the data we can conclude that most route planners do not incorporate indoor infrastructures in route calculations. This is most likely given by a lack of available indoor data (e.g. Bing in Figure 3-1). Reasons for this are likely related to the fact that indoor data gathering has only just begun over the last few years. Also, the geographical area of the query could account for the unavailability of data in some areas, since companies developing route planners will put most effort into areas with the highest commercial value (e.g. European route planners have no detailed data available from the city center of Seoul). Among route planners which do have some indoor data available, there is a dramatic difference in their level of detail. Data ranges from very rough (e.g. Google Maps in Figure 3-1) to quite detailed (Naver in Figure 3-2 and Figure 3-8, and Mappy and Via Michelin in Figure 3-1). When this indoor data is available, the disparate route planners mostly use it integrated with their outdoor networks in the shortest path calculations (Section 3.2.1.1).

The data problem is more pronounced with regard to underground structures. Usually both the entrance points and the underground network are not available (Figure 3-4). Even with the most accurate information available, there are issues in calculating the optimal routes. Although the entrance location and attributes are used as connectors between outdoor and indoor network data, the actual underground network structure is not mapped or known. This results in a lack of knowledge about the 3D infrastructure which can have a detrimental effect on navigation instructions (no indication of how to move in the underground area requires the user to rely on the available exit signs or other information) and calculation of shortest path (the result is mostly not the shortest path because of the movement in three dimensions with entrance choice based on the shortest aboveground path). In that case, the route planner uses the knowledge of the various entrances of an underground system and the time needed to move from one to another to calculate the shortest routes.

Second, the discussion from Section 3.2.2 implies that address matching is a problem for both outdoor as well as for indoor navigation. Outdoor address matching links the address to a single entrance/exit point, no matter what the destination of the query is. Not differentiating between the start point of the query with respect to the destination leads to inaccurate routing. Indoor address matching is done through linear interpolation of the indoor network structure (if available). When no indoor infrastructure is available, addresses are matched through projecting the central point on the closest outdoor network edge (Figure 3-4 and Figure 3-5). The accuracy of the storage and location of the addresses is thus of major importance for routing in general and can highly influence optimal routing calculations.

Third, the connection of indoor and outdoor networks is mostly guaranteed when the travel mode remains the same and the entrance data is available (Figure 3-1 and Figure 3-8). However, changing of mode of locomotion influences the route calculation making the calculations more complex (Figure 3-7). This depends on both the data quality of the indoor-outdoor connection as well as the general accuracy of the outdoor network. This will be an issue for the future expansion of indoor-outdoor navigation applications with optimizations of route calculations.

3.3.2 Indoor navigation: product-to-market implications

3.3.2.1 Data acquisition, standards and accuracy

Data is the main ingredient for navigation and route planning. Within the area of outdoor navigation applications, a wide variety of data sources is already available from a mix of local and global data providers. The main spatial data providers are Navteq, TeleAtlas and Google. Historically, Holland-based TeleAtlas and American Navteq were interwovenly used in many navigation applications. However, purchases of the main data providers by commercially independent navigation producers (Navteq by Nokia and TeleAtlas by TomTom) lately resulted in individual vouching for your own data set. As a result, Google (who had just signed a deal for using TeleAtlas data) switched to individually conducted data gathering for their US dataset. Additional reasons for this move were said to be the lack of accuracy and coverage in the United States from the TeleAtlas data (http://blumenthals.com/blog/2009/10/12/google-replaces-tele-atlas-data-in-us-with-google-data/). Google increased with this step its intention as one of the main contenders for spatial data information. From these data providers, no comprehensive efforts have currently been made to expand their spatial data set with ubiquitous indoor data.

As seen in the examples above, data is also crucial in the incorporation of indoor infrastructures in analysis and route calculation. The feasibility of indoor data acquisition is in this regard challenged and unseen. Nowadays, the available spatial datasets are mainly being updated and created using aerial images and mobile mapping vans. These methods are however not suitable for indoor mapping. Technically, a consensus is still lacking on a universal indoor tracking method as solution for the unavailability of GPS signals in buildings. One of the results is that the currently used user input from GPS tracks for updating and editing OpenStreetMap data cannot be applied here unless a ubiquitous indoor tracking system has been developed. Other options for indoor data gathering include photo modeling and laser scanning of individual buildings (Biber et al., 2004); but this is work intensive, expensive and not a comprehensive way of solving the data problem. Currently, many indoor data already exists in the form of for example You-Are-Here maps, CAD plans, CityGML or IFC models. These data represent the topographic building structure developed from certain application fields (e.g. structural building development, orientation purpose, evacuation maps). The problem with these indoor data sources is the huge diversity in data structure, completeness, availability, data coverage and level of detail. The area and institutional rules of the country also influence the specificity of the data source. As long as no generally accepted indoor standard is developed or a method to incorporate every possible indoor data source, comprehensive indoor data inclusion will remain challenged (Nagel et al., 2010).

In either way, from these data sources correct networks have to be deducted. Since there is still no consensus on an appropriate and mathematically sound relation between data source and network creation for indoor environments, this is an additional problem needed to be solved before real indoor navigation can happen (Nagel et al., 2010). From the OGC and research environment attempts are currently made to develop a general framework and data standard (similar to GDF) for indoor navigation (Nagel et al., 2010). This is a promising step towards creating a background data model which can be used independently of the data input source.

3.3.2.2 Indoor geocoding challenges

A second major challenge in indoor navigation and route planning is the geocoding of the users input to a geographical location or spatial unit. The term geocoding refers to assigning a geographic code based on certain input information. Mostly geocoding is synonymous with address matching, arising from the prevalent use of transforming postal addresses into geographic coordinates (Goldberg et al., 2007). However, the input source can contain any other type of locational data (e.g. named buildings). Apart from the input, the fundamental components of the geocoding methodology include the processing algorithm, the reference dataset and the requested output (Goldberg et al., 2007). The challenges with the processing algorithm include identification of the separate parts of the input consistent with the reference data set (i.e. standardization and normalization process), matching of the best candidate with reference to the input data and determination of the appropriate geocode for output (Goldberg et al., 2007). The reference dataset consists of the data with which the input data will have to be matched. The output can be any geographically referenced object matching with the input data (Goldberg et al., 2007).

Goldberg et al. (2007) mention frequently induced errors in the outdoor geocoding methodology. With the most commonly used linear interpolation techniques, several assumptions are already made that affect the resulting geocoding accuracy (e.g. addresses are assumed to all exists with equal parcel width). This methodology is also only restricted to outdoor address location finding, mostly on street level. However, other methodologies (e.g. area based or hybrid address matching) have similar problems and disadvantages. The reliance of 2D GIS data sources precludes the ability for highly precise geocoding of 3D structures with multiple addresses (Goldberg et al., 2007).

Indoor geocoding is susceptible for even more difficulties. First and foremost, the existing semi-uniformity in outdoor addressing is completely non-existing indoors due to country-related differences and a less rule based structure. For example, a 3D address consists of a 2D building address and a 3D subunit address, describing the location of a building's interior room (Lee, 2009). Lee (2009) suggests a 3D address geocoding methodology. It is based on a two-step process with first determination of the building within the geographical area (following the outdoor geocoding methodologies), followed by a street-like linear interpolation technique applied on an internal network of the building. This approach disregards the problems of discontinuous room numbering, for which transition tables can be a solution. Second, a reference dataset for indoor environments is not available. Outdoor geocoding methods mostly use existing street network data set (e.g. TIGER) with the range of house numbers linked to the street intersection or spatial street feature in the database. As long as no standard for indoor data exist, reference datasets will not be available for address matching.

3.3.2.3 General feasibility issues

Concluding, we are still far apart from consistently incorporating indoor environments in routing applications. Challenges remain in data availability, storage, network completeness, linkage to the outdoor networks and geocoding. Technical innovations, research and creativity in the routing with less data might improve the feasibility for success in the next years. It is shown that the availability and quality of outdoor and indoor data and their connection is of high importance for the resulting route calculations. It appears that it is not feasible to gather and maintain all indoor data accurately from all buildings in the next years, since this would require a huge amount of data collection and maintenance. However, such a complete data gathering is not always necessary. Even small enhancements in indoor data can have a huge influence on routing (e.g. pointing out all connection points between indoor and outdoor environments, even without the actual indoor network would make the address matching more accurate and would also provide possibilities to have more optimal routes as for example shown in Section 3.2.3). More accurate information will of course result in optimal route calculations.

With all the above mentioned challenges, it is not possible to do a complete data acquisition for a combined indoor-outdoor navigation. We should seek to focus on large infrastructures and transportation networks with more specific navigational directions. The benefits of accommodating navigation in those infrastructures are bigger since a lot of people daily use and rely on those. These structures are also quite often fixed and stable over long periods of time, making the indoor data gathering and maintenance also more feasible. As is shown in the examples, the 3-dimensional network aspect is here of major importance to enhance routing for everyone.

An important role in data acquisition and address matching will be for the public. Over the last year, an increase has been seen in the public participation for outdoor data following the success of the data acquisition in OpenStreetMap (i.e. Wikipedia style updating and editing of data). This was noticed and built upon by other internet based applications and could also be a solution for indoor routing applications. Already at this moment users can change addresses and location of addresses for outdoor routing. Once the technology is ready for continuous indoor tracking and more user input is allowed, this could open up the indoor world too.

3.4 Conclusion

With this comparison of how current route planners use indoor infrastructures in the calculation of pedestrian routes, several active problems with this indoor-outdoor connection are identified. The most stringent limitation of current route planners in this realm is the availability of accurate data of indoor infrastructures. This data should consist of network information, additional semantic enrichments and all entrance points. As can be seen from the examples above, nonexistent or inaccurate information can lead to sub optimal routing, and even to a lack of routing in many cases. However, when the appropriate data is available, very precise routing information is proven to be calculated. It is pointed out that even small data additions, such as entrance and exit points of major infrastructure projects, can have a huge influence for pedestrian routing. Secondly, outdoor address matching techniques cannot directly be applied to indoor datasets. Immediate indoor-outdoor connection for navigation applications still have a long way to go. This research fits in with the ongoing awareness of indoor and outdoor navigation and more specifically it gives an overview of the data requirements for navigational applications. Future applications will more often focus on this indoor-outdoor connection, not only in navigation but also for wider analyses and applications.

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4

MEASURING THE EXITABILITY OF BUILDINGS: A NEW PERSPECTIVE ON INDOOR ACCESSIBILITY

Modified from: VANCLOOSTER, A., NEUTENS, T., FACK, V., VAN DE WEGHE, N. & DE MAEYER, P. 2012. Measuring the exitability of buildings: A new perspective on indoor accessibility. Applied Geography, 34, 507-518.

ABSTRACT

In the last decades, geographers' attention has been drawn to the vertical dimension of space and indoor environments due to population growth and concomitant city expansion. While traditional geography has long studied merely horizontal relationships of spatial processes and phenomena, recent years have also witnessed a growing number of studies that have sought to extend traditional spatial analysis tools to three-dimensional and indoor environments. In line with these developments, this paper proposes a new indoor accessibility measure which quantifies the quality of access to exits, called *exitability*. In this, the movement of people with respect to its three-dimensional environment, the user characteristics and the surrounding occupant interactions is considered key. Since the accessibility of exits is most important during evacuations, the calculation of *exitability* uses existing evacuation flow models. In a case study, we demonstrate the usefulness of *exitability* measurements through an application on existing building data.

4.1 INTRODUCTION

In the last decades, population growth and concomitant city expansion have exerted more and more pressure on urban space. Recent years have not only witnessed horizontal urbanized spreading, but also vertical building developments. These are triggered by a pinching deficit in land availability (e.g. Hong Kong), constructions of iconic single-phase mega-projects (e.g. Dubai) and enforced rules from governments revitalizing residential inner-city areas (Hwang, 2006; Abel, 2010; Wilson, 2010). The three-dimensional vertical city was born and with it the requirement of dealing with the corresponding complexities of multi-level building structures.

Past urban geographical research has unfolded the opportunities and limits of cities through extensive geospatial analysis (Ban & Ahlqvist, 2009; Batisani & Yarnal, 2009). Research of inner-city mobility (Keeling, 2008; Antipova et al., 2011), accessibility analysis and studies of optimal time-space distributions (Kwan & Weber, 2003; Neutens et al., 2010; Neutens et al., 2012; Versichele et al., 2012), all reveal elements of the spatial distribution and interactions of people and businesses within the two-dimensional urban city.

In this paper, however, we focus on the city as a three-dimensional complex and more specifically on the multiple units that make up the 3D environment. We argue that spatial concepts need to be adapted to the intricacies of indoor environments, given the following differences between indoor and outdoor environments. First, the space itself is physically highly divergent. Outdoor space is considered mostly as non-built environment, not enclosed and large scale while indoor environments are mainly enclosed and constrained by the architectural infrastructure on a small scale (Li, 2008; Walton & Worboys, 2009). Second, wayfinding tasks in multi-level buildings have proven to be more challenging than outdoors, for reasons of disorientation (due to multiple floor levels and staircases), and less visual aid (e.g. landmarks are less obviously recognizable; corners and narrow corridors prevent a complete overview) (Hölscher et al., 2007). As such, building occupants are faced with a deficient perspective on the building structure, influencing their movement behavior (Hölscher et al., 2007). Third, the scale level of analysis is for indoor building complexes more restricted than outdoors. Analysis techniques are required to cover the range of macro- to micro-scale environments when combining indoor with outdoor space. As a result, the increased complexity of the three-dimensional vertical city induced by these differences can impact movement patterns and wayfinding choices of building occupants. Spatial analytical functions that focus on discovering and measuring this relationship between spaces and human movement will have to consider these intricacies.

With the increasing attention to the specificities of indoor spaces, the challenge was raised of adjusting analytical methodologies to the indoor environment. In this paper, we focus on one type of spatial analysis, namely accessibility. The aim is to examine accessibility within an indoor three-dimensional environment. A methodology will be put forward to analyze the accessibility of exits from building units (room-to-exit accessibility). Hence, the proposed accessibility measure will be termed *exitability*. The measure builds upon traditional outdoor accessibility concepts and extends those to the three-dimensional indoor environment. Relying on commonly used evacuation models, we will demonstrate how the concept of *exitability* can serve as a measure for the efficiency of the spatial building design in enabling evacuation of building occupants.

The remainder of the paper is organized as follows. Section 4.2 elaborates on the definition of *exitability* and its relationship to accessibility. In Section 4.3, the model behind the *exitability* measure is discussed and framed within the existing state-of-the-art on evacuation modeling. In the case study in Section 4.4, the *exitability* measure is calculated for a university building with multiple analyses showing its strength for spatial analysis of the 3D indoor environment. This paper is completed with a conclusion on the discussed issues.

4.2 Exitability in relation to accessibility

4.2.1 Defining exitability

To measure the quality of access to exit points, a function is required to objectively characterize spatial differences in access within and across buildings. For this, we develop a new type of indoor accessibility measure, termed *exitability*, which measures the occupants' ease of reaching exits within a building. Therefore, *exitability* is focused on the movement of the building occupants itself. This occupant movement depends on the structure of the spatial environment, including the topological building structure, the semantic structure and the building geometry, as well as the user environment, with the distribution of people per spatial unit. Access to exits is most important during emergency situations and the ensuing evacuation. As such, our definition of *exitability* accounts for movement of all building occupants to the exits during evacuations. For each room, it is calculated as the exit time needed for the movement of every occupant in the room to the exit. The total *exitability* of a building is quantified through averaging the individual *exitability* values of the separate rooms. The methodology for the calculation of *exitability* is explained in more detail in Section 4.3.

4.2.2 Analogies and differences with accessibility measures

The developed *exitability* measure intersects with various threads of research. Its foundation relies on traditional outdoor accessibility measures. Both have a similar goal of quantifying the qualitative degree of connectivity between different places or persons (Kwan, 1999). Accessibility measures are widely used in urban transport and planning research as a tool to analyze and model activity patterns of customers in outdoor space (Kwan & Weber, 2008; Neutens et al., 2008). However, the setting for *exitability* has changed to the indoor three-dimensional world. *Exitability* has also more strictly defined origin and destination sets. The interior building entities correspond to the origins while the exit features represent the destinations. In addition, the attraction of exit locations is modeled by closely considering the collective movement from building occupants to these exits.

Since *exitability* is defined for indoor environments, it is conceptually linked to indoor accessibility measures. So far, the latter has been developed from two divergent angles of research: (i) the quantification of individuals' indoor mobility limitations and (ii) spatial analysis of the built environment. The first strand of research aligns with a growing awareness of movement difficulties of people in buildings in the last decade (Sakkas & Pérez, 2006). This has led to requirements for building design and standards to measure and compare their proficiency at appropriately adapting space to everyone's needs. By considering buildings as user service providers, Sakkas and Pérez (2006), for example, defined indoor accessibility as a measure of quality of all representative service paths through a building. Church and Marston (2003), for their part, proposed a relative accessibility measure, which allowed the detection of access differences relative to distinct user groups. Beside these theoretical approaches, the European Union developed the European Passe-Partout index (2011) as a method to assess the accessibility of buildings with regard to disabled people, following legal recommendations from various countries. This index lists for every building how well it is adapted to the specific requirements of persons with limited mobility based on predefined parameters. These indoor accessibility indices are mostly used as recommendations for adapting existing buildings to the requirements of physically impaired persons (Otmani et al., 2009), limiting their scope to solely this specific group of people. However, when assessing the general accessibility of building exits, all building occupants should be taken into account, while still retaining a high interest in previously considered groups. Therefore, these indoor accessibility measures cannot be used as a model for grasping the spatial interrelationships between multiple building units.

The second line of inquiry includes recent work from Kim et al. (2008) and Thill et al. (2011) which demonstrates the calculation of accessibility measures in buildings by considering human movement. They both use a different methodology, with Kim et al. (2008) buttressing up their method with the space syntax theory; while Thill et al. (2011) employ a traditional gravity-based model. Apart from their incorporation in a three-dimensional built environment, both approaches calculate the accessibility of a single spatial unit with regard to pedestrian movement under non-emergency situations, while in our research *exitability* is measured under evacuation scenarios. Also, our calculation is based on the actual movement of occupants and not like the aforementioned approaches based solely on distance and geometric characteristics of the building. With these limitations, none of the currently available indoor accessibility measures is able to fully quantify the quality of access to exits during evacuations, on which we focus in this paper.

4.3 METHODOLOGY FOR CALCULATING EXITABILITY

4.3.1 STATE-OF-THE-ART IN EVACUATION MODELING

Evacuation analysis and response has a wide interest for various researchers in understanding and preventing hazardous situations (VanLandegen & Chen, 2012). Partly due to a string of major world events (e.g. attacks on the WTC in 2001, London bombing and hurricane Katrina in 2005), the need for developing evacuation models for building environments has grown progressively over the last decades. This renewed interest brought along a boost in the development of sophisticated computer simulation models.

Historically, studies on building evacuation modeling originated from pedestrian movement models since the 1970s. In these studies, human behavior and movement was quantified and modeled under both non-emergency and emergency conditions and this mostly from a static context (Gwynne et al., 1999; Cepolina, 2004). From this period onward, flow-based mathematical formulas became widely available (e.g. the formulas from Fruin (1971) and Predtechenskii and Milinskii (1978)) (Hamacher & Tjandra, 2001; Santos & Aguirre, 2004). A second research surge began in the early 1980s with the development of computer simulations for evacuation modeling (Gwynne et al., 1999; Hamacher & Tjandra, 2001; Santos & Aguirre, 2004). Here, at least two strands of research can be recognized. First, ball-bearing, fluid-dynamic and flow-based models extended the mathematical flow models with individual occupant modeling and queuing. However, these aggregate models still treated individuals as homogenous groups acting together (Santos & Aguirre, 2004; Castle & Longley, 2008) with the speed and direction of human movement determined by physical constraints. The aforementioned models were later on slowly replaced by individual level modeling with humans as active agents, which made it possible to link human movement with human behavior (Gwynne et al., 1999). The development of automata allowed for the processing of dynamic characteristics (Gwynne et al., 1999; Castle & Longley, 2008).

Based on the above review, we can draw some conclusions on the existing models and the remaining research challenges. First, a multitude of highly complex and sophisticated simulation models is available for evacuation and pedestrian movement. The chosen model for a certain application depends on the purpose of the application, the scope and the requirements on among other things the level of detail, input data, output, computational strength and runtime (Kuligowski, 2008). Second, many parameters influence the evacuation process, ranging from the characteristics of the emergency situation to the human reaction and behavior, user experience and built environment. Even within this research field, there is no consensus yet on the correct implementation of all these parameters; with criticism especially towards the method and data of human behavior incorporation (Averill, 2010). Gwynne et al. (1999) recognized a trend towards implementing more and more behavioral characteristics to match the real human reaction in case of emergencies. More recently, Zheng et al. (2009) confirmed this trend by proposing combinations of various approaches to study crowd evacuation, employing rules from one approach on the basic principles of the other approach. However, no evacuation model already fully addresses all behavioral aspects involved in emergency situations and evacuations. Additionally, not all of the behaviors involved are yet fully understood and analyzed (Gwynne et al., 1999; Kuligowski, 2008).

With the above conclusions in mind, we chose to employ a coarse network flow model from a global perspective with homogenous mapping of occupants and queuing. While this model is used for calculating the *exitability* based on flow movement during evacuations, it is important to emphasize that the evacuation principle is not the main parameter of interest here, but is solely comprehended as the most stringent situation precluding optimal accessibility. The focus is on the general level of *exitability* within buildings, not on the effects of a particular emergency event on occupant movement (as is generally the case in previous work). Therefore, the individual and random characteristics of an emergency situation and ensuing evacuation itself are left unconsidered. This allows us to make not only comments about the accessibility during evacuations, but also under non-emergency situations and their effects on particular spatial inter-room differences.

4.3.2 CALCULATION OF EXITABILITY

4.3.2.1 Spatial model

For calculating *exitability*, a representation model of the enclosure space is required, in this case a three-dimensional data model that represents the internal structures of the built environment. We employ a coarse network model implemented as a network graph that discretizes space into subregions, all internally connected (Gwynne et al., 1999). This has the advantage of representing all necessary topological relationships between the spatial building units while preserving a close connection with the actual movement of human beings (Lee, 2004). The model is equivalent to the widely used 'Geometric Network Model' (GNM) of Lee (2004) where the pure connectivity graph ('Combinatorial Network') (Figure 4-1a), containing solely topological relationships, is transformed into a geometric network (Figure 4-1c). This is attained through enhancing the 'Combinatorial Network' with geometry information and creating a sub-graph for linear phenomena (e.g. corridors) into the node-edge structure.

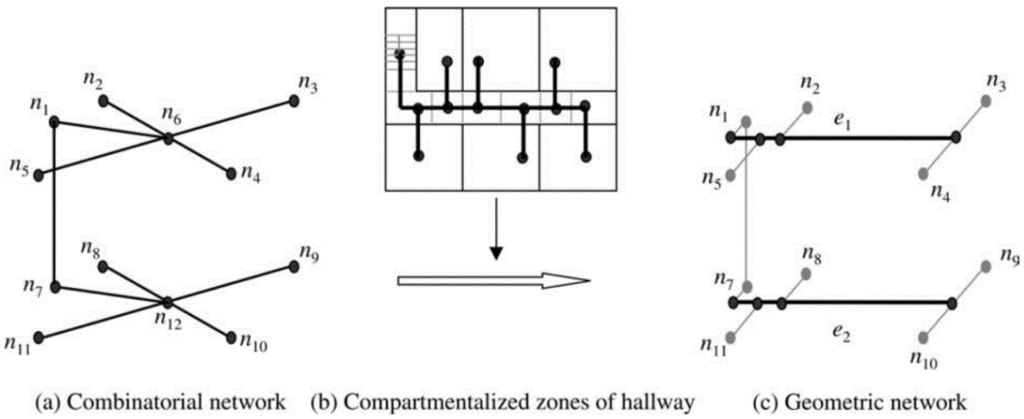

Figure 4-1 Design of the 'Geometric Network Model' (Source: Lee, 2004)

As such, the GNM is an abstraction of every building's connectivity structure with additional geometric information enabling network analysis equivalent to road network analysis. Additional information necessary for this analysis can be stored in either the nodes or the links interconnecting these nodes, or in both.

4.3.2.2 Flow model

For calculating *exitability*, the occupants' movement is represented as a continuous flow of homogenous groups of people (Santos & Aguirre, 2004). Flow-based evacuation models are commonly based on the following assumptions (Kratchman, 2006):

(1) all persons will start to evacuate at the same time;
(2) occupant flow will not involve any interruptions caused by decisions of other building users;
(3) all or most of the persons involved are free from disabilities that would significantly impede their ability to keep up with the movement of a group.

The above mentioned assumptions will also apply to the calculation methodology of *exitability* for different reasons. For example, the first assumption implies that pre-movement times are omitted in the calculation of the final evacuation times. The pre-movement time in evacuations is the time for occupants to detect and respond to the emergency situation (Fahy & Proulx, 2001; Gwynne et al., 2003). A multitude of data on delay times has already been collected from various studies, but using them should be done with the highest prudence (Fahy & Proulx, 2001; Gwynne et al., 2003). After all, mistakes are frequently induced in the sense that the original context of the data is often lost and ignored (Gwynne et al., 2003) and the data is mostly building, situation and occupant specific (Fahy & Proulx, 2001). Also, an evacuation model with no or less behavioral perspective and homogenous groups (like the one applied in our calculation) might benefit from not implementing these delay times given the inherent focus on group behavior rather than individualism. After all, pre-movement times are a simplification of the behavioral process due to an emphasis on the time delay rather than on the decisions and actions of occupants responding to the evacuation itself (Kuligowski, 2008). The second assumption implies that occupants are homogenously modeled without any personal decision making and behavior. People will continuously keep moving in the direction of their choice, only hindered by co-occupants on the same path influencing the flow density. In current evacuation modeling research, a dichotomy exists between behavioral (individualistic) and non-behavioral (group) modeling of occupants (Gwynne et al., 1999; Kuligowksi, 2008). This assumption and our calculation are in accordance with the homogenous group modeling. As discussed in Section 4.3.1, there is no consensus yet on a comprehensive methodology for modeling human behavior, with current models using significant simplifications of the behavioral processes during evacuations (Kuligowski, 2008). Their implemented behavior is either predefined by the user or based on inconsistent prescribed information entirely dependent on the user's expertise (Kuligowski, 2008). Also, behavioral modeling would significantly increase the complexity and computational requirements, and differentiations between randomly imposed behaviors are not crucial to grasp differences in quality of access of exits. For these reasons, we opted to leave behavioral decision patterns out of the calculation methodology and only focus on the actual movement of the occupants influenced by density variations due to co-occupants' movement. The third assumption recalls the focus of the model to non-disabled persons making it more general than some of the current indoor accessibility measures only focusing on disabilities (Section 4.2.2).

4.3.2.3 Network flow calculations

The calculation of *exitability* is defined by the flow of building occupants departing from the central node in each room. Their movement speed is determined by the group density, which can change over time, and by the maximum capacity constraints of each edge, which in turn are determined by the minimum width of the passageways. This minimum width is used as approximation of the maximum possible walking space since in reality groups of people spread out to the maximum available space (Yuan et al., 2009). The crowd density varies with time and location according to the non-uniform distribution of occupants. The formulas to calculate the speed are based on the pedestrian flow model of Predtechenskii and Milinskii (1978). Since the movement speed of people not appears to have changed over the years, this flow model can be and is still widely applied in other models (Fahy & Proulx, 2001).

The crowd density (D) of a stream of people is calculated in this model as a fraction of the number of people (N) and the personal space area (f) on the occupied space (Figure 4-2 and Equation 4-1). The personal space area is the area in which no other person will move. It is based on the mean dimensions of an adult in mid-season street dress (Fahy, 1994) and has a fixed value of 0.113m². The stream is calculated for a certain occupied area, limited by the maximum width of personal interaction (δy) and the maximum length of possible interaction for a person (δx). The interaction width can be taken approximately as the maximum width without obstacles of the spatial unit. The length of occupant interaction is set as 1m and records as such the number of people moving in the 1m area around the occupant.

$$D = N\, f / \delta x\, \delta y \qquad (\mathrm{m}^2/\mathrm{m}^2) \qquad \text{(Equation 4-1)}$$

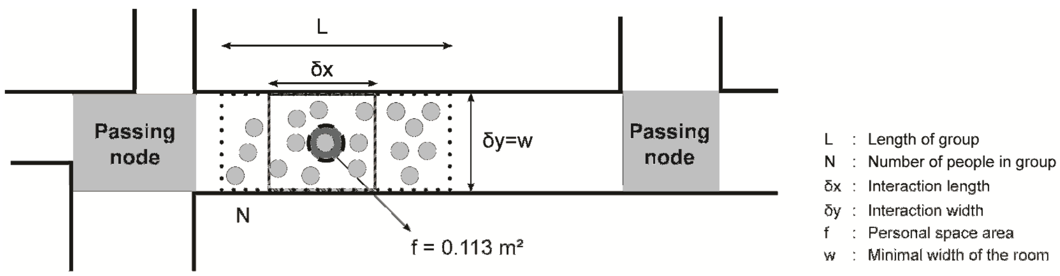

Figure 4-2 Parameters in the pedestrian flow model

In non-emergency situations, the mean velocity in open horizontal space (V) can be calculated, using Equation 4-2, as a function of the crowd density based on observations of people walking (Predtechenskii & Milinskii, 1978):

$$V = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \quad \text{(m/min)}$$
$$\text{for } 0 < D \leq 0.92 \qquad \text{(Equation 4-2)}$$

The crowd density has an optimal value of 0.92m²/m², although higher values are accepted. However, empirically this is used as the maximum allowed density (Fahy, 1994). In emergencies, the movement speeds (V_e) are somewhat different with the same densities, since people are reacting more anxiously. Equation 4-3 shows the relationship between these two velocities, differentiating between movement through openings and in horizontal space, and movement on stairs (Predtechenskii & Milinskii, 1978):

$$V_e = \mu_e V \quad \text{(m/min)} \qquad \text{(Equation 4-3)}$$
where $\mu_e = 1.49 - 0.36D$ (for horizontal paths and through openings)
$\mu_e = 1.21$ (for descending stairs)

Queuing is handled by combining different groups when they meet each other, reducing their velocity and adding waiting times. As a result the maximum capacity on each edge may be reached.

4.3.2.4 General workflow of the model

In our flow-based movement model, occupants move from a room to the closest exit – that is along Dijkstra's (1959) shortest path (distance-based). However, it would also be possible to use the most familiar route or the shortest time to the exit, but this implementation is left for future work. The model does not allow dynamic changes in exit choice, which implies that all occupants follow the physically shortest path leaving personal decision making unconsidered.

The main parameters in the flow calculation are *Path*, *NodeMovement* and *PassingNodeMovement* objects[4]. Per room (and thus source node) a *Path* object is created storing the shortest path to the selected exit for this room. A *NodeMovement* object represents a group of people moving along an edge from start node to end node. This makes it easy to obtain the current position

[4] The different object classes are indicated with a capital letter and in italic. The methods are in bold.

of each group (per time and location) during the evacuation. It also allows modeling the flow of people within a certain passing node over time. Every passing node stores a *PassingNodeMovement* object containing lists of *NodeMovements* with the arrival times and waiting times for every source node passing through this passing node.

The main idea behind the flow model is the merging and moving of the crowd to their closest exit taking into account in- and outflows of adjacent nodes. The main method **Algorithm** loops through all paths starting with the path with the shortest distance to the selected exit. With every selected path, the method **EdgePassing** runs over the entire path from its source node to the selected exit. In this loop, every subsequent edge between two nodes is selected, starting with the source node and ending when the exit node is reached. Within this method, flows are checked for incoming and outgoing groups to and from the start node of the edge. Then, the population is moved over the selected edge from start node to end node.

The incoming flows of groups of people coming from adjacent nodes are continuously calculated in every passing node using the **IncomingFlows** method (Algorithm 4-1 and Figure 4-3). This method checks for every edge arriving in the passing node whether groups of people can possibly interact with the currently selected arriving group. Only groups arriving before or together with the selected group can interrupt its movement. Groups arriving earlier in the selected passing node have no direct impact on the selected *NodeMovement* in incoming times. However, they can still have a delaying effect on the outflow of the selected *NodeMovement*. Then the program recursively checks for subsequent *NodeMovements* along the same path until the resulting time frames overlap. Overlap is treated through attaching waiting times or merging both groups, depending on the relationship between both timeframes. The procedure stops when all possible interacting flows are calculated in the selected passing node.

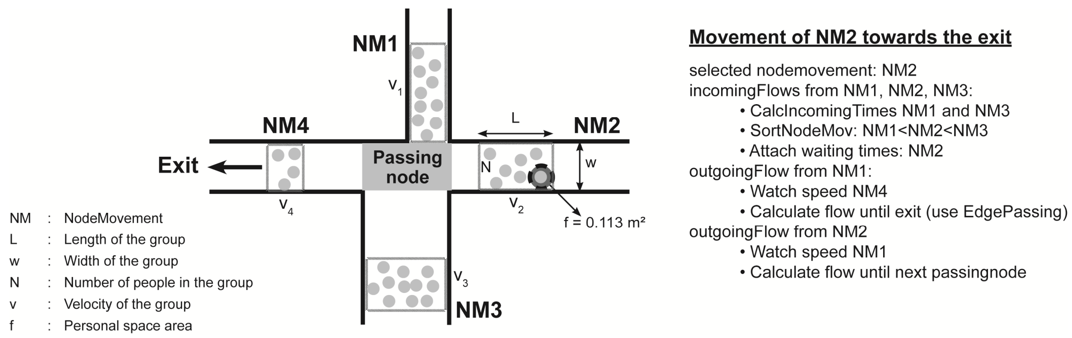

Figure 4-3 Movement in a *PassingNode*

```
IncomingFlows (PassingNode selectedPN, NodeMovement selectedNM)

FOR EACH (NM from NMList arriving in selectedPN)
    tempNM = NMlist(i)

    IF (tempExit == selectedExit AND temppreviousPN ≠ selectedpreviousPN
        AND tempSource == tempPrevious)
        CalculateMovingTimes (previousPN to selectedPN for tempNM)

        IF (temptimes<selectedtimes)
            CalculateIncomingFlows (previousPN of tempNM, tempNM)
            SortNodeMovementsOnTimeFrameSmalltoLarge (previousPN)
            AttachWaitingTimes(NMlist)

            FOR (NM from previousPN with tempEndTimes>selectedStartTimes)

                IF (selectedStartTimes<tempStartTimes)
                    AttachWaitingTimes (tempNM)
                ELSE IF (selectedStartTimes>tempStartTimes)
                    AttachWaitingTimes (selectedNM)
                ELSE
                    Merge both groups together


Variables

NMList        ArrayList of all NodeMovements in a certain Passing Node
tempNM        temporary NodeMovement
selectedNM    selected NodeMovement
previousPN    previous PassingNode
selectedPN    selected PassingNode
```

Algorithm 4-1 Algorithm of the IncomingFlows in a selected *PassingNode*

The outgoing flow from this selected passing node can be interrupted by preceding *NodeMovements* moving at a slower speed, which can result in catching up and overtaking of groups (Figure 4-3 and Algorithm 4-2). All *NodeMovements* will form a queue of consecutive groups moving at the speed of the first group. The **OutgoingFlows** procedure calculates this by iterating over all *NodeMovements* arriving in the selected passing node until the originally selected *NodeMovement* is reached. If an overtaking risk exists within the movement over the selected edge, the speed is adapted to that of the predecessor. This group is then selected and the method **EdgePassing** is invoked moving this group further towards the exit. Afterwards, the **OutgoingFlows** method will pick up from the originally selected *NodeMovement* moving the group to the next passing node.

At the end of the **OutgoingFlows** method, the selected group will be assigned a certain evacuation time. The whole process starts over again by selecting the next *Path* object in the method **Algorithm** until all paths are scanned and the different evacuation times are known.

```
OutgoingFlows (PassingNode selectedPN, PassingNode nextPN)

WHILE (NM from NMList arriving in selectedPN ≠ selectedNM)
    select NM(i) in NMList as part of Path(i)

    IF (Path(i) has not reached the exit)
        SortNodeMovementsOnTimeFrameLargetoSmall (nextPN)
        CalculateMovingTimes (selectedPN to nextPN for NM(i))

        IF (NM(i) and firstNM of sortedList have similar previousPN AND
            NM(i)<firstNM)
            adjustVelocity of NM(i) to velocity of firstNM

        IF (Path(i) ≠ selectedPath)
            selectedPath = Path (i)
            edgePassing (Path(i))


Variables
NMList              ArrayList of all NodeMovements in a certain PassingNode
firstNM             NodeMovement currently last arriving in nextPN
selectedNM          selected NodeMovement
nextPN              next PassingNode
selectedPN          selected PassingNode
selectedPath        selected Path
edgePassing(Path)   main method looping through every edge of a Path until
                    the exit has reached
```

Algorithm 4-2 Algorithm of the OutgoingFlows in a selected *PassingNode*

4.4 CASE STUDY

The goal of this case study is to show the capabilities of *exitability* for spatial analysis of indoor environments and its added value of interpreting inter-room differences in *exitability*. Questions to be answered include (but are not restricted to): How accessible is a certain exit? What is the least accessible area in the building? How does the *exitability* change with changing population? and How many people can exit the building within 5, 10 or 15 min?

For this analysis, an existing building (S9) on the University Campus De Sterre in Ghent (Belgium) was used. This four-story building has three main exits and one evacuation exit. The main exits are situated on opposite sides of the longest side of the building with two exits closely connected (Exit 2 and 3). The building consists of four main lecture halls, three computer rooms, two smaller lecture rooms and many offices. These different compartment types correspond to a varying population density. Staircases, exits and corridors have no population since they are mainly used as connectors for movement between the various compartments. Rooms are one to seven person offices while the lecture halls can accommodate between 50 and 300 people each. The total maximum population of the building is 1446 occupants. Figure 4-4 visualizes the spatial location of the various compartments with their corresponding population. For this case study, the building was digitized and transformed into a dataset of nodes with id, room number, room type and population; and edges, with id, start node, end node, cost of the edge, minimal passage width and type of the link . The dataset consists of 213 nodes and 470 unidirectional edges.

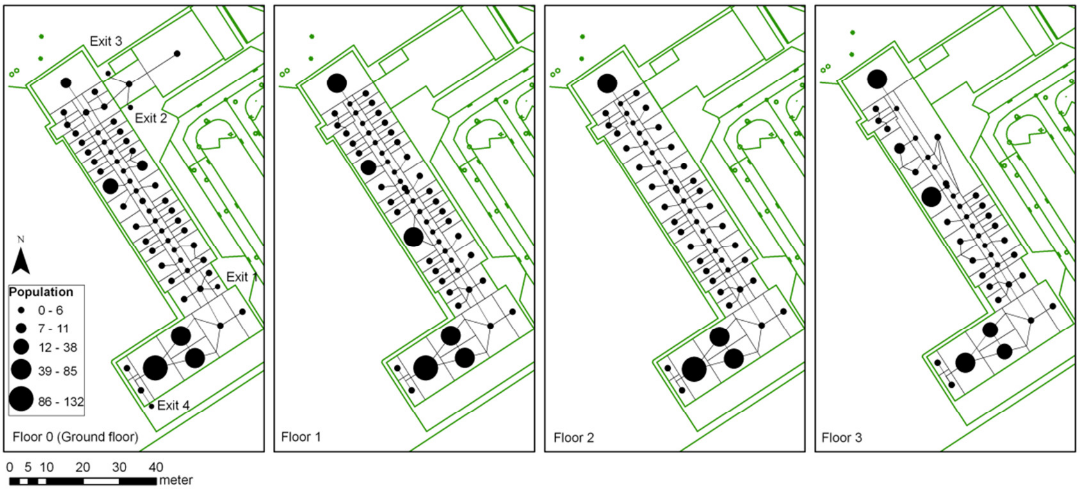

Figure 4-4 Population distribution in the base scenario

We will discuss two separate issues: a basic scenario with various questions with regard to the buildings *exitability* and secondly some scenarios where we change the original dataset to see how changes in environmental parameters affect the *exitability* of the building.

4.4.1 Spatial analysis of the base scenario

In this scenario, the building is completely occupied with every compartment having its maximum number of building occupants. All four exits are available for evacuation with the exit choice for the single building occupant based on the shortest distance of the relevant room to the closest exit node. Table 4-1 shows the population load of each exit. Exit 2 and 3 are joined since no differences in *exitability* can be detected between both exits due to their opposite location. From this table, it can be concluded that overall a major discrepancy exists in the load of the three exits as exit 1 handles the majority of the total building occupants (more than 50%).

Exit choice	# populated compartments	Population	% of population
Exit 1	67	779	53.87
Exit 2 and 3	33	267	18.46
Exit 4	4	400	27.66

Table 4-1 Distribution of the population over the different exits

4.4.1.1 How exitable is this building? What are the least accessible areas?

Figure 4-5 shows the result of the *exitability* calculations for the building with the individual *exitability* values per room. The spatial distribution of arriving times shows that the best *exitability* can be found in the rooms adjacent to the exits and the stairs, while more distant rooms have much higher values. The highest *exitability* values are found on the top floor and in the main lecture halls. These areas prove to be the most vulnerable in case of evacuations and require special attention. Some rooms have considerably higher *exitability* values than their neighboring rooms, due to higher population rates and queuing. For example, the offices in the main corridor on floor 1 have a similar population and distance to the exit but some rooms show worse *exitability* values due to congestion. The total maximum *exitability* is 626 seconds for the main lecture hall on the first floor. The average *exitability* is fairly low with 180 seconds with a standard deviation of 147. Figure 4-6 shows the percentage of people who are able to leave within a range of 1 to 10 minutes. It is demonstrated that 50 percent of the building occupants can reach the exit within 5-6 minutes and 95% of the building can be evacuated within 10 minutes.

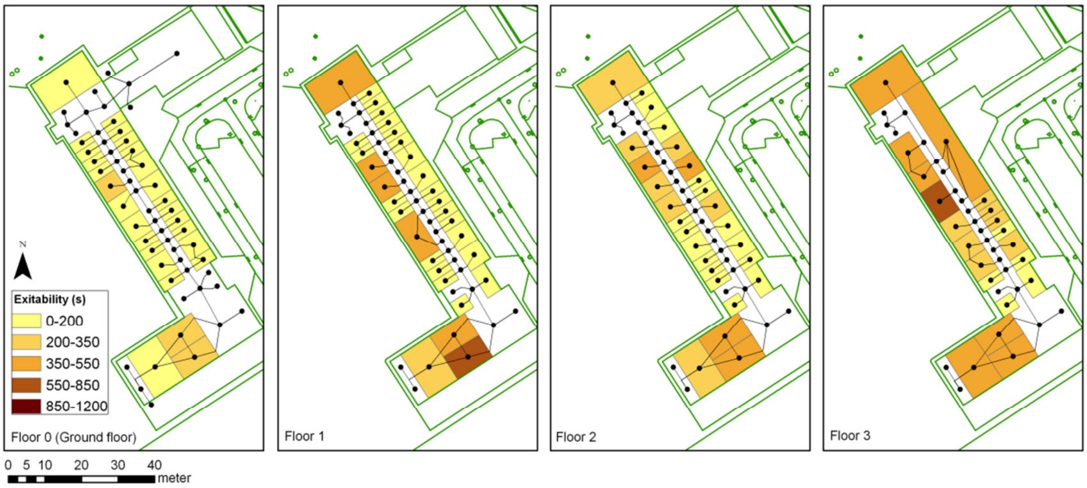

Figure 4-5 *Exitability* values for evacuation towards all exits in the base scenario

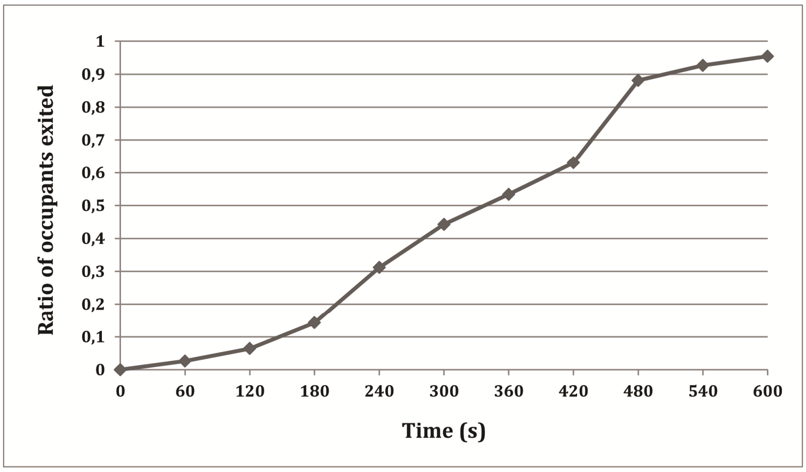

Figure 4-6 Ratio of people able to exit within a certain time limit

4.4.1.2 What is the influence of distance on exitability?

Previous results showed that higher floors have higher *exitability* values. This proves to be a logical result due to the direct relationship between the physical closeness of those rooms to their selected exit and the times needed for evacuating. Figure 4-7 supports this claim with an almost linear relationship between distance and exit times for some source nodes, clearly subdivided per floor (solid ellipses). Rooms on higher floors have considerably higher *exitability* values given the flocking effect near stairs along the path to the exit. In fact, those stairs can be seen as intermediate exit points and the effect of walking towards stairs is similar as the effect of walking to an exit.

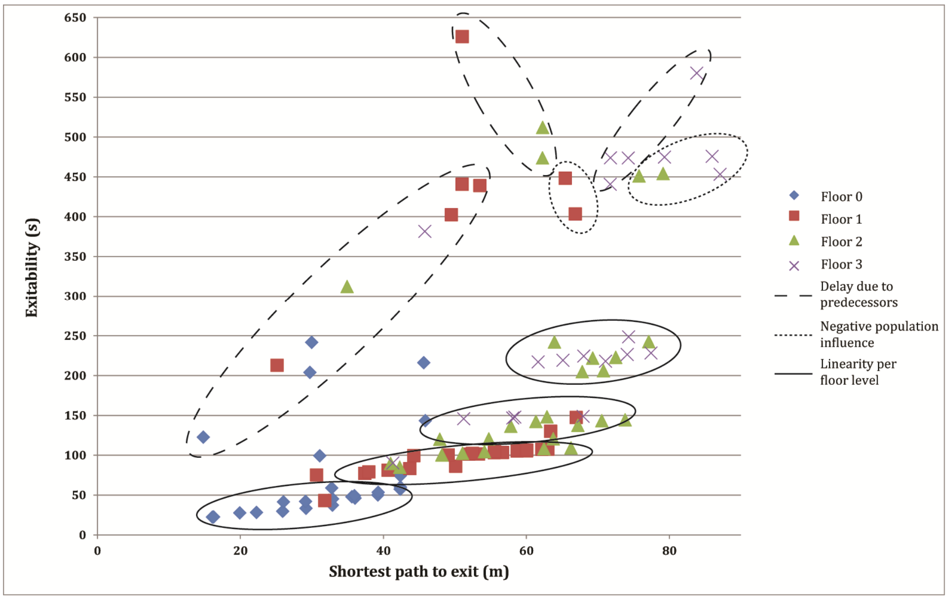

Figure 4-7 Comparison between shortest path and *exitability*

However, several outliers create a more nuanced view. Higher floor levels show more variability in values per level (e.g. more differences in colors in Figure 4-5). This supports the spatial pattern of *exitability* values with fast evacuations for rooms close to the stairs and slower *exitability* for rooms in the middle of the central corridors (delayed by slower groups and main lecture halls). Also, the dashed ellipses in Figure 4-7 group source nodes with high population densities (e.g. the main lecture rooms on the south end of the building), showing higher *exitability* values than expected due to a slower movement of each group. This slackened movement also has a delaying effect on subsequent groups of people from adjacent source nodes. The dotted ellipses show these rooms which tend to be located in the middle of the central corridors and are hindered by movement of the rooms closer to the stairs. They have higher *exitability* values than expected given their population and location. In contrast, some rooms have low *exitability* values even with long shortest paths. This positive influence is caused by low population values and unhindered movement to the exit given their immediate closeness to the stairs (no congestion due to predecessors).

4.4.1.3 How accessible are the exits?

The distribution of the *exitability* values differs with the exit choice (Figure 4-8). Most rooms are closest located to exit 1, resulting in on average rather low *exitability* values. This means that rooms evacuating through exit 1 are able to get out in a fairly fast way, even with a heavier load on this exit. The statistical values for exit 2 show a reasonably concentrated distribution with slightly higher *exitability* values. Only four rooms (i.e. main lecture rooms) use exit 4 in case of an evacuation, resulting in less congestion even with the high occupancy rate. The average *exitability* rate for the entire building is 330 seconds. Occupants exiting through exit 1 and 2 have 5-10% higher averages, while the average *exitability* for exit 4 is 20% lower than the average for the building. This lower value is influenced by the reduced number of compartments evacuating through this exit and a smoother occupant movement. Movement to exit 2 is the most unfavorable given the fact that a reduced occupant load on this exit results in higher *exitability* values.

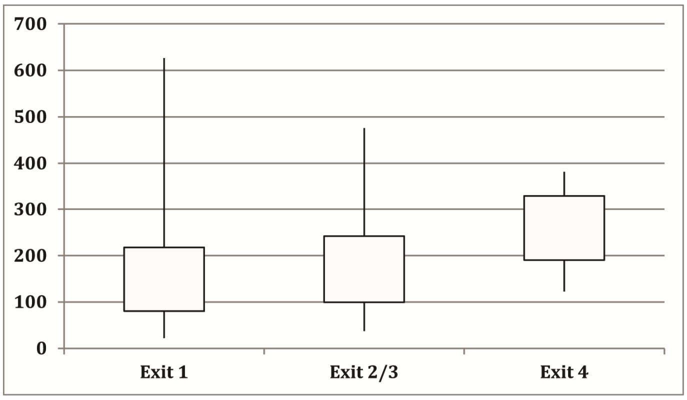

Figure 4-8 Distribution of *exitability* over the various exits in the base scenario

4.4.1.4 How does the exitability change with only a single exit available?

In emergency situations, some exits might be unavailable for evacuations. This spatial concentration of exit possibilities leads in the extreme case to only one usable exit which in turn results in a drastic decrease in available exit routes. Since the data set contains three building exits, this scenario is subdivided in three cases, one for each exit. Figure 4-9 shows the statistical distribution in each case and for comparison reasons also the distribution of the base scenario with all exits in use. Figures 4-10, 4-11, 4-12 show the *exitability* results per available exit. From these visualizations, it can be concluded that a decline in available exit possibilities with the same spatial population distribution has a major influence on the resulting *exitability* values.

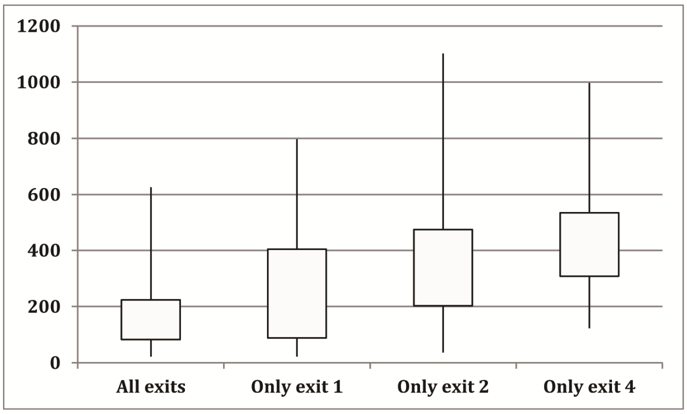

Figure 4-9 Distribution of *exitability* over the various exits with only 1 exit available

The results show that evacuations along exit 1 run quite smoothly. This is similar to the base scenario where already many occupants usually use this exit. As a result, the extra load on this exit (i.e. from occupants normally using exits 2 and 4) has no significant effect on the total *exitability* of the building. Additionally, exit 1 has the largest opening width which accelerates the evacuation process even more. However, the *exitability* values are in comparison with the base scenario on average higher and with a greater internal distribution (Figure 4-9). A similar view can be detected for evacuations along exit 4, although the effect is worsened. Occupants from the main lecture halls still have immediate access to the exit (due to its physical closeness), but a slackening effect occurs to the groups following. This is a result of the slower processing of the large groups from the lecture halls and the considerable smaller door width of the exit. This in turn affects the *exitability* values of rooms further removed from the exit queuing behind the preceding slower groups. The scenario with only exit 2 available is the most alarming for lecture halls opposite to the exit. Occupants from those rooms have to walk considerably further and are impeded on their way to the exit by predecessors and smaller opening and corridor widths. The distribution of the different values are however similar to the other scenarios with higher base values (Figure 4-9).

Second, Figures 4-10, 4-11 and 4-12 show that the *exitability* values differ over the multiple floor levels, with the lowest value on the ground floor and the highest values on the top floor. This is consistent with the direct relationship between distance and evacuation time. However, the data show a striking phenomenon with the more unfavorable *exitability* values from floor level 1 compared to those from level 2. This is attributed to the initial congestion originating from occupants from level 1, while occupants on level 2 have to traverse a longer distance and at the time arriving on level 1 already have to deal with less congestion and hinder from predecessors.

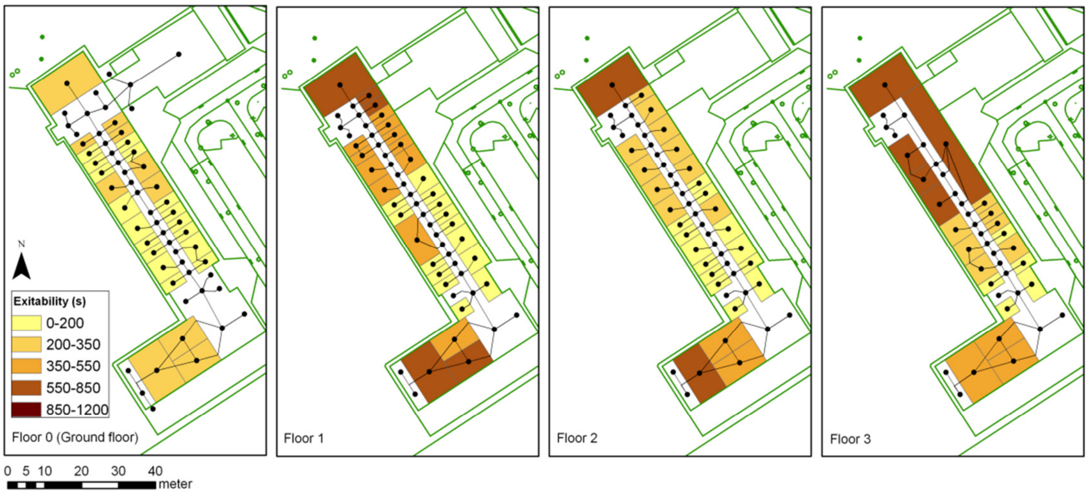

Figure 4-10 *Exitability* values for evacuation towards exit 1

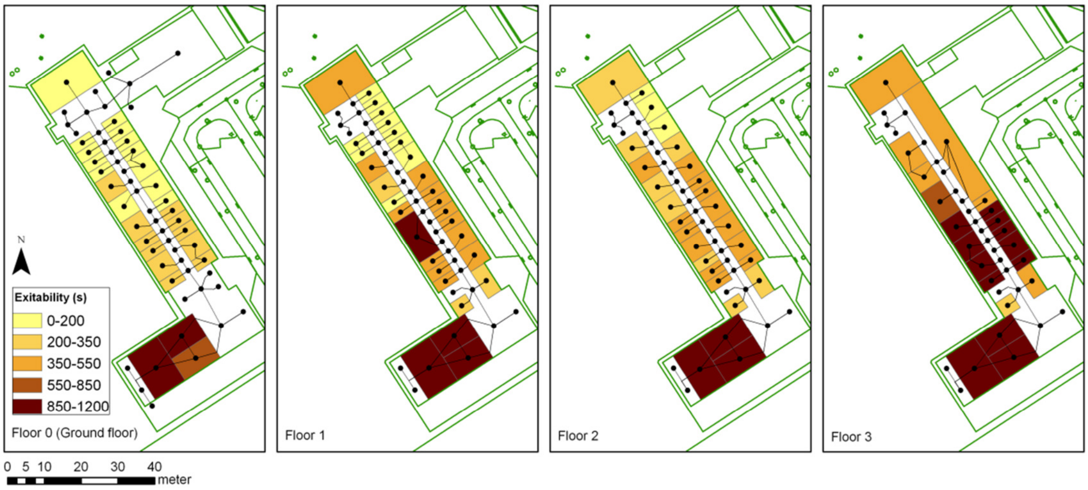

Figure 4-11 *Exitability* values for evacuation towards exit 2/3

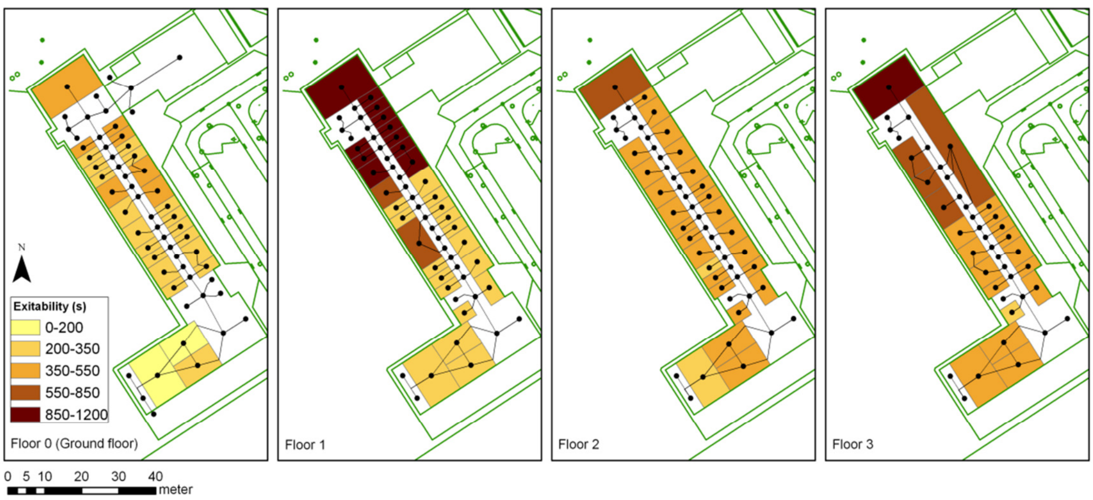

Figure 4-12 *Exitability* values for evacuation towards exit 4

Third, rooms with an average occupancy rate and an immediate connection to the stairs hold higher *exitability* values than rooms further away. However, the occupancy rate may result in a deteriorating effect (e.g. the main lecture rooms in the south).

4.4.2 Effect of population and corridor width on exitability

4.4.2.1 How does the population distribution influence exitability?

The capability of the building is tested for coping with a drastic population decrease which corresponds to reality since during holidays the lecture and computer rooms are not used. Compared to the base scenario the whole population is more than 5 times smaller with only occupants in the offices resulting in a total of 248 persons.

Figure 4-13 shows that the *exitability* values decrease with decreasing occupancy. All rooms have considerably lower *exitability* values, with inter-room differences attributed to disparities in physical distance and the slight difference in occupancy rate for some rooms. The result also shows a more linear relationship between distance and *exitability* values compared to the base scenario (although slower movement on stairs and discrepancies in occupancy rates impedes perfect linearity).

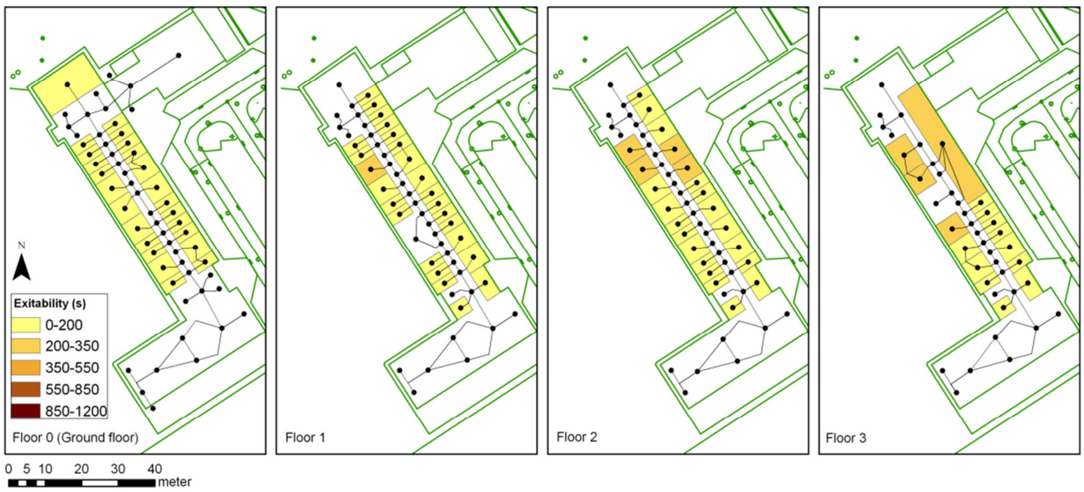

Figure 4-13 *Exitability* values for evacuation towards all exits with decreased population

4.4.2.2 How does a decreased corridor width change exitability?

The corridor width of the main corridors on the different floor levels was narrowed from 4m to 2m to be more realistic with the presence of cupboards preventing the complete use of the corridor. This test allows examining the influence of the physical building characteristics on *exitability*. Figure 4-14 shows that the effect of smaller corridor widths is minimal on the *exitability* values in this case study. This can be explained by the limited number of occupants that is affected by this change in corridor width along their path to the exit. As shown previously, the main lecture halls with high occupancy rates can considerably deteriorate the evacuation process. However, half of the building occupants in this scenario have the same evacuation path characteristics as in the original context. In this case, only some rooms are affected with a slightly higher *exitability,* and this mainly on floors 2 and 3. After all, they have to travel the longest path and are more sensitive to congestion and queuing behind slower predecessors. The other trends described above are similar for this scenario with major distance influence and primarily congestion from highly populated rooms.

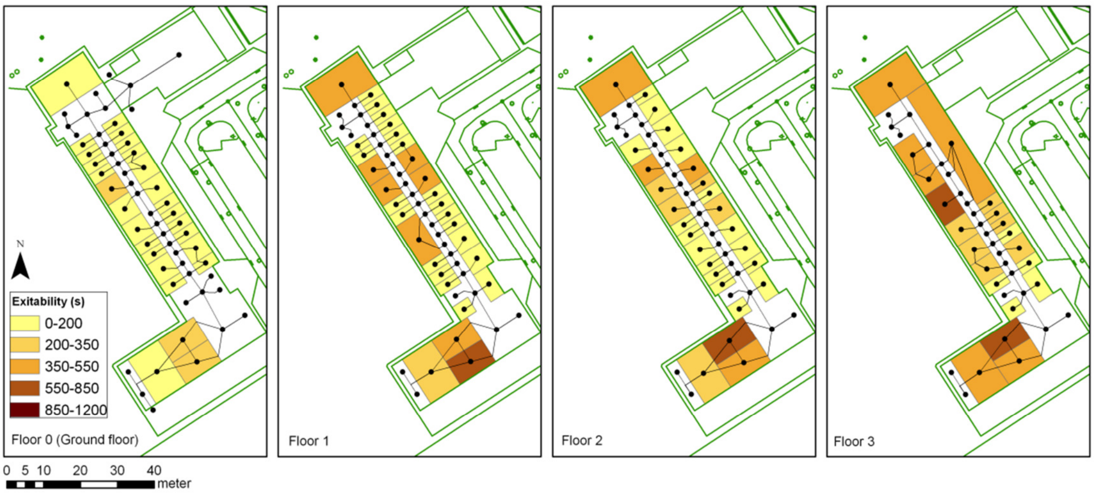

Figure 4-14 *Exitability* values for evacuation towards all exits with decreased corridor width

4.5 Conclusion

In this paper, we have put forward a new indoor accessibility measure, termed *exitability*, to analyze the accessibility of exits from within the various spatial building units (room-to-exit accessibility). Since *exitability* portrays the easiness with which occupants can reach building exits, it focuses on the movement of the building occupants from their internal building location to the exit. The calculation methodology is based on flow models and is illustrated in a case study regarding the efficiency of a spatial building design and room occupancy on the ease to evacuate a building. The results obtained in the case study indicate the importance of the physical distance on *exitability*. The further physically removed from an exit, the higher the chances that the *exitability* will be worse compared to rooms nearby. This effect is however modulated by the flow size of building occupants. In particular, congestion or extended population movement results in higher *exitability* values than expected on grounds of spatial proximity alone.

For the building considered in the case study, no significant problems were detected with regard to the quality of access of the various rooms (e.g. all rooms have within 10min access to an exit). While the results of course specifically apply to this particular building with a certain population distribution and building context, it is important to highlight the more general advantages and possibilities with calculating *exitability*. First, comparing room values of *exitability* can result in showing major discrepancies between rooms or floor levels which show the quality of the building design. For example, it allows one to see how changes in parameters like corridor or door width or the position of exits might affect the overall *exitability* of a building and show the need of changing design configurations. Also, the accepted population distribution can be analyzed with regard to the exit load or the spread per floor level, which can result in changes to allow a more optimal *exitability*. In addition, clusters of rooms with worse exitability can be detected which might be not noticeable at first sight. Furthermore, several buildings can be compared in terms of overall *exitability* to reveal which buildings allow to be cleared more easily.

The contribution of our work to the academic literature is at least two-fold. First, with respect to evacuation modeling, we have demonstrated the possibilities of spatially analyzing a building's feasibility of dealing with emergency situations. Second, *exitability* quantifies a qualitative relationship of access. As such, it can be used to optimize space-time decisions for users within buildings. The extension towards indoor environments is in line with the gradual refocus of geospatial applications towards the three-dimensional indoor built environment. *Exitability* also deals with the constraints of indoor environments. Previous indoor accessibility measures have been developed either for pointing out mobility issues for the physically impaired or for spatial analysis. Our work fits in with the latter, but tries to calculate accessibility not based on solely geometrical parameters, but also on actual movements of people.

As future work, an extension to this *exitability* measure can be considered, where *exitability* is calculated under non-emergency situations and even with different destination points. In that case, *exitability* is closer defined to the traditional accessibility measures. Adaptation to this concept opens the world to analysis of accessibility in all situations. As such, we believe that we made valuable contributions with our research to a better understanding of the intricacies of indoor environments.

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5

EVALUATING SUITABILITY OF THE LEAST RISK PATH ALGORITHM TO SUPPORT COGNITIVE WAYFINDING IN INDOOR SPACES: AN EMPIRICAL STUDY

Modified from: VANCLOOSTER, A., OOMS, K., VIAENE, P., FACK, V., VAN DE WEGHE, N. & DE MAEYER, P. 2014. Evaluating suitability of the least risk path algorithm to support cognitive wayfinding in indoor spaces: An empirical study. Applied Geography, 53, 128-140.

ABSTRACT

Over the last couple of years, applications that support wayfinding in indoor spaces have become a booming industry. Finding one's way in complex 3D indoor environments can still be a challenging endeavor, partly induced by the specific indoor structure (e.g. fragmentation, less visibility, confined areas). Appropriate algorithms that help guide unfamiliar users by providing 'easier to follow' route instructions are so far mostly absent indoors. In outdoor space, several alternative algorithms exist, adding a more cognitive notion to the calculated paths and as such adhering to the natural wayfinding behavior (e.g. simplest paths, least risk paths). The aim of this research is to extend those richer cognitive algorithms to three-dimensional indoor environments. More specifically, the focal point of this paper is the application of the least risk path algorithm, i.e. an algorithm developed to minimize the risk of getting lost, to an indoor space. This algorithm is duplicated and extensively tested in a complex multi-story building by comparing the quality of the calculated least risk paths with their shortest path alternatives. The outcome of those tests reveals non-stable results in terms of selecting the least risky edges in indoor environments, which leads to the conclusion that the algorithm has to be adjusted to the specificities of indoor space. Several improvements for the algorithm are proposed and will be implemented as part of future work to improve the overall user experience during navigation in indoor environments.

5.1 INTRODUCTION

Finding one's way in unfamiliar environments can sometimes turn out to be a challenging endeavor as people get disoriented and lose their way. Golledge (1999) defines being lost as 'a state which occurs when the wayfinding process fails in some way'. In behavioral and cognitive sciences, navigation processes have already been widely studied (both indoor and outdoor) with navigation typically defined as cognitively consisting of locomotion and wayfinding components (Montello, 2005). Wayfinding is thereby the process of determining and following a route between origin and destination and is often guided by external aids (Golledge, 1999). In the context of this paper, we focus on these guidance aids that can improve wayfinding and not on the cognitive act of wayfinding itself.

The setting for our research is limited to indoor spaces as wayfinding research in indoor environments has repeatedly demonstrated the challenges of successfully performing navigation tasks in a complex three-dimensional space (e.g. disorientation after vertical travel, less visual routing aid, deficient cognitive map creation) (Hölscher et al., 2009). Appropriate guidance to simplify the act of wayfinding is hereby a crucial factor, especially for unfamiliar users that will rely more heavily on external indoor navigation aids. Such navigation aids come in various forms, but all contain some kind of model of space enhanced with routing instructions and localization technology (Nagel et al., 2010). In the last decade, a wide variety of indoor navigational models (Brown et al., 2013) have been developed, but a general framework still has to reach full maturity (Nagel et al., 2010). Apart from these typical network models based on traditional graph theory, the Space Syntax society opened up research on aspects of visibility and connectivity in spatial building configurations and their impact on pedestrian movement (e.g. Turner et al., 2001; Parvin et al., 2007). These models will however not be considered in the current research.

Beside navigational models, navigation guidance also relies on appropriate and accurate algorithmic support. Algorithms for 3D indoor navigation are currently restricted to Dijkstra (1959) or derived shortest path algorithms (e.g. Kwan & Lee, 2005; Thill et al., 2011). However, the results of those algorithms often exhibit non-realistic paths (e.g. using complex intersections, avoiding main walking areas) in terms of what an unfamiliar indoor wayfinder would need, to navigate a building comfortably. To date, few researchers have attempted to approach algorithms for indoor routing differently, for example incorporating dynamic events (Musliman et al., 2008), or modelling evacuation situations (Atila et al., 2013; Chapter 4). In contrast, for outdoor environments, several 'cognitive' algorithms (e.g. paths minimizing route complexity (Duckham & Kulik, 2003; Richter & Duckham, 2008), hierarchical paths (Fu et al., 2006)) have been developed that add a more qualitative description to routes by using a more cognitive cost heuristic than traditional shortest path algorithms (Table 5-1).

Algorithm	Cost heuristic (minimization criterion)
Shortest path algorithm (e.g. Dijkstra, 1959)	Path length
Hierarchical shortest path algorithm (Fu et al., 2006)	Computational time
Simplest path algorithm (Duckham & Kulik, 2003)	Intersection complexity (number of edges + intersection type)
Simplest path algorithm (Mark, 1986)	Path length + intersection complexity
Simplest instruction algorithm (Richter & Duckham, 2008)	Intersection complexity + spatial chunking
Least risk path algorithm (Grum, 2005)	Path length (50%) + Risk value (50%)

Table 5-1 Comparison of several cognitive algorithms and their cost heuristic

These 'cognitive' algorithms have the aim to simplify wayfinding by providing routes that are easier to follow, more intuitively correct, and in general more adhering to how people conceptualize routes to unfamiliar users (Tsetsos et al., 2006). Several cognitive studies have indeed indicated that during routing, humans value equally as much the form and complexity of route instructions as the total path length (Duckham & Kulik, 2003). These algorithms have not yet been implemented in indoor cases, although the need for cognitively rich algorithms is even more pronounced in indoor space compared to outdoors. As such, the main goal of our research is to translate existing outdoor 'cognitive' algorithms to an indoor environment and provide indoor route calculations that are more aligned with indoor wayfinding behavior. In a different part of our study, the implementation of the simplest path algorithm in indoor environments is being considered.

However, this paper explicitly focuses on the implementation and testing of the least risk algorithm of Grum (2005) in a three-dimensional indoor environment. The least risk path algorithm, minimizing the risk of getting lost, is especially interesting for indoor application as the structure of indoor spaces induces more getting-lost episodes (Hölscher et al., 2006). An algorithm lowering the probability of getting lost by taking less complex paths could as such prove valuable in reducing indoor wayfinding difficulties. Specifically, we want to investigate whether the results of the least risk path algorithm have the same connotation and importance in indoor spaces as in its original outdoor setting. Also, the least risk path algorithm is analyzed for its applicability in providing route instructions that adhere better to the natural wayfinding behavior of unfamiliar users in indoor space.

The remainder of the paper is organized as follows: Section 5.2 elaborates on the definition of risk in the algorithm and for indoor wayfinding; in Section 5.3, a case study is presented to evaluate the algorithm for its suitability in supporting indoor cognitive routing; Section 5.4 discusses the conclusions from our study and possible improvements for the algorithm.

5.2 DEFINING THE RISK OF GETTING LOST IN INDOOR WAYFINDING

5.2.1 LEAST RISK PATH ALGORITHM

The least risk path algorithm as described by Grum (2005) calculates the path between two points where a wayfinder has the least risk of getting lost by selecting all edges and intersections with a minimal risk value. This risk value is measured at every intersection and is defined by the cost for taking a wrong decision at that intersection. The algorithm assumes that (i) the person taking the path is unfamiliar with its environment, and (ii) when taking a wrong path segment, the wayfinder notices this immediately and turns back at the next intersection (Grum, 2005). While these assumptions might be quite strict, Grum (2005) also acknowledges that the algorithm needs to be tested for its representativeness of the actual behavior of users.

The formula for the calculation of the risk value at intersection i and the total risk of an entire path p is as follows:

$$Total\_Risk(p) = \sum PathLengths + \sum RiskValue(i) \qquad \text{(Equation 5-1)}$$

$$RiskValue(i) = \frac{2 * \sum PathLength\_Wrong\_Choices}{No\_Possible\_Choices} \qquad \text{(Equation 5-2)}$$

Equation 5-2 indicates that the risk value is dependent on the number of edges converging on the decision point, combined with the length of each individual segment and is as such a measure of average length of a wrong edge at that intersection. The multiplication by two points at the idea that, when taking a wrong edge, the user is supposed to return immediately along the same edge, traversing that edge twice. By defining the risk value in this way, the algorithm favors paths with combined long edges and easy intersections. The formula for the total risk of a path (Equation 5-1) balances the sum of all intersection-based risk values with the length of the actually taken edges. Both elements contribute in this case equally to the total risk of a certain path.

The algorithmic structure of the least risk path algorithm is similar to Dijkstra's shortest path algorithm (1959) with a continuous loop over all nodes including the following three consecutive steps:

(1) Detect the next smallest node
(2) Change the selected node to the next smallest node
(3) Adjust cost calculation for adjacent nodes (Algorithm 5-1; Figure 5-1)

However, in the third step, the least risk path differs significantly from the Dijkstra algorithm since the cost value is not only dependent on the length of the edge but also on the risk value of each intersection that is passed which in turn is dependent on the previous route taken and the length of its adjacent edges. The following steps in the **AdjustCostCalculation** method are consecutively executed:

```
Calculate the number of edges leaving from selected node and select each
edge successively

CASE A (Endnode of selected edge has not been selected):
       STEP 1: Calculate total risk values for endnode based on all
               possible routes arriving in selected node
       STEP 2: Store the minimal value by comparing it with the currently
               stored value in endnode and add the node to the least risk
               path

CASE B (Endnode of selected edge has been selected BUT adjacent nodes have
not been selected):
       STEP 1: Calculate the number of edges leaving from endnode and
               select each edge successively
       STEP 2: Calculate total risk values for endnode based on all
               possible routes arriving in selected node and the
               connection between the selected node and its adjacent node
       STEP 3: Store the minimal value by comparing it with the currently
               stored value and add the node to the least risk path
```

Algorithm 5-1 AdjustCostCalculation method for adjacent nodes

Figure 5-1 shows an example network with two consecutive situations during the execution of the 'adjust cost calculation'. Figure 5-1 (left) illustrates the case where Node4 is selected as next smallest node in the network. Node4 has a least risk path of [Node0-Node2-Node4]. From Node4 all edges leaving this node (i.e. edges a, b, c) are consecutively chosen and new total risk values are calculated for their respective endnodes (i.e. Node3, 5, 6). To calculate the total risk value for Node5 with path [Node0-Node2-Node4-Node5], the risk value of Node4 together with path length b is added to the total risk value of Node4. Node5 and Node6 are in this case calculated for the first time (Case A). Node3 has been calculated before with path [Node0-Node1-Node3]. These previous total risk values are compared with the newly calculated values for the path [Node0-Node2-Node4-Node3] and only those values are stored that are the smallest in total cost (Case A).

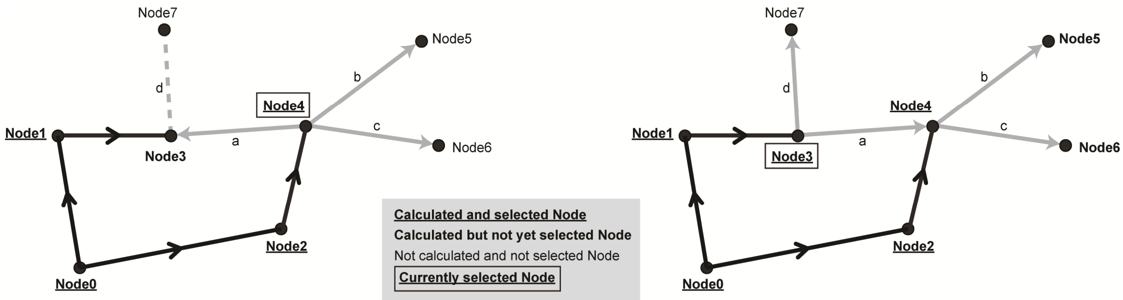

Figure 5-1 Two example situations of the implementation of the adjust cost calculations algorithm for adjacent nodes

Figure 5-1 (right) illustrates the next situation in the algorithm. From all nodes being calculated but not yet selected (i.e. Node3, Node5, Node6), Node3 has the smallest cost values and is the next selected node. His least risk path is hereby defined as [Node0-Node1-Node3]. Again, all neighboring edges (a, d) and endnodes (Node7, Node4) are chosen. Node7 has not yet been selected nor calculated (case a) and will be calculated as a path [Node0-Node1-Node3-Node7]. As Node4 has already been calculated and selected (Case B), Node5 and Node6 are being calculated with previous pathnodes [Node0-Node1-Node3-Node4] as this path could possibly be less costly than through (the already saved cost of) path [Node0-Node2-Node4]. The total risk values for both possibilities are compared in case b and the smallest value is stored.

Given the fact that the only difference with the Dijkstra algorithm is in the cost calculation, and there the additional calculations only affect the amount of edges in the selected node, the computational complexity is similar to Dijkstra, being $O(n^2)$.

5.2.2 THEORETICAL DEFINITION OF THE RISK OF GETTING LOST IN WAYFINDING RESEARCH

As defined in the previous section, the goal of the least risk path algorithm is to minimize the risk of getting lost. However, Grum's algorithm does not clearly state what a 'minimal' risk exactly signifies, especially given the complexity of indoor wayfinding for unfamiliar users. Several methodologies can be suggested to determine the actual riskiness of paths, ranging from physically testing the accurateness with real test persons, to simulating the wayfinding problems in an agent-based environment. For this paper, as a benchmark we selected a series of objective parameters that have been demonstrated, in previous wayfinding literature, to contribute to the risk of getting lost in both indoor and outdoor space.

It is believed that three factors contribute to the ease of getting lost in buildings during wayfinding: the spatial structure of buildings, cognitive maps created during wayfinding and the individual strategies and spatial abilities of the user (Carlson et al., 2010; Hölscher et al., 2006). At this point, we only account for the structure of the building itself for several reasons. First, Hölscher et al. (2006, p.284) specifically state: 'many have wayfinding problems because of architecture that only rudimentarily accounts for human spatial cognition'. Peponis, et al. (1990) agree that the degree of wayfinding is mainly dependent on configurational factors. Second, an algorithm that supports wayfinding in various building settings and for various user typologies should be independent of specific spatial-cognitive abilities of a certain user. Also, not all users of a building are at the same level in terms of ability, strategy selection or experience (Carlson et al., 2010). Third, the algorithm is developed for aiding unfamiliar users in their wayfinding tasks. The users therefore have not yet built up a cognitive map of the environment. As such, the parameters, proposed as benchmark, define the theoretical risk of getting lost during wayfinding and all relate specifically to the spatial building structure itself (Table 5-2).

Benchmark parameter	Significance for wayfinding
Route efficiency	Total path length (Hölscher et al., 2011)
Route complexity	Number of turns and streets used (Hölscher et al., 2011), also referred to as step depth (Hölscher et al., 2006)
Number of curves	In wayfinding, the direction strategy, often used by familiar users, continuously minimizes the angle between destination and current position (Hölscher et al., 2011). Less curves help following this strategy and maintain indoor orientation. Unfamiliar users, following a planned strategy, also benefit from fewer curves to feel more at ease and keep

Benchmark parameter	Significance for wayfinding
	orientation.
Corridor width	Wide streets are considered more salient (Hölscher et al., 2011). Equivalent in indoor space, the selection of wider corridors can be important to reduce the risk of getting lost.
Redundancy	I.e. a decrease in decision points that the user has to pass. Fewer nodes along a path have proven to decrease wayfinding difficulties (Peponis et al., 1990).
Integration value	Quantifies to what extent each space is directly or indirectly connected to other spaces. People naturally move to the most integrated nodes when navigating through a building (Peponis et al., 1990). Novices rely even more on following the paths of high connectivity and integration (Hölscher et al., 2012).
Probability of path choice at an intersection	I.e. the weighting of which paths are most likely to be taken. An uneven distribution of probability exists at each intersection, especially given the fact that more integrative spaces naturally gather more people (Peponis et al., 1990).
Number of visible decision points	Unfamiliar participants, during the initial exploration of a building, rely mostly on local topological qualities, such as how many additional decision points could be seen from a given node (Haq & Zimring, 2003). Also, a lack of survey places with open views and long lines of sights has shown to enhance stops and hesitations (Hölscher et al., 2012). Apparent dead ends often lead to misunderstanding and make people less reluctant to choose this path (Hölscher et al., 2012).

Table 5-2 Benchmark parameter set and their significance for wayfinding

These parameters (Table 5-2) all influence the chances of getting lost during wayfinding and will help determine whether the proposed least risk paths coincide with theoretically defined parameters of riskiness. However, the individual weighting of these parameters still has to be decided on. Therefore, we currently use this benchmark set as a way to analyze several example routes that have been calculated (Section 5.3.3.2). A more elaborate evaluation is planned as future work for adjusting the initial cognitive algorithm.

5.3 CASE STUDY

5.3.1 DATASET: CREATION AND MODEL

The applicability of the least risk path algorithm for use in complex indoor environments is evaluated by thoroughly testing it in a case study building. The selected indoor environment is the 'Plateau-Rozier' building of Ghent University. It is a complex multi-story building with several wings and sections, arranged over different floor levels, not all of them being immediately accessible. It is assumed that the mapped indoor space is complex enough with many corners and decision points to assume reasonable wayfinding needs for unfamiliar users. Indeed, previous research executed in this building has shown that unfamiliar users can have considerate difficulty recreating a previously shown route through the building (Viaene & De Maeyer, 2013).

For application of the least risk path algorithm, the original floor plans have been manually converted into a three-dimensional indoor network structure (Figure 5-2). Automatic derivation of indoor networks has long been focused on as one of the problematic areas for indoor navigation applications. Recent efforts have shown possibilities of automatically assigning nodes to each room object and connecting them when they are connected in reality (Anagnostopoulos et al., 2005; Meijers et al., 2005; Stoffel et al., 2008). However, the development of a comprehensive methodology for automatic network creation requires a thorough foundation and agreement on the appropriate and optimal (i.e. user friendly) network structure of indoor environments which supports the user in his navigation task (Becker et al., 2009). Up to this point and as far as we know, this is still missing in indoor navigation research.

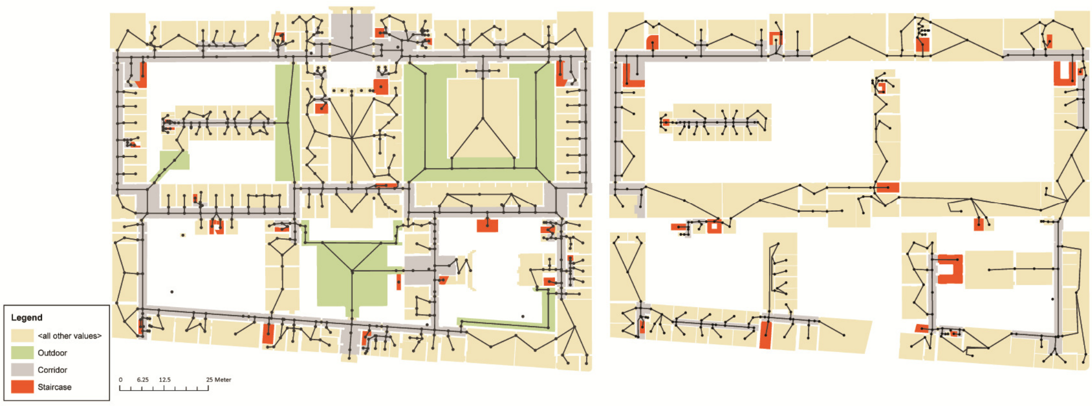

Figure 5-2 Floor plan of the ground floor (left) and first floor (right) with their 3D indoor network

For this research, only the ground floor and first floor were considered. The network structure is chosen to be compliant to Lee's Geometric Network Model (Lee, 2004) as this structure is widely accepted and is currently put forward as indoor network model in the IndoorGML standard proposal (OGC, 2014). In this model, each room is transformed into a node, forming a topologically sound connectivity model. Afterwards, this network is transformed into a geometric model by creating a sub-graph for linear phenomena (e.g. corridors), which enables network analysis. The position of the node within the rooms is selected to be the geometrical center point of the polygons defining the rooms. This premise implies that the actual walking pattern will sometimes not be conform to the connectivity relationships in the network inducing small errors in the calculations of shortest and least risk paths. We will need to verify whether or not this error is significant in the total cost of certain paths. The selection of corridors to be transformed into linear features is based on the map text labels indicating corridor functionality. These areas also appear to be perceived as corridors when inspecting the building structure itself in the field. Obviously, this topic is depending on personal interpretation and choice. Therefore, in future research, the dependency of the performance of cognitive algorithms on the indoor network topology will be investigated.

5.3.2 General results of analysis

The goal of this case study is to assess the least risk path algorithm for use in indoor environments and this by comparing the calculated paths of the least risk path algorithm with the results of the shortest path algorithm. More specifically, we want to (i) compare how much the least risk paths decrease the risk of getting lost compared to the shortest paths, (ii) if the least risk path algorithm actually reduces the navigational complexity of the paths and (iii) if the results of the least risk path calculations indoor have a similar improvement to their shortest path equivalents compared to the outdoor case.

The entire dataset of the case study building consists of more than 600 nodes and more than 1,300 edges. This required a computation of almost 800,000 paths to exhaustively calculate all possible paths between all nodes for both the shortest path and least risk path algorithm. This will also include trivial paths (e.g. between close neighbors) without any path difference. However, we chose to compare all paths instead of defining an arbitrary distance without any theoretical foundation. For each path, the total length and risk values for the intermediate nodes are calculated in both the shortest and least risk path algorithm.

5.3.2.1 Path length and risk value comparison

Over the entire set of results, on average the difference in path length between least risk paths and their respective shortest paths is found to be around 4.5 m with a decrease in risk value of 15.6 m (i.e. the average sum of the lengths of wrong edges at each intersection along the path). These values align with the original definition of both algorithms and their different cost minimization criterion. The length of a path described by the least risk path algorithm (total risk value minimization) is designed to be equal or longer than its equivalent shortest path (length minimization) by providing a less risky detour. The least risk path algorithm will more likely calculate routes with fewer intersections, away from the major corridors where many choices appear, while the shortest path will go for the most direct option ignoring the complexity of the individual intersections.

Over the entire dataset, a least risk path indoor is on average 4% longer than its respective shortest path. Although 53% of least risk paths are longer than their equivalent shortest paths, the majority (almost 99%) of paths are less than a quarter longer (Table 5-3).

Length increase	Number of paths	Ratio of total paths
Equal path lengths	160,984	46.64
]0%-5%]	87,681	25.40
]5%-10%]	50,773	14.71
]10%-25%]	41,196	11.94
]25%-50%]	4,363	1.26
> 50%	159	0.05
TOTAL	**345,156**	**100.00**

Table 5-3 Classification of path length increase

This indicates that while half of all paths seem to deviate from the shortest path to obtain a theoretically less risky route (otherwise their lengths would be equal), those deviations are mostly limited in size. Taking into consideration that the total path length of both shortest and least risk paths in this indoor space are already quite short (109.42 m to 113.89 m with standard deviations of 45.69 m and 48.54 m respectively) due to the restricted building size, the found limited path length differences are of even less significance. Most deviations from the shortest path will only have a single node-edge couple difference. These results point to an at first sight almost equivalent path choice by both algorithms, implying that either (i) the shortest path algorithm is already selecting paths that are least risky to get lost on or, (ii) they give an indication that the least risk path algorithm is actually not calculating less risky routes and as such might not be well defined for use in indoor spaces. A further examination of both ideas follows in Sections 5.3.2.2 and 5.3.3.

5.3.2.2 Navigational complexity analysis

As the aim of the least risk path algorithm is to lower the total risk of getting lost, the type of selected paths and more specifically their navigational complexity should be lowered given an increased total path length. Navigational complexity is in this case defined by the number of intersections passed and the average number of choices at intersections. Table 5-4 shows that for both the number of intersections and the average number of choices at an intersection the results are lower in the case of the least risk path algorithm than for the shortest path algorithm. However, the differences are quite small which demonstrates that the least risk path algorithm does not significantly decrease the navigational complexity of the final path.

	Shortest Path algorithm	**Least Risk Path algorithm**
Number of intersections	18.16	17.84
Average number of choices at an intersection	3.09	3.03

Table 5-4 Summary of the navigational complexity results over the entire dataset

A classification of the paths according to length increase (Table 5-5) shows (i) that for both risk value and average number of choices the values gradually decrease for least risk paths with increasing path length differences. These results are as expected as for having a significant deviation from the shortest path, the least risk path should provide in avoiding significantly riskier areas to get lost than the alternative paths. Although even with less complex intersections for the least risk path algorithm, the differences are still almost negligible. Remarkably, (ii) for the number of intersections, least risk paths with large increases in total path length show an increase in number of intersections compared to the shortest paths. As the initial point of the algorithm is to lower the total risk of getting lost as a whole, even with a path length increase it should contain fewer and less complex intersections. This is at this point not the case for the number of intersections. Again, all differences appear to be quite small, validating the originally raised questions about the applicability of the original least risk path definition for indoor usage.

Length increase	% increase in Risk Value	% increase in number of intersections	% increase in average number of choices
Equal path lengths	0.00	0.00	0.00
]0%-5%]	-0.18	-0.04	-0.02
]5%-10%]	-0.34	-0.04	-0.04
]10%-25%]	-0.51	-0.02	-0.06
]25%-50%]	-0.70	0.05	-0.09
> 50%	-1.05	0.08	-0.21

Table 5-5 Differences following the classification in path length increase

5.3.2.3 Comparison with the outdoor case

Compared to the results obtained by Grum (2005) in the original outdoor setting, the total risk value for the least risk path is minimal and the length is longer than its shortest path. The outdoor least risk path is 9% longer than the shortest path, while in our dataset an average increase of 4% is detected. However, a true comparison between indoor and outdoor results is difficult as the author only calculated a single path in outdoor space. With respect to the results of the navigational complexity, the outdoor least risk path has more intersections (14 versus 12 in the shortest path) but a lower average number of choices at each intersection (3.14 versus 3.5). These results are also in accordance with the findings in the indoor setting, but again these results should be cautiously approached given the limited number of calculations in the outdoor variant.

5.3.3 PATH EMBEDDING IN INDOOR SPACE

This section focusses on the actual paths themselves and their spatial embedding, i.e. the spatial location of the edges and nodes. More specifically, we will (i) calculate the correlation between shortest and least risk paths and (ii) assess the actual riskiness of the paths by relating to the previously defined benchmark parameters. The general aim is to identify how alike or different the calculated paths are and if the selected edges are avoiding complex and confusing areas in the building to ensure a lower risk of getting lost.

5.3.3.1 Correlation between paths

For calculating the correlation between each shortest and least risk path, the entire path was rerun with comparisons edge per edge. For a general path correlation measure, an overlap ratio is defined as the sum of all edge lengths that are mutually used in both the least risk and shortest path calculations divided by the total path length of the shortest path. On average, over the entire dataset, an overlap factor of 80% is found; for the subset of data with paths with different spatial embedding an average overlap of 62% is found. This result is in both cases quite high, confirming that most paths have a similar spatial embedding between both algorithms. Divided over the various classes of path length increase (Figure 5-3), it is obvious that with a large path length increase for the least risk path algorithm, the overlap between shortest and least risk path sharply diminishes as both paths are considerably different in length. With this subset of paths with a path length increase, on average 82% of intersections on the shortest paths are located in a corridor, while this value is reduced to 78% for the least risk path algorithm. This demonstrates that when deviations from the shortest path are made, these mostly occur by avoiding main corridor areas.

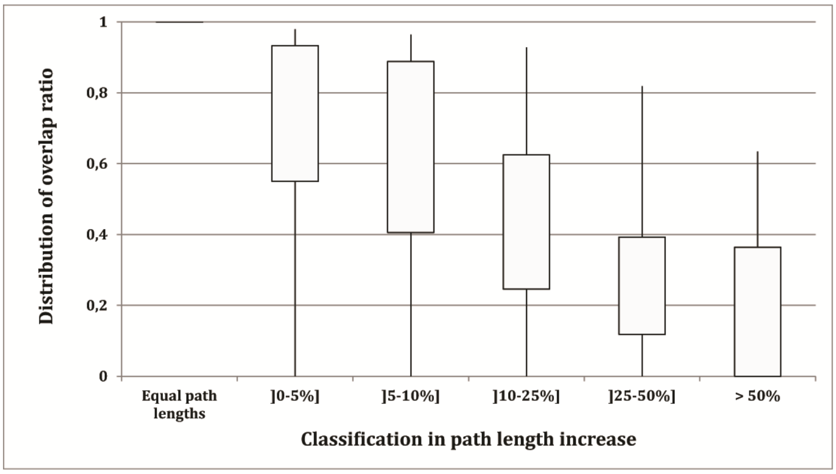

Figure 5-3 Distribution of overlap ratio per class of path length increase

A second analysis aims to demonstrate the edge use, defined as the number of times all paths from a certain source node pass by this edge. This analysis was applied to an example source node to maintain visualization clarity, but the calculation is applicable to all source nodes. The result is a map showing the use of each edge by varying line thickness, and this for both the shortest path and least risk path algorithm. The example source node is located in a room in the upper left corner on the first floor, close to a main staircase. Figure 5-4 shows a significant difference in the resulting embedding of paths between the shortest path and least risk path algorithm, even though the average path length and risk value difference is respectively limited to 7.7 m and 13.9 m, which is in line with the found limited differences. More in detail, in the Dijkstra case, from the source node a large amount of paths stay on the first floor to go to a more southern located staircase and deviate from there to the specific rooms. For the least risk path algorithm, to access the same nodes in the southern part of the building on the ground floor, a large amount of paths immediately descend to the ground floors and choose a specific corridor and outdoor area to find their way through the building. Additionally, nodes that have limited path choice generally take the same path in both cases (for example the northeast corner and middle/middle-east corridor on 1st floor). Although the conclusions above are specific for this example, these results also imply that the location of the stairs is of major importance in the selection of the paths.

Figure 5-4 Path use of the shortest path and least risk path algorithm (source node 1086)

5.3.3.2 Benchmark comparison

In this section we specifically look at the paths which have a different spatial embedding and investigate if the selected least risk path edges in those cases are actually less risky than the ones selected by the shortest path algorithm. The edges are examined on their theoretical riskiness, as defined by the benchmark parameter set, i.e. parameters that have proven to be influencing the risk of getting lost in various wayfinding experiments (Section 5.2.2).

The first example relates to the analyses in Figure 5-4, as it showed significant path embedding differences for certain areas. All paths with start point on the first floor and end point somewhere in the grey rectangle on the ground floor are analyzed. The dashed line in Figure 5-5 designates the least risk paths, while the black line visualizes the shortest paths to the grey rectangle.

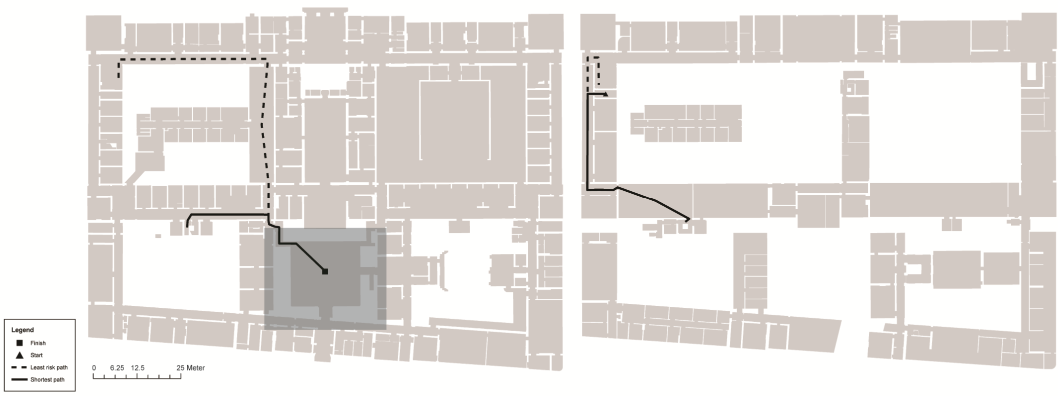

Figure 5-5 Path visualization comparing shortest and least risk path (floor 0 left, floor 1 right)

With respect to the parameters in the algorithm itself, the results in Table 5-6 show that the least risk paths are significantly less risky (according to its definition) by taking a 21% longer route (in this example). The other parameters as defined in the benchmark set show quite similar results for both algorithms. The number of turns and curves and the width of corridors are equivalent, as is the number of spatial units passed. Regarding general visibility and lines of sight along the path, the least risk path algorithm shows slightly better results. It can be concluded that both paths are theoretically fairly similar in terms of riskiness. However, in this case, the authors would probably suggest the least risk path as path to an unfamiliar user, mostly because the edges that are selected traverse major corridors and a very visible staircase. The path taken by the shortest path algorithm has to traverse a spatial unit labelled 'room' to reach a minor staircase on the first floor. The other edges being part of the shortest path are equivalent in importance. This example shows that sometimes minor differences determine whether a path is suitable to be recommended for unfamiliar users.

Benchmark parameters	Shortest paths	Least risk paths
Risk value of the entire path (m)	103	67
Total path length	128	155
No. of turns	9	9
No. of spatial units passed	8	9
No. of curves	1	1
Width of corridors (m)	3.2	3.2 and 5
No. of decision nodes passed	29	25
No. of visible decision nodes at each decision node (average)	2	1.5

Table 5-6 Results of the benchmark parameters for the example

A second example shows a shortest and least risk path with both start and end points being located on the ground floor (Figure 5-6). This example is chosen as it resulted in one of the largest differences in path length increase, and the path choice itself is also significantly different.

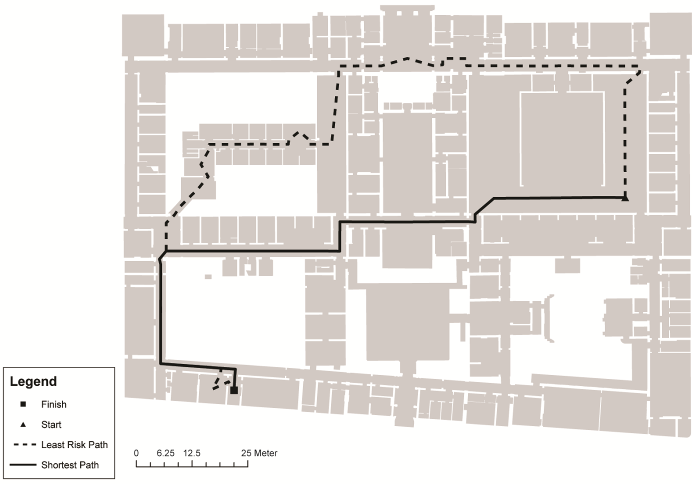

Figure 5-6 Comparison of a typical shortest and least risk path (floor 0)

Table 5-7 enumerates on the parameters used in the algorithm itself (first 3 lines) and the selected benchmark parameters. For the parameters used in the algorithm itself, the results are as expected: a lower total risk value for the least risk path with a considerable lower risk value at the individual decision points, by choosing a longer route (43% longer in this case). The other parameters, however, show a different side of the coin, with better results for the shortest path algorithm in terms of reducing the risk of getting lost. For example, the shortest path has 7 turns in its description, while the least risk path requires 12 turns. Wayfinding literature has extensively shown that more turns considerably increase the risk of disorientation and as such also the risk of getting lost by taking wrong decisions. The chosen corridors in the least risk path algorithm are generally less integrated, with less visibility towards the next decision points (4.68 versus 5.17) and a higher route complexity (more decision nodes passed on the total route, more curves and more spatial units passed). Above result indicates a less comfortable (and much longer) route traversing for unfamiliar users compared to the shortest path. In this case, the least risk path algorithm performs worse in terms of choosing less risky edges which completely undermines the initial intentions of the algorithm. The suggested shortest path will probably be closer to the natural wayfinding behavior of unfamiliar users compared to the least risk path algorithm. Together these examples demonstrate that even though an accurate route is often proposed by the least risk path algorithm, just as often a more risky and uncomfortable route is suggested.

Benchmark parameters	Shortest paths	Least risk paths
Risk values of decision points (average; m)	274.27	166.36
Risk value of the entire path (m)	445.07	411.79
Total path length	170.80	245.43
No. of turns	7	12
No. of spatial units passed	6	13
No. of curves	0	3
Width of corridors (m)	3.2	3.2 and 2
No. of decision nodes passed	29	37
No. of visible decision nodes at each decision node (average)	5.17	4.68

Table 5-7 Comparison of the parameters between an example shortest and least risk path

5.4 DISCUSSION

5.4.1 SUMMARY OF THE RESULTS OF THE CASE STUDY

The case study revealed some interesting results with regard to the applicability of the least risk path algorithm in indoor spaces. First, it was shown that on average least risk paths are only 4% longer than their respective shortest paths, with 47% of the entire dataset having equal path lengths and as such equal spatial embedding. Also, from the paths deviating from their shortest path equivalent, 98% has a limited deviation (less than 25% longer path length) of only here and there a different side route and this mostly through rooms avoiding main corridor areas. Second, the navigational complexity analysis showed again similar results over both algorithms, but the least risk paths were often longer with a similar path complexity. If the least risk path algorithm decides to deviate from the shortest path alternative, it should be supported by taking less risky and complex routes, which is not the case. Third, for paths with a significantly different path embedding, the least risk path ended up sometimes less risky when compared to our benchmark parameter set, but evenly as many times the shortest path would be preferred as least risky.

This leads to the main conclusion that the least risk path algorithm does not return stable results in terms of selecting the least risky edges in indoor environments. For short path lengths the similarity between both algorithms in terms of path embedding seems reasonable as the density of the indoor network (and the importance of staircases in the indoor graph) impedes many deviations. However, on longer total path lengths, deviations have been noticeable, sometimes for the better, but evenly as many times it resulted in taking theoretically more risky and cognitively more difficult routes. Also, the deviations from the main corridor to side rooms are running counter to typical wayfinding strategies. Therefore, we are inclined to say that at this point for indoor wayfinding, the least risk path algorithm calculates alternative routes between two points, without necessarily reducing navigational complexity. This leads us to believe that the least risk path algorithm and its definition of risk should be investigated in more detail and altered to be more aligned to the specificities of indoor wayfinding. In the following section, we will discuss several reasons for this misalignment between algorithm and the specific indoor situation and afterwards propose some improvements to the original algorithm.

5.4.2 REASONS FOR MISALIGNMENT

5.4.2.1 Risk value definition

The minimization criterion of least risk is composed of a path length value and a risk value. For most algorithms, the total path length plays in some way a vital role in determining which edges get selected. The introduction of the risk value is specific to this algorithm and could be one of the reasons for the current inaccurate results. At this point, the risk value takes into account the number of streets converging at an intersection and their individual lengths, to obtain a kind of average length of a wrong edge at that intersection. In the following paragraphs, the implications of defining the risk value in this way are examined in more detail.

First, the individual lengths of the wrong segments are key in the calculation of the intersection-based risk value. By only utilizing the length of wrong edges, the algorithm will initially always select the edge with the longest individual path length, as this edge would add the most to the average wrong path length if not selected. The more equal all edges at an intersection are, the more similar the risk values will be. During the entire run of the algorithm, a more balanced optimum will be created over time were sometimes edges are selected with a slightly lower risk value. However, during the actual wayfinding act the individual lengths and length ratios between all edges at an intersection is not necessarily of importance in having more or less chances of getting lost during the trajectory. Selecting as many possible long edges is important (theoretically less intersections over the total path length), as long as this not results in bumping into really complex or confusing intersections. The algorithm actually does provide this selection of long edges in its current form. However, selecting an edge with a slightly shorter length but with other parameters that reduce navigational complexity (e.g. a long line of sight, wide and open corridor …) might often be more important for overall risk reducing than just the length of the edge in relation to the other edges alone.

The second parameter in the formula of the risk value calculation is the number of choices at an intersection. This parameter aims to cover the effect of the intersection's complexity (i.e. the amount of edges converging at an intersection) on the risk of getting lost. The analyses in section 5.3.2 have shown that the average number of choices at an intersection in the least risk path algorithm is fairly similar to the results of the shortest path algorithm.

This implies that this parameter in the calculation of the risk value does not necessarily add much to the final risk value. Fig. 8 plots the relationship between intersection complexity and risk value. It shows an exponential relationship where with increasing intersection complexity the risk value increases with relatively smaller amounts. This demonstrates that the amount of edges converging actually does have an importance on the risk value. However, after a certain point, the relative importance of adding more choices at an intersection does not really have a significant effect on the final risk value. Even though having a slight increase of possible choices at an intersection might not add much more discomfort for the wayfinder itself, his chance of picking the right option does actually decrease.

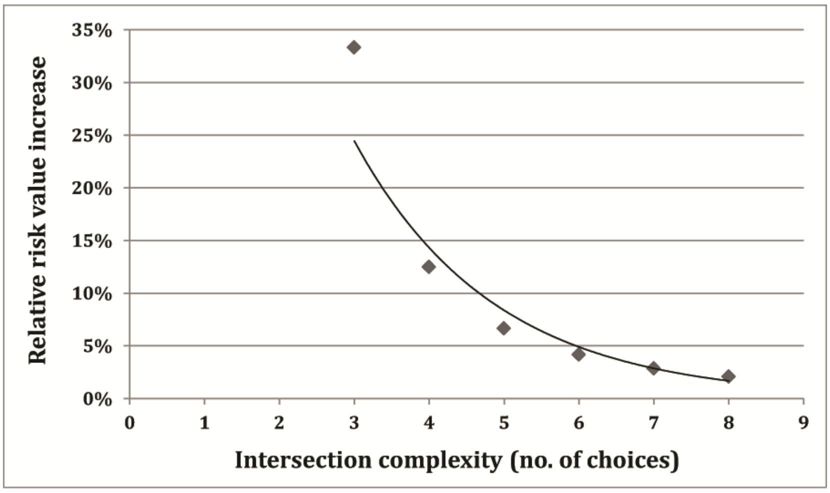

Figure 5-7 Relationship between intersection complexity and relative risk value increase

In conclusion, some aspects in the risk value calculation do seem to make sense helping people avoid getting lost and choosing more optimal paths. However, the importance of the intersection complexity is not as profound as might actually be necessary in wayfinding. At this point, the selection of the longest possible edge gains the upper hand over the intersection complexity. This might indicate a possible reason for the wrongful selecting of less risky paths and requires adjustment of the original definition of risk value.

5.4.2.2 Network definition

At this point, the least risk path algorithm indoor was tested using a Geometric Network structure as defined by Lee (2004). Apart from representing each spatial unit by a single node, the key element of this network structure is the transformation of corridor–labelled units to linear features. As described in Lee (2007, p.516) 'the 3D GNM is a topological data model representing the connectivity relationships among discrete objects and the geometric properties of objects in three-dimensional space (e.g., location in 3D space, distance between two rooms, and length of a hallway)'. The transformation of corridors into a sub network consolidate hallway nodes in the combinatorial network by projecting and connecting door way points onto the medial axis of the corridor (Lee, 2004). The goal of this transformation is to upgrade a solely topological model of connectivity relationships into a geometric network model representing more accurately paths of movement between all units. As an effect, each corridor is often subdivided in many nodes in front of each doorway interconnected by short edges (Figure 5-8).

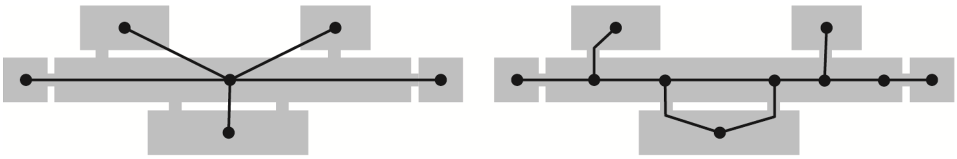

Figure 5-8 Topologic connectivity network (left) versus geometric network (right)

This particular subdivision creates unrealistic results in our calculations of least risk paths. With the creation of these synthetic hallway intersections, more intersections have to be possibly passed, with each intersection adding more weight to the total risk value of the path. Also, as discussed previously, the original algorithm selects the longest edge in each intersection in its risk calculation. Figure 5-9 shows that this can lead to deviations of the final least risk path from the main corridor as the longest edge in the intersection leads towards a room on the side having two connecting doors to the corridor. This was also confirmed in Section 5.3.3 with deviations in the least risk paths being mostly through room areas instead of corridors. On top of that, this example also demonstrates that avoiding the short edges of the main corridor leads to a lower total risk value as the node in the selected room does not cause the calculation of an additional risk value (the node has only two edges converging). The exact examination of the influence of this particular network type on our results of the least risk path algorithm is subject for future work.

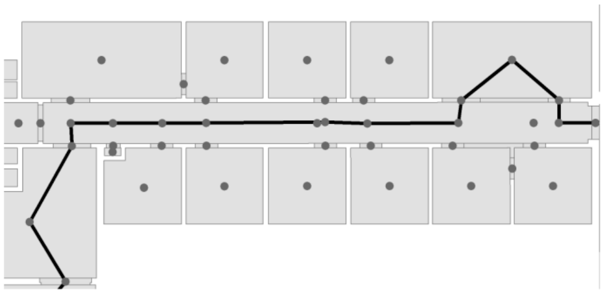

Figure 5-9 Zoom of the example from path selection in Figure 5-6

This example shows an unrealistic walking pattern as there is no apparent reason in the eyes of the wayfinder for this deviation from the straight corridor line. Also, knowing exactly which room to enter is more complicated in this case with many doors and rooms on both sides of the corridor inducing more options and choices to be made. This illustrates an additional problem with this type of network. When having to traverse an entire corridor, the synthetic hallway nodes are often not perceived as intersections or decision points by the user. This was also proven in wayfinding experiments where participants explicitly stated not requiring any landmark checkpoints in a corridor, as only new information was needed when choices had to be made about the remainder of the route (Viaene & De Maeyer., 2013). It also underlines the difference between outdoor urban networks and the indoor equivalent: in outdoor space each intersection represents a formal decision point, while this is not necessarily the case in indoor environments. This is especially true when traversing a corridor with only closed doors (often in office buildings) leading to private rooms, while the unfamiliar user might only have access to the publically traversable corridor.

5.4.2.3 Indoor versus outdoor space differences

Indoor and outdoor spaces are considerably distinct in structure, constraints and usage. Although both environments are often consisting of linear structures with obstructions, the human perception during navigation is entirely different. Outdoor urban environments have mostly a wider view with no covering which is sensed as uncluttered and orderly space, even in dense city environments. Indoor environments have often more discontinuities and are totally covered, which is perceived as a fragmented, enclosed and clustered environment (Richter et al., 2011). This difference in human perception has to seep through in the algorithmic support as it highly influences the risk of getting lost. This also demonstrates why the risk value for indoor application might require a more complex and coherent approach compared to outdoor spaces.

The transformation into an appropriate network has shown to create some additional problems for application of the algorithm. This has its origin in the different network complexity of both spaces. Most buildings contain several major corridors with rooms on the side containing only one exit, while outdoor street networks are in general more integrated leaving several options for path alternatives. This also explains the high similarity in results between least risk and shortest paths in our indoor tests. There are often not many options to deviate from the shortest path, making the deviations that occur being more important to provide users in an easier navigation experience.

5.4.3 POSSIBLE IMPROVEMENTS TO THE ALGORITHM

5.4.3.1 Weight adjustment

Several options for adjusting the internal weight balance are possible in the algorithm. The most straightforward one is altering the relevance given to the parameters in the current algorithm. In the original implementation of the least risk path algorithm, both the length of the path as well as the sum of the risk values at intermediate decision points add an equal weight in the calculation of the overall risk value. Changing this ratio of length versus risk value might result in a more cognitively correct selection of least risk paths indoor. To examine this, the original definition can be improved by adding two parameters α and β, one for each variable, with their mutual sum always equal to 1.

$$Total\_Risk(p) = \propto * PathLengths + \beta * RiskValue(i) \quad \text{(Equation 5-3)}$$

$$\propto + \beta = 1 \quad \text{(Equation 5-4)}$$

As an example of this process, the weights of the path presented in Figure 5-5 are altered with the results visualized in Figure 5-10.

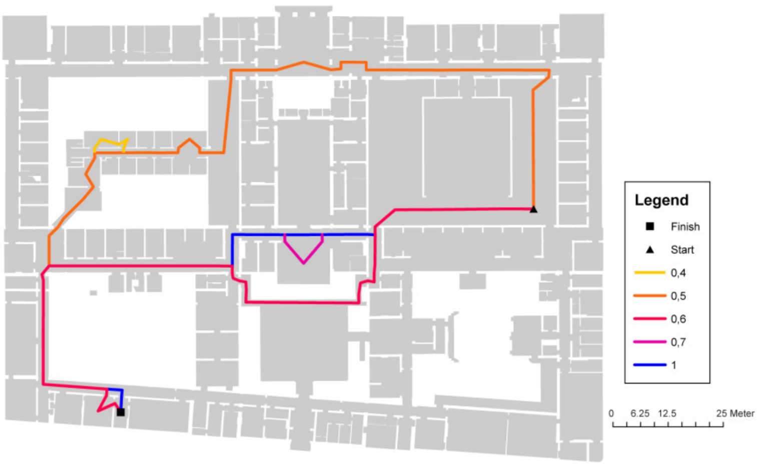

Figure 5-10 Weight adjustment by changing the mutual importance of risk value versus path length

The orange line (α=0.5) visualizes the original least risk path with equal importance to path length and risk value. Changing the importance of the length to a lesser amount apparently does not change much in the final path choice in this example. Only an additional deviation through non-corridor areas (α=0.4) is included as a result of the added importance to the risk value calculations, which leads to an even higher avoidance of short edges and intersections. From α=0.6, the route starts to coincide more with the shortest path (α=1). However, the route deviates to an outdoor courtyard area to later on join the original shortest path again. Even though in both cases the path traverses main corridors and outdoor areas, an unfamiliar user would probably prefer the shortest route as its least risk path, as it does not require any physical changes of spatial unit in contrast with the least risk path (α=0.6) (physically going outside using two small doors). This extra attribute might also need to be added to the network. Note that in case of α=0.7 the path deviates once more from the main corridor due to the definition of both network and risk value. In this case, given the high weight to path length in favor of risk value, the network structure will be the defining variable. A more hierarchical network structure is thus highly recommended. This is only an example showing the possibilities of altering the mutual relationship of the main parameters defining the total risk value. At this point we cannot give any further indication on the best ratio of α and β parameters as it requires comparisons between multiple start- and endpoints and even in buildings with a different spatial structure.

A second possibility of weight adjustments exists in changing the internal definition of risk value by adding more parameters relevant to minimizing the risk of getting lost during wayfinding. In section 5.4.2, it was already proven that the current definition of risk value is rather limited with the selection of the longest possible edge gaining the upper hand over the intersection complexity. In Table 5-2, several other factors were listed as theoretically important in optimizing wayfinding situations. The individual weighting of these parameters is up for future research. However, we would like to propose a division of the current risk value into an intersection based risk value and an edge based risk value (Equation 5-5).

$$Total_{Risk(p)} = \propto * PathLengths + \beta * RiskValue(i) + \gamma * RiskValue(edge)$$

(Equation 5-5)

The risk value of selected edges is of importance since at this point no aspects denoting the overall individual importance of each edge apart from the edge length (e.g. width, number of curves, integration value) are yet incorporated in the assessment of risk. These variables are tightly linked to the edge structure and completely independent of the intersections themselves. On intersection level, other aspects that can influence the edge choice for continuation of the path, like the directional orientation of each edge at the intersection, are also not yet considered. The intersection-based risk value can also be influenced by the same parameters denoting the individual importance of the edge, but on a more local level. For example, the sight of several small corridors and a single large corridor at an intersection will highly influence path choice and comfort when selecting the widest corridor and not the smallest variant. Experiments with defining various risk value definition with more parameters from Table 5-2, individually weighted, are considered as future work.

5.4.3.2 Other possible algorithmic improvements

In this final section, we will suggest some other improvements to the original algorithm which will be tested and compared in our future research.

First, the risk value of a decision point is currently calculated based on the assumption that the wayfinder recognizes his mistake at the first adjacent node and returns from there to the previous node. The question could be raised whether it is actually realistic that people already notice at the first intersection that they have been going wrong. An increasing compounding function could be suggested taking into account the possibility of going further in the wrong direction.

Second, given the importance of an appropriate network topology, a more sophisticated algorithm could select routes that preferentially use more important or higher classified edges to be in line with users hierarchical spatial reasoning. The main question here is which hierarchical structure should be used and how should it be defined. In outdoor navigational research, the road classification often serves as natural hierarchy. However, this hierarchy is much harder to define for indoor spaces. A possibility could be to discover the latent natural hierarchy of the indoor graph by using the reach metric introduced by Gutman (2004).

Related to this topic is the importance of staircases, as it was proven that they are key elements in the indoor path selection. The fact that you have to walk up and down staircases during a certain route could be naturally having a greater weight because taking a wrong decision might result in walking up and down the stairs twice. On the other hand, chances of making a wrong decision by changing floors are likely to be slimmer given the effort required for vertical movement. Additionally, it has been found that the number of rotations on a staircase plays a major role in keeping stability in the user's cognitive map. Hölscher et al. (2012) identified many getting-lost episodes due to disorientation after leaving a staircase, sometimes even on the wrong floor.

Fourth, Hölscher et al.'s (2009) wayfinding research has proven that people's strategy choice indoors varies with different navigation tasks. Tasks with either a floor change or a building part change result in no problems, with the participants first changing to the correct floor or building part. However, for tasks with changes in both vertical and horizontal direction, additional information is required to disambiguate the path choice. An algorithm that wants to minimize the risk of getting lost in a building necessarily needs to account for these general indoor wayfinding strategies as they correspond to the natural way of multilevel building navigation for all types of participants.

5.5 CONCLUSIONS

In this paper, the least risk path algorithm as developed by Grum (2005) in outdoor space was implemented and tested in an indoor environment to examine its suitability for indoor wayfinding. The results of those tests have shown that with a slight increase in path length, theoretically less risky paths were calculated. However, further analyses have demonstrated that these least risk paths are not necessarily significantly different, nor are they optimal in terms of reducing navigational complexity and getting-lost episodes. This leads to the conclusion that a dissonance exists between the original definition of the algorithm and its implementation in indoor environments. Several suggestions were made to improve the algorithm, ranging from changes in the calculation of the risk value, to individual selection and weighting of the parameters involved, to the influence of the indoor network topology. The aim for future research is to discover the best optimization of the algorithm to make it more compliant with the cognitive notion of indoor wayfinding. More generally, this research will aid the development of appropriate tools that improve navigation experiences in indoor spaces.

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6

COMPARING INDOOR AND OUTDOOR NETWORK MODELS FOR AUTOMATICALLY CALCULATING TURNS

Modified from: VANCLOOSTER, A., VAN DE WEGHE, N., FACK, V. & DE MAEYER, P. 2014. Comparing indoor and outdoor network models for automatically calculating turns. Journal of Location Based Services, 148-165.

ABSTRACT

The goal of this paper is to compare several indoor and outdoor network models for wayfinding, on their suitability for automatically calculating turns. Automatic turn calculations are of relevance in providing improved cognitive algorithms for route guidance, as it has been widely recognized that routes with minimal angular deviations are easier to follow. It is demonstrated that the currently available indoor network models not allow accurate calculation of the number of turns along a path, while the common outdoor route networks do. This discrepancy is found to be rooted in an inconsistent definition of indoor decision nodes which in turn is linked to the inherent differences in space structure between indoor and outdoor environments. Additionally, it is proven that these also have a major influence on the generation of accurate indoor route instructions. Recommendations for future research within the context of both turn calculations and verbalizations of directional changes are made, as well as in the broader context of indoor spatial analyses.

6.1 INTRODUCTION AND BACKGROUND

According to Montello (2005), as long as people have to decide where to go and how to get there, navigation will remain one of the fundamental behavioral problems for human cognition. Navigation processes are said to consist of both locomotion and wayfinding components (Montello, 2005). Wayfinding is thereby the process of determining and following a route between origin and destination and is often guided by external aids (Golledge, 1999). In the context of this paper, we focus on these guidance aids, improving users' wayfinding experiences, and not on the cognitive act of wayfinding itself. The setting for our research is limited to indoor spaces as research on indoor environments has repeatedly demonstrated the challenges of successfully performing wayfinding tasks in complex three-dimensional spaces (e.g. disorientation after vertical travel, less visual routing aid, deficient cognitive map creation) (Hölscher et al., 2009).

Even though wayfinding aids for indoor spaces have gained an enormous amount of interest over the last decade, indoor algorithmic support is still mostly confined to common shortest path algorithms (see Chapter 5). In outdoor environments, a set of more 'cognitive' algorithms has specifically been created to deal with wayfinding challenges by providing routes that are more intuitive to follow and more adhering to how people describe paths to unfamiliar users. Several of those algorithms rely on a minimization of number of turns as main cost heuristic (e.g. fewest turns path algorithm, simplest path algorithm). Indeed, turn minimization has been recognized as an important route selection criterion, next to distance and time (Golledge, 1995). Also, routes of minimal deviations are often perceived more optimal and comfortable (Winter, 2002). Providing these comfortable and easy to follow routes, is even more important indoors than outdoors, as external cues and extrinsic points of view are less manifest in indoor spaces (Padgitt & Hund, 2012). A major part of algorithms with turn minimizations is the automatic calculation of turns. Therefore, the goal of this paper is to examine turn calculations on indoor networks and compare them with known efforts in outdoor space. The following sections give an overview of several turn conceptualizations and definitions. Section 6.2 and Section 6.3 demonstrate turn calculations on both outdoor road networks and various indoor space representations. In Section 6.4, several challenges of the indoor application of turn calculations are discussed in more detail.

6.1.1 TURN CONCEPTUALIZATIONS IN WAYFINDING RESEARCH

Over time various definitions and measures for detecting turns have been proposed, embedded on different conceptualizations of space. Most commonly, turn calculations are of interest for calculating fewest turns paths minimizing the number of directional changes and this using a route graph (Hillier & Iida, 2005). The simplest path algorithm extends this thought as it calculates paths with a minimal route description complexity based on the required amount of information at each intersection. Although simplest path algorithms exist under multiple variants (Mark, 1986; Duckham & Kulik, 2003; Richter & Duckham, 2008), all of them attach a larger cost when dealing with turns. Winter (2002) from his part proposed a line graph to describe turns as edge-edge relationships in response to the common more costly approaches of splitting up graphs in multiple nodes or adding turn penalty tables. Since nowhere is mentioned what exactly is considered a turn, it can only be assumed from the construction rules of the line graph that every outdoor intersection gives occasion to turns. On the other hand, Jiang and Liu (2010) compute fewest turns paths based on a 'natural routes' concept, i.e. where various street edges are merged into a single road. In this case, not every junction is considered a decision point and turns are only counted when changing from one natural road to another, not the directional changes within a natural road.

Space Syntax community presents a highly different view on space structures. One of their conceptualizations of space is the axial map, i.e. a graph of axial lines representing visibility relationships by drawing the fewest longest lines of sight which traverse all convex spaces (Turner et al., 2001). On this axial map, a spatial integration measure can be calculated, quantifying the number of turns to reach all street segments. As such, it forms a measure of the cognitive complexity of reaching a street and is found to predict pedestrian usage (Turner et al., 2001). The connectivity relationship present in the graph topology models in this case turns as a visual transition instead of the pure connectivity of roads and edges in previously discussed road graphs.

6.1.2 DEFINITION OF A TURN

In general, a turn can be defined as a directional change from a reference line (Cambridge Dictionary). The angle is a central point in this definition, consisting of the corner between two distinct rays issuing from the same vertex. In case of navigation systems and concurrent route instructions, not every change of direction has to be labeled turn. Evidence has shown that some turns are more important to humans than others (Turner, 2001). However, there is no agreement on which angles form the boundary for deciding the significance of a directional change. For example, Mark (1986) describes in his simplest path algorithm that an angular change above some threshold incurs a maximal turn cost of 9. However, the threshold itself has not been mentioned. In more recent wayfinding literature, a turn is defined as a decision to deviate from the straight ahead by more than 45° (Hölscher et al., 2011).

The definition of a turn is also tightly linked to the user's perception on making a significant change in direction, which in turn is connected to how people verbalize navigational paths. Route instruction verbalization is characterized by three main components: (i) structure of decision point; (ii) the action itself (directional change or not), and (iii) salient features (Klippel et al., 2012). To model the intended action at intersections, different directional models have been developed over time. For example, Klippel et al. (2005) present an eight-direction model with each sector having an increment of 45° in the prototypical directions, which has been confirmed in behavioral experiments to include all elements relevant for human direction giving at intersections in city street networks.

The authors decide to concur with this idea and will describe a turn as any directional change deviating from the straight ahead by an angle of 45° or more. Obviously, there are possibilities to alter this threshold and calculate its impact on the results of the number of turns over various algorithmic tests. In this paper, turns are only counted at intersections where path alternatives were available and a decision had to be made. Although in future work, this can be extended to include all types of turns and curvature.

6.1.3 ALGORITHM TO AUTOMATICALLY CALCULATE THE NUMBER OF TURNS

To automatically determine the exact number of turns on a path, it is required to calculate each angle created by three consecutive nodes in the path. One of the alternatives to measuring the size of angle utilizes the gradient, i.e. the grade of a slope, which is equal to the tangent of the angle. As such, Algorithm 6-1 calculates the angle between two connected edges by using the x- and y-coordinates of the nodes that form the start and end points of the intersecting lines. Figure 6-1 visualizes the various components used in the algorithm.

```
FUNCTION CalculateNodeCoordinateTurns (Path <Edges,Nodes>):
NoTurns = 0;
FOR each node (Nmiddle) in path
    Select previous (Nstart) and next node (Nend)
    Startslope := (ymiddle-ystart)/(xmiddle-xstart)
    Endslope := (yend-ymiddle)/(xend-xmiddle))
    Tangent of Turnangle := ((Endslope-Startslope)) /
        (1+(Endslope*Startslope))
    IF(Turnangle > threshold)
        NoTurns++;
RETURN NoTurns;
```

Algorithm 6-1 Node-coordinate based algorithm for turn calculations

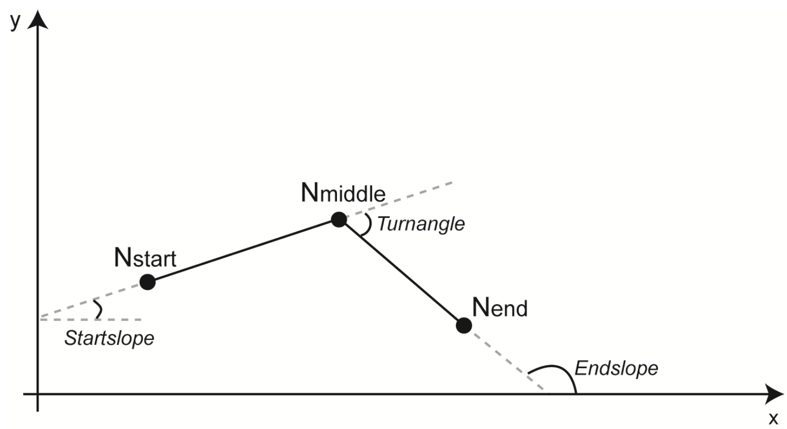


Figure 6-1 Visual explanation of the node-coordinate based algorithm for turn calculations

Note that in case of dealing with vertical connectors in 3D indoor space (e.g. staircases or elevators), the slopes would have to be calculated in the vertical plane. Also, depending on the type of staircase and the accuracy with which the network describes the inner complexity of the object, additional turns will have to be calculated on intermediate levels, coinciding with the curvature of the path (Stoffel et al., 2008).

6.2 TURN CALCULATION ON OUTDOOR NETWORK MODELS

As mentioned in Section 6.1.1, several examples of algorithms with turn minimization in outdoor environments have been proposed, largely based on traditional route graphs. In this section, we use such route graphs to calculate turns with the coordinates of the individual nodes as key elements. More specifically, we will review as example of an outdoor network the automatic turn calculations on the international Geographic Data Files (GDF) standard as this is a well-documented example of outdoor street networks (ISO, 2002).

6.2.1 GDF STANDARD BACKGROUND

The GDF standard is an international standard used in outdoor route calculations. It contains multiple classes of typical objects for outdoor navigation, with the 'roads and ferries' data model being the most interesting in this context (Figure 6-2). The road network can be represented at two different levels of detail (level 1 and level 2). A Road is defined as a Level 2-Feature composed of one, many or no Road Elements and forms a connection between two Intersections. It serves as the smallest independent unit of a road network at Level 2. A Road Element is defined as a linear section of the earth, designed for vehicular movement. It serves as the smallest, independent unit of the road network at Level 1 and is bounded by Junction Elements (ISO, 2002).

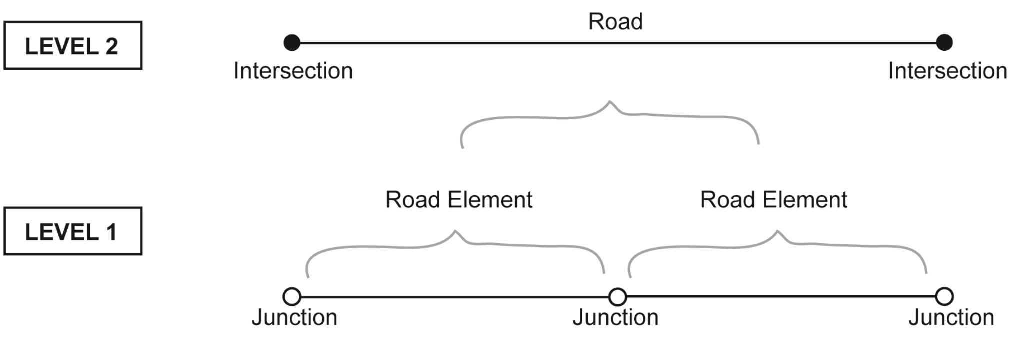


Figure 6-2 Part of the data model 'Roads and Ferries' over various levels of detail

6.2.2 Application of automatic turn calculation algorithm to GDF

The relationship between Roads, Road Elements and Intersections can adopt various shapes. These situations correspond to the figures 15, 16 and 18 in the GDF standard (ISO, 2002; p.26).

- Road containing 1 Road Element: a 1-on-1 mapping of the original Road Element (Level 1) to a Road in level 2 (Figure 6-3, left column).
- Road containing 2 Road Elements: 2 Road Elements can be aggregated into 1 Road on level 2 if each Road Element is a one-way Road and the Road is one single functional unit (Figure 6-3, right column).
- Road containing no Road Elements: all Road Elements are mapped onto either one of the Intersections (Figure 6-4).

In the following sections we examine these situations in light of their feasibility to accurately calculate turns using Algorithm 6-1.

First, for Roads with a single Road Element, the example in Figure 6-3 (left) demonstrates that this network model supports accurate turn calculations. Having a path from A to D, the angles in nodes B and C can be easily calculated with Algorithm 6-1. For example, for the turn angle in B, nodes A and C are used respectively as N_{start} and N_{end}. A perceptive turn zone of 90° (45° left and right of the straight ahead) designates all areas that are not considered as turns. In this case, line BC deviates more than 45° from the straight ahead (line ABD) introducing a (right) turn in node B. The same principle applies for the turn calculation in node C where a left turn is calculated.

For Roads containing two Road Elements (Figure 6-3, right), the example shows a similar situation. However, in this case the intersections on level 2 are split up in multiple junctions on level 1. This leads to a more intricate turn calculation in node C. Over the entire path, four decision points have to be passed, with node C consisting of three junctions. In node C_1, the wayfinder has to continue his path straight ahead (line C_1C_2 forms the extension of line BC_1), while in node C_2 a left turn is calculated (segment C_2C_3 is located outside the perceptive turn zone in node C_2). Finally, in node C_3, a continuation of the straight ahead is required and as such no change in the number of turns can be detected. However, the adjoining verbal instructions required to support wayfinding along this path have to be altered; i.e. 'take the second street on the left'. Note that in this case, taking the first street on the left (i.e. going left in node C_1) will not be allowed due to the directionality of the separate streets.

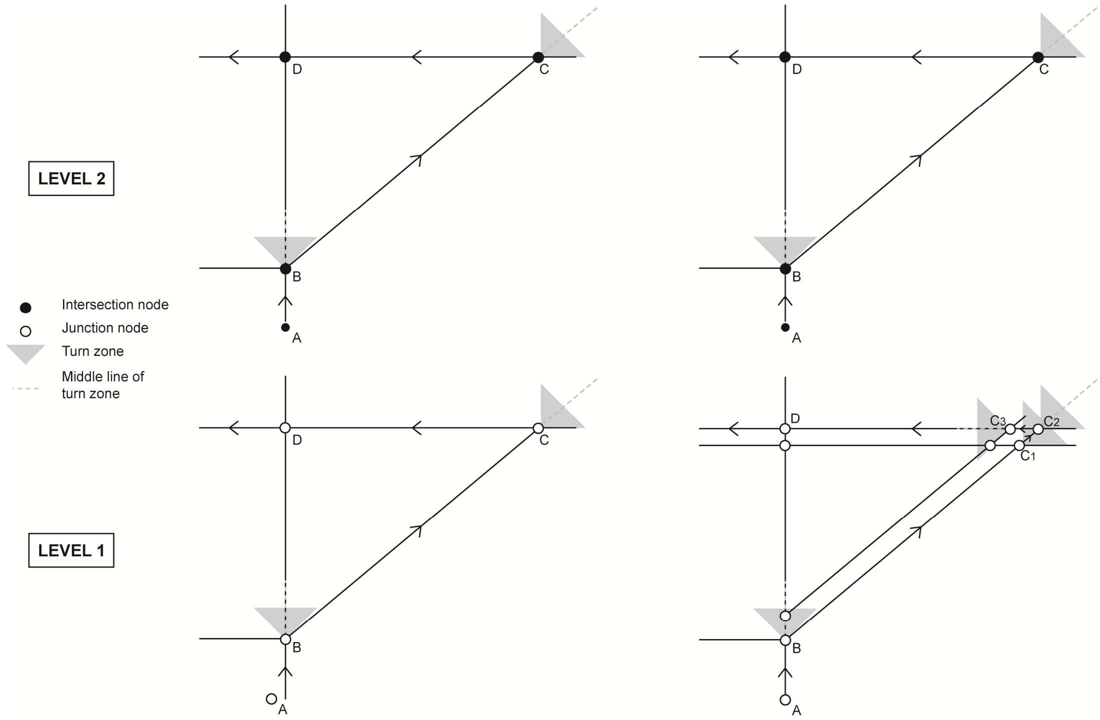


Figure 6-3 Turn calculations on a Road with 1 (left) and 2 (right) Road Element(s)

In case of Roads with no Road Elements (Figure 6-4), a path from A to D shows that only one turn (in node B or node E in a level 2 model) is recorded, which is in line with the expected decision making of a wayfinder. On level 1, the angle made by the segments BCD is precisely located within the perception turn zone. Even if this was not the case, the angle in node C should never be counted as a turn, as it is not a real decision point but rather a merging point with the main road through node D. The decision to turn right is already made in node B.

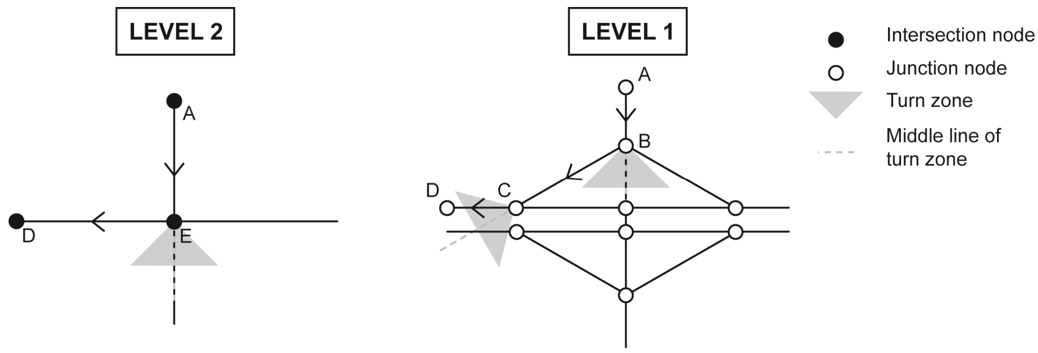


Figure 6-4 Turn calculations on Roads with no Road Elements

In conclusion, as most of the movement on roads is quite guided and restricted, the calculation of turns does not induce any problems in common road and intersection situations. Independent of the level of detail at which the roads and intersections are modeled, the node-coordinate based algorithm works as expected for turn calculations on outdoor networks.

6.3 Turn calculation on indoor network models

As research on indoor navigation is still in its early stages, the standardization of indoor network models has not yet reached full maturity. Graphs are, also indoors, the main navigational model fitting the requirements of connectivity. Various network options have so far been proposed, starting from a direct spatial unit representation with adjustments resulting in three main clusters: corridor derivation, cell decomposition and visibility partitioning. Figure 6-5 presents two example paths for each of the indoor network representations. Path 1 connects node 1 and node 2 and path 2 links node 3 with node 4. Table 6-1 presents the results of the turn calculations using Algorithm 6-1 over the different indoor networks.

Indoor network options	Path 1	Path 2
Center-Node Network	3	1
GNM (only room nodes)	4	6
GNM (room and door nodes)	7	8
Cell-decomposed model	6	6
Visibility-based model	3	1
Actual walking pattern	6	2

Table 6-1 Comparison between the calculated number of turns using various indoor network structures

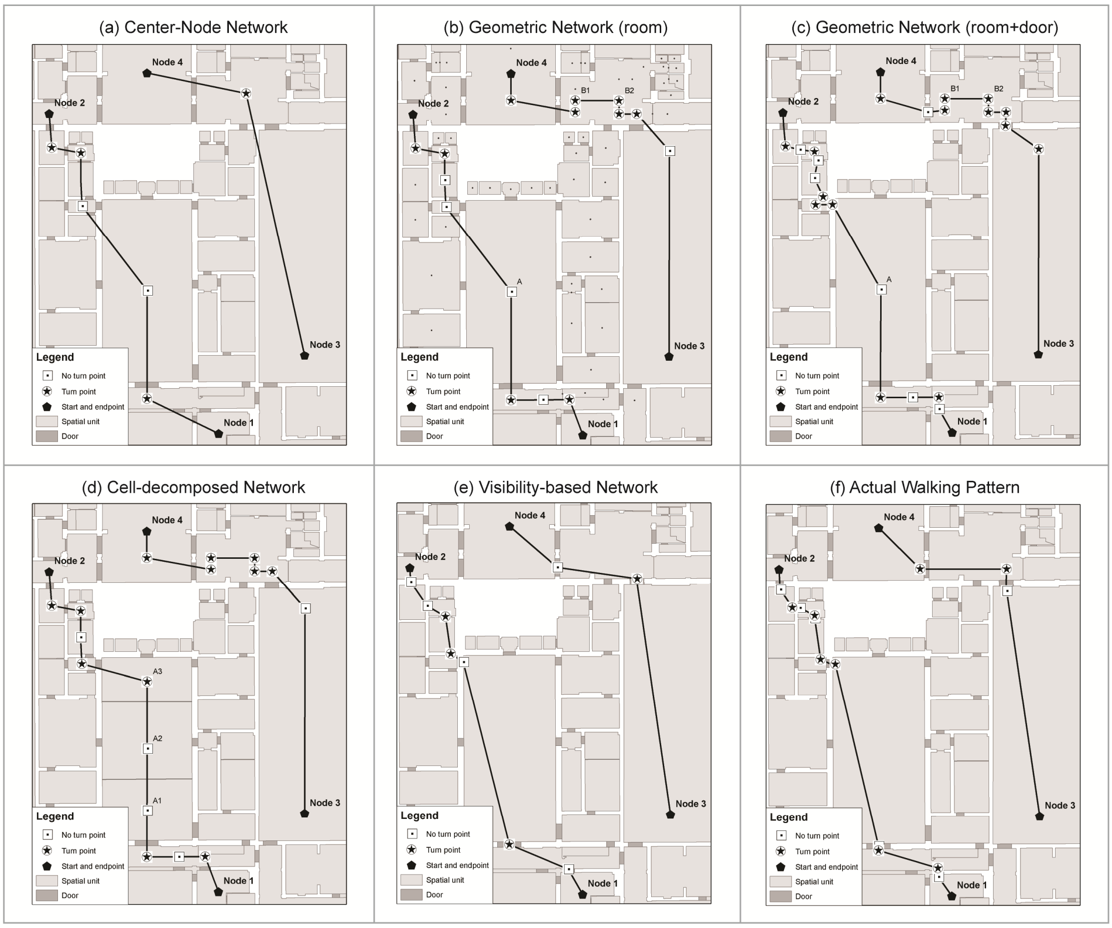


Figure 6-5 Overview of several indoor network structures and their influence on turn calculations. (a) Center-Node Network; (b) Geometric Network Model (GNM) with only room nodes; (c) GNM with room and door nodes; (d) Cell-decomposed Network Model; (e) Visibility-based model; (f) Actual walking pattern

6.3.1 CENTER-NODE NETWORK

The center-node network model is the most elementary indoor network possible with a 1-on-1 relationship between geometrical building structure and graph. Each spatial unit is represented by a node at its center point, with the edges representing the connectivity relationships between the separate spatial units (e.g. Lorenz et al., 2006; Stoffel et al., 2007). This purely topological connectivity model serves as base for several variations, discussed in the next sections, improving some of its shortcomings.

Applying this model to our turn calculation algorithm, results in a non-accurate accounting of turns. The main problem is the non-realistic representation of the actual walking pattern. Given the fact that the intermediate nodes are located in the center of each spatial unit, the edges connecting those, are theoretically modelled to go through walls. Also, it is not very realistic that a person walking through a building will each time pass by the center of the room to decide where to go next.

6.3.2 Geometric Network Model

Corridors hold an important position within the internal building structures as they are the major connecting sections that link multiple functional building units. A geometric network model represents those corridors by a subgraph within the total building graph, which results in a more realistic representation of the actual walking pattern indoor. Several options have been developed with the corridor as line structure (e.g. Lee, 2004).

Again, a significant miscalculation in the number of turns is visible due to a mismatch between the indoor network and the actual walking pattern. Most often, these mistakes are induced in large open areas which are either modeled (i) by a single node or (ii) by multiple nodes in a subgraph, both inducing unrealistic and unnecessary turn behavior. Node A (on path 1) forms the topologic representation of a spatial unit, in this case a quite large room. The created angle using solely this center node is in this example smaller than our threshold of 45°, not creating a turn while in the actual walking pattern a turn is experienced. Also, because of this unrealistic center point, the consecutive edges and nodes create further miscalculations. The angle itself is defined by the wrongful modeling (under-modeling of the spatial unit) of the walking pattern. On the other hand, the main mismatch in path 2 occurs around nodes B_1 and B_2, a corridor subdivided in various sub-nodes according to the Straight-Medial Axis Technique (SMAT) (Lee, 2004). However, the actual walking pattern ignores this over-modeling of the spatial unit and takes a more direct door-to-door path.

6.3.3 Cell-decomposed Model

In a cell-decomposed model, large open areas, generally modeled by a single node, are subdivided into multiple cells portraying more accurately the internal room complexity, with each individual cell modeled by a single node. Having a more detailed representation of a large open area also creates a closer representation of the actual walking pattern through those areas, with for example avoidance of obstacles and inaccessible areas. The creation of cells can be proposed for several reasons such as room size, concavity and functionality (Lorenz et al., 2006). However, automatic transformation between input floor data and cell creation is currently lacking.

The node-coordinate based turn algorithm returns with the cell-decomposed model a more accurate result than with any of the previous models, as the main room around node A is subdivided into three cells, labeled A_1 to A_3. This results in the calculation of a turn in node A_3, which aligns to the actual walking pattern of a user when traversing this room. However, the main problem still remains on deciding which units should be modeled into multiple cells and how they should be subdivided.

6.3.4 Visibility-based Model

Modeling unit by unit often does not correspond to the actual walking pattern of users in the building, as humans rely on a more visibility based spatial reasoning. In such a straight door-to-door visibility-based model, all doors (nodes in the graph) are connected with an edge when there is a direct line of sight. For non-immediate visible door nodes, a visibility partitioning (e.g. Stoffel et al., 2007; Zheng et al., 2009) can be performed, creating intermediate nodes.

The results of the turn calculations using a direct door-to-door visibility based network model show that the algorithm not necessarily calculates correct results. The visibility model returns less angles compared to the actual walking pattern because of its immediate door-to-door connections making the user sometimes go in an extremely sharp angle through a door. This model has also no immediate connection with the actual spatial units themselves, losing an important aspect for route instructions as people mostly connect with those spatial units and not with the doors connecting them.

6.4 Discussion

Previous analyses have shown that with current indoor network models and a simple node-coordinate based algorithm, the exact number of turns could not consistently be deducted in indoor spaces. On outdoor networks, the turn calculation results align with the perceptive notion of turns. In this section we go back to the construction theory behind the networks to discover the reasons for these different results and their implications in a broader context.

6.4.1 Difference between morphological and decision nodes

Before delving in into the actual construction rules of network nodes, it is important to establish the difference between decision nodes and morphological nodes. Decision nodes can be defined as nodes created at intersections having multiple choices of next possible paths for the user. The opposite is true for morphological nodes inducing a change in direction without facilitating a choice between different paths (i.e. internal curvature). Both types of nodes can be found in outdoor and indoor networks. However, in most cases, only decision nodes are used for calculating routes.

The type of node influences the results of turn calculations. For example, Figure 6-3 and Figure 6-4 both showed examples where the outdoor network consisted of only decision nodes. However, Figure 6-6 demonstrates that outdoor networks can contain strong intermediate curvature between two consecutive intersections. By using only the coordinates of the decision nodes in the turn calculations, no turn is detected in Node 2 (the outgoing edge is located in the 45° turn zone). However, when taking the last node before and the first node after the intersection (Node 2) into account (in this example Node A and Node B), independent of their type, a turn is accounted for in this intersection, as such coinciding with the actual perception of a left turn. Therefore, Algorithm 6-1 will need to take into account both decision nodes and morphological nodes and always rely on the last node before and the first node after the decision node to base the 45° threshold area upon. The 45° threshold area still only applies to decision nodes as turns are only defined in those nodes where a decision is pushed upon the user.

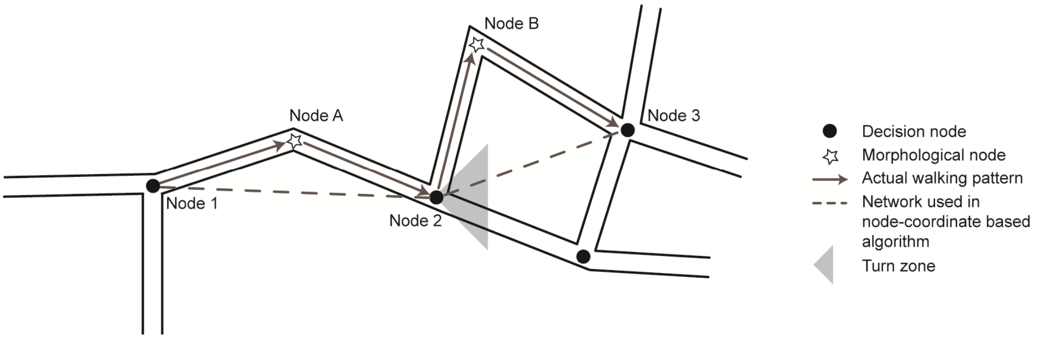


Figure 6-6 Morphological and decision nodes in an outdoor road network

This disambiguation between node types and their influence on turn calculations also holds for indoor networks. Both coordinates of the last node before and the first following the indoor decision node have to be used in Algorithm 6-1. As such, a more accurate perception of turns can be calculated, independent of where exactly the nodes are placed in (indoor) open areas.

6.4.2 Decision node creation rules in networks

Decision points play a pertinent role in the segmentation of route as goal-directed behavior (e.g. Klippel et al., 2005), since a wayfinder follows route segments to a decision point where a directional choice is made leading to a new route segment. This definition assumes an underlying network structure of space where the crossing of separate branches creates decision points.

In the construction of roads and intersections in the GDF standard, the basic guideline is functionality in terms of car driving. An Intersection is created when the extended sides of the roads overlap, at which two Junctions will be combined into one (Figure 6-7). If this is not the case, the two Junctions remain as two independent Intersections. An intersection can only occur where a choice between multiple road segments is available and as such a decision is pushed upon the users. The angle for deciding whether turning into a side route is defined as turn, is then modeled in this point following the direction where the wayfinder came from. Since centerlines of roads are quite easily constructed, defining outdoor decision points is fairly straightforward as they coincide with the actual point of decision making.

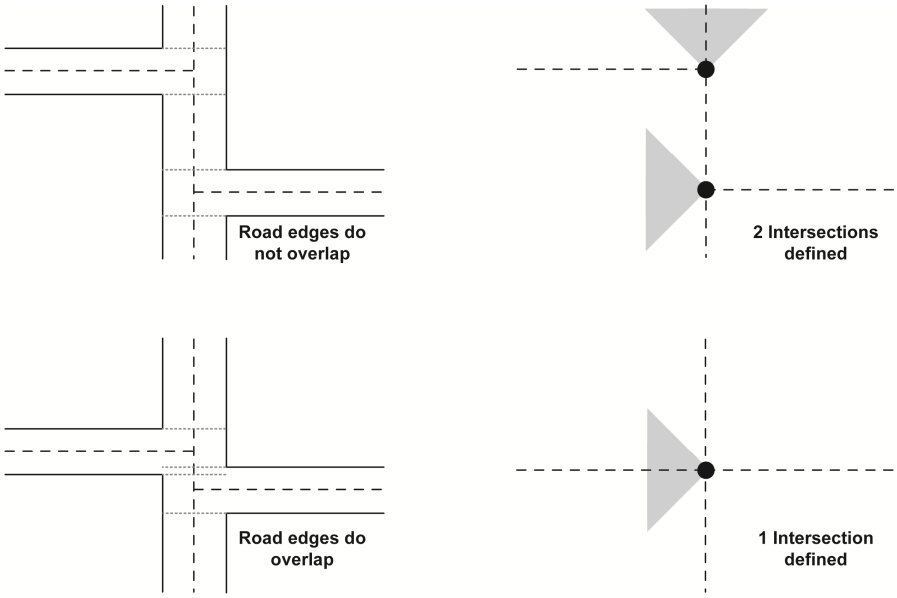


Figure 6-7 Intersection construction rules in the GDF standard (based on ISO, 2002)

In indoor space, the various networks demonstrate a different creation theorem for indoor decision nodes (Table 6-2) and this theorem is key to the wrongful calculation of turns in indoor environments. Remark that a similar subdivision is made between decision nodes (where the user has to make a choice between multiple directions) and morphological nodes (visualizing the internal curvature).

The indoor network model closest to the actual walking pattern in terms of decision node criterion is the visibility-based network. This network also returned the closest results in terms of turn calculations. Their common concept is the importance of doorways as starting point for decision making. However, the actual walking pattern alters this idea as not necessarily the door opening itself, but locations in front of the door opening itself can disambiguate between possible choices. This is a result of the fact that as humans, we walk in a plane perpendicular to the door opening. Additionally, some choices cannot be made in the door opening itself due to the concavity of rooms, and a point further within the room serves then as decision point.

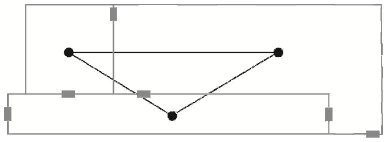
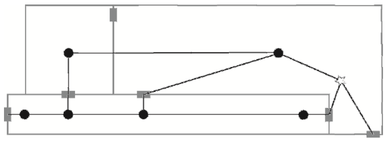
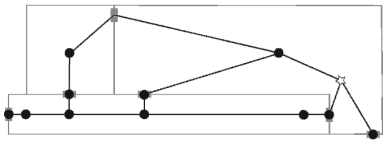
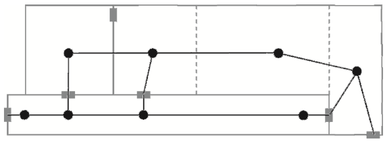
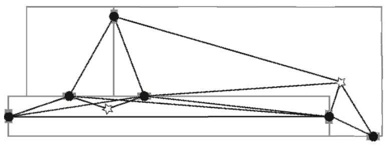
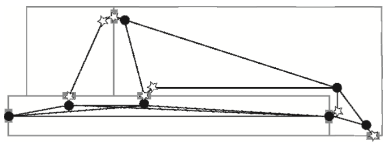
Network model	Decision node criterion	Visualization
Center-Node Network	Center of the room	
GNM (only room nodes)	Center of the room + door projections on corridor line	
GNM (room and door nodes)	Center of the room + door projections on corridor line + doors between all rooms	
Cell-decomposed model	Center of the room + door projections on corridor line + center of functional unit within a large room	
Visibility-based model	Doors between all rooms	
Actual walking pattern	Doors between all rooms and/or intermediate nodes along the visibility path	

Table 6-2 Decision node criterion for several indoor networks

As the different indoor models rely on various decision node criteria, it might be interesting to draw some parallelisms between the outdoor intersection creation and the indoor equivalent. After all, the outdoor turn calculations completely coincide with the actual perception of turns, while all indoor models return in some way wrongful turn results.

First, an exact copy of the intersection creation from outdoor space (Figure 6-7) to indoor environments is shown in Figure 6-8 (left). The idea is that indoor intersections are formed through the crossing of centerlines modeling the various rooms. Intersections can only be formed when two rooms are connected through a doorway. For example, rooms C and D are connected through a mutual door and as such their centerlines cross at a point in room D. Even though this network returns good results in terms of turn calculations, the main problem is that the created decision points are not necessarily linked to specific spatial units themselves. For example, although room B has a path through the center of its unit connecting rooms A and D, the spatial unit itself is not modeled by a separate node, creating a loose relationship between the network graph and how people actually reason about indoor units. This is also the reason why most indoor networks at this point are built from modeling each spatial unit individually.

A slightly adjusted model draws centerlines through the actual doorways connecting two rooms (as doors have been proven to be key in the calculation of turns) perpendicular to the plane of the wall where the door is located. The same problem with the disconnected relationship between graph and spatial unit remains, although the graph itself resembles the actual walking pattern more closely. However, in some cases (e.g. room E), the decision point is located outside the space of the spatial unit itself, making it not useful in the automatic calculation of the turns (Figure 6-8, right). As such the question remains to where exactly the decision point in indoor space should be best located, to be used in turn calculations.

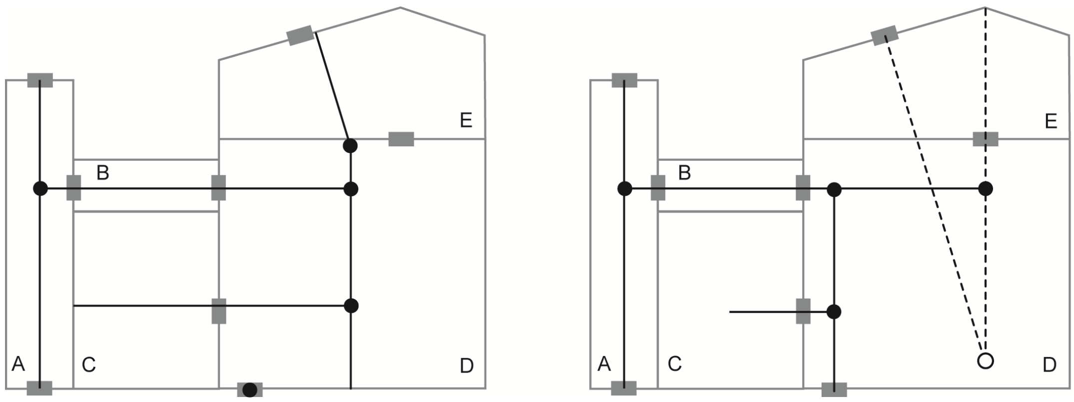


Figure 6-8 Creation of indoor decision nodes at the intersection of the extended doorways

6.4.3 Influence on verbal route instructions

There is an inherent link between directional changes detected by measuring the geometrical angle of change in movement and verbal route instructions with which those directional changes can be explained to users.

The generation and analysis of the effectiveness of outdoor route instructions has already experienced a long history within spatial cognition research (e.g. Daniel et al., 2003). More recent are studies examining the different components of why some parts of directions are perceived as being more difficult than others and how this can help in improving automated route guidance systems (Hirtle et al., 2010). Providing and following accurate route instructions in indoor environments are found to be more critical than outdoors (due to less external clues to maintain orientation). It is also more beneficial to know the particular routes than to know what cardinal direction to follow (Padgitt & Hund, 2012). However, the following example demonstrates the intricate relationship between route instruction generation and indoor networks.

Using the visibility-based network (for its relationship to actual walking patterns), the 45° turn threshold is drawn in the door opening. Every next door opening, located in this zone, is considered as 'straight ahead' from the previous door. For example, in Figure 6-9 (left), doors B and C are considered straight ahead from door N, while doors A and D require respectively a left and a right turn. However, the area of 45° turn angle extends indefinitely into the open space area, making doors that are actually requiring a turn, fit in the area of 'straight ahead'. For example, in Figure 6-9 (middle) door A is now considered as being straight ahead from node N, even though it is located at the exact same location in a slightly expanded spatial unit. Note also that again door C is considered straight ahead, even though it is part of a perpendicular wall on the right side of door N. One could discuss why door D is considered to be on the right and door C on the straight ahead of door N, while verbal instructions might distinguish them as 'close right' versus 'far right'. As such, the thresholds distinguishing those verbal descriptors might require a finer granularity in modeling the indoor spatial unit as to map the right description to the actual wayfinding perspective.

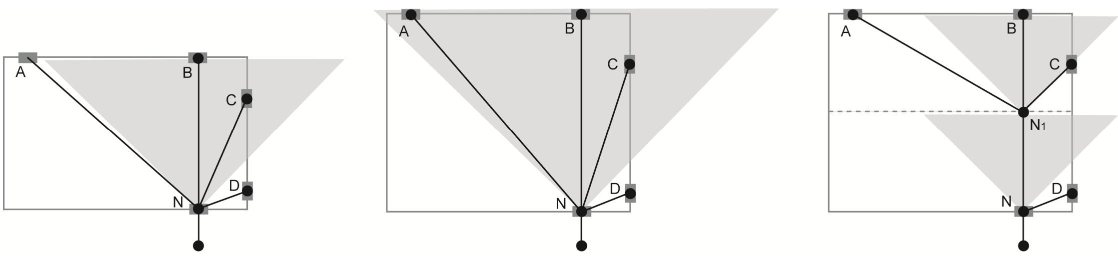


Figure 6-9 Doors as decision nodes in indoor space

A space subdivision (similar to the cell-decomposition model) could be the solution where the spatial unit is subdivided into smaller areas each being modeled by a single node (Figure 6-9, right). In this case, the room is subdivided into two cells, making that only door B is in the straight-ahead zone. To reach door A from door N a left turn is required, while doors C and D can be reached by making a right turn. In turn, this example highlights a problem of scaling, i.e. to what extent does the space need to be subdivided into smaller sub units to capture the full meaning of the various verbal route instructions and as such also the correct interpretation of directional changes?

The example in Figure 6-9 demonstrates the problematic nature of using indoor networks in the disambiguation of turns and in the generation of route instructions. Additional problems arise when considering the relationship between direction concepts, their directional models and the underlying spatial structure in which the performed action is embedded (Klippel et al., 2012). Indeed, participant's strategies for verbalizing route instructions are found to change along with the complexity of the intersections (Klippel et al., 2012). While angular directions allow some flexibility, i.e., they can be modeled in different sectors (right versus sharp right), the concept for straight seems to be an axis as far as simple intersections are concerned (Klippel et al., 2004). However, this becomes more complex if the action to be instructed takes place (a) at a complex intersection or (b) if competing branches require a disambiguation of the situation.

Route instructions for indoor space have not yet been studied that extensively. To our knowledge, the work of Mast et al. (2012) is one of the only ones touching upon the complexities of indoor verbal route instruction generation. They conclude that generic route instructions are not sufficient as they rely on network representations which are not able to model the indoor spatial complexities. For example, open spaces might not contain any clearly identifiable paths or decision points, making it illogical to impose a network structure. Instead, Rüetshi and Timpf (2005) define the concept of scene spaces with a hierarchical arrangement of objects as opposed to network spaces containing an inherent network structure. Mast and Wolter (2013) use this distinction for a more accurate creation of indoor route instructions. They conclude that even though wayfinding through both space concepts requires the determination of next possible directions, a clear delineation of 'decision points' in scene space is much harder. This is in line with our conclusions made in Section 6.4.2. However, their work in defining improved ways to generate route instructions in scene spaces is still in progress.

6.4.4 Concluding remarks

This discussion has led to the following main conclusions in a more general context of indoor navigation research and indoor Location-Based Services.

First, the mapping of movement to decision nodes in the network is the main challenge, not the calculation of turns themselves. This is due to the inherent differences between indoor and outdoor spaces, more specifically the contrast between the freedom of movement in indoor spaces versus more regulated and restricted movement in outdoor street networks. It can be concluded that not a single indoor network model at this point is all encompassing in dealing with turns. Every network poses new challenges to turn calculations. The visibility-based network might be the closest in modeling walking patterns, as it relies on similar concepts (visibility aspect, decision points in doorways). However, turn calculations are not accurate due to the sharp angles with which some doorways are entered. On the other hand, cell decomposition allows the mapping of spatial units with a finer granularity (which can help for example the accuracy of route instructions) but there is no theorem on the exact size and location of those cells.

Some situations will indeed lead to better results in terms of turn calculations, but this seems more related to the geometry of the spatial units and not necessarily to the network description itself. As such, for more accurate turn calculations, doors form the key element together with treating every spatial unit by itself. At this point, we are developing a network independent algorithm for indoor turn calculations in line with the perceptual notion of directional changes in indoor space instead of trying to come up with a 'perfect' indoor network.

Second, on top of the already hampered turn calculations, the specificities of indoor spaces pose some additional challenges for the generation of indoor route instructions. Imposing a network-based verbal route instruction creation method on scene space objects impedes the effectiveness of those instructions. However, the practical implementation of scene versus network space into indoor wayfinding and algorithms is not applicable yet and this for several reasons: (i) indoor route instruction creation is still at its infancy with the main problem remaining the definition of scene spaces and the categorization of all possible semantic objects that make up indoor scenes (Mast & Wolter, 2013); (ii) Aiding wayfinding by providing appropriate algorithms requires selecting paths from a network (Golledge, 1999). Algorithms for navigation need a topology of connectivity to run on, which cannot be provided by the strict containment hierarchy present in scene spaces. Network models on the other hand are based on modeling this topologic relationship of connectivity, also indoors. How the network should be structured to capture the requirements for indoor route instructions remains currently still an open question.

Apart from a different theory for indoor route description modeling, the relationship of direction concepts and intersection types indoors is also up for further investigation. We might not have to deal with different types of intersections indoor in the strict sense but might require a vaguer concept. Empirical tests on what is perceived as a turn in different indoor situations could be a first step towards an increased knowledge on the topic. This should be combined with tests on which indoor route instruction accompanies which indoor situation. Indeed, one can compute easily turns, but did the person moving really make a change in direction and did he perceive it as such?

Although we focused on solutions for indoor turn calculations (and as such facilitating for example the application of fewest turns path algorithm indoors), bringing other algorithms and analytical functions to the indoor world can pose similar challenges. The inherent problem still remains the modeling of indoor areas by networks. Even though indoor environments are open space areas, they are still bounded by multiple impenetrable boundaries (at least for human users in navigation applications). Many data sources assume an 'ideal space', i.e. represented by unbounded homogenous space with Euclidean distances (Okabe & Sugihara, 2012). However, ideal space is far from the real world, especially with respect to indoor environments. Indoor analyses have to deal with constraint, non-Euclidean space. While a simple indoor context can get by with a network abstraction, the coarseness of this representation can become inconsistent with more complicated analyses. As shown in Section 6.3, various options for indoor networks have already been presented. It is however not clear yet what and if there is a perfect indoor network available. Ongoing research on 3D routing using the IndoorGML standard (OGC, 2014) might be a valuable start for further research on determining an improved structure of indoor networks. On the other hand, more research might be required for the development of improved methodologies for indoor analyses tailored to the specificities of indoor spaces. A starting point can be the work of Okabe and Sugihara (2012) presenting common analytical concepts adapted to network spaces.

Additionally, one can examine the results of these analyses over the various available indoor network options in order to provide a more comprehensive indoor network structure and understand the implications on analytical results.

6.5 Conclusion

In this paper, the problem of automatic turn calculation on indoor network models was highlighted. Accurate turn calculations are of relevance for a consistent implementation of cognitive algorithms based on minimization of turns as cost heuristic (e.g. fewest turns path, simplest path algorithm). Turn calculations based on a node-coordinate based algorithm were executed in both an example of an outdoor road network and several indoor network models. While in outdoor space, accurate results could be obtained independent of the level of detail, all indoor network options showed aberrations with the actual perception of indoor turns. It was demonstrated that these aberrations were rooted on a different creation of networks and as such also a different underlying meaning and formation of decision points. This is due to the inaccurate modeling of indoor scene spaces by networks which generalize both the required granularity for navigation applications as well as the appropriate modeling of verbal route instructions and directional changes. Therefore, we suggest the development of a network independent algorithm for indoor turn calculations in line with the perceptual notion of directional changes in indoor space. Furthermore, more research is required into the relationship between indoor network structures and the results of indoor analyses.

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7

AUTOMATING TURN CALCULATIONS FOR THE INDOOR APPLICATION OF THE FEWEST TURNS PATH ALGORITHM

Modified from: VANCLOOSTER, A., OOMS, K., VIAENE, P., FACK, V., VAN DE WEGHE, N. & DE MAEYER, P. 2014. Automating turn calculations for the indoor application of the fewest turns path algorithm (Submitted to the International Journal of Geographical Information Science).

ABSTRACT

The goal of this paper is to introduce a procedure for automatically calculating turns in indoor spaces. Automatic turn calculations are of relevance in the implementation of simplest path and fewest turns path algorithms. Indeed, these algorithms aim at improving the complexity of route instructions by among others minimizing the total number of turns. The amount of turns along a path is thereby required to coincide with the actual user's perception of turns during locomotion. Previous research has demonstrated that current indoor network models do not facilitate accurate calculation of the number of turns along a path, in contrast to common outdoor networks. The main reason for this, are the existing differences in decision node criteria between indoor and outdoor networks and the mapping of movement to those decision nodes. Therefore, this paper introduces a new procedure for automatically calculating turns in indoor spaces, which works independently of the underlying indoor network structure. As a result, it can be used in any indoor modelling situation. The idea behind the algorithm is based on a direct door-to-door walking pattern combined with a more human perception-based notion of turns. As an example of its functioning, the algorithm is applied in the indoor implementation of the fewest turns path algorithm and will also allow future application in the indoor simplest path algorithms.

7.1 INTRODUCTION

As long as people have to decide where to go and how to get there, navigation will remain one of the fundamental behavioral problems for human cognition (Montello, 2005). Over time, navigation and wayfinding processes have been widely studied (e.g. Golledge, 1999) with wayfinding thereby defined as the purposive, directed and motivated process of determining a route between origin and destination, supported by a cognitive map of the environment (Montello, 2005). Since not all users, and especially users unfamiliar with their environment, command a sufficient cognitive map for successful wayfinding, this process is often guided by external aids (Golledge, 1999).

The main objective of this research comprehends the provision of such guidance aids to support wayfinding experiences of users in an unfamiliar environment. We specifically chose to limit our environment of study to indoor spaces as wayfinding research has repeatedly demonstrated the increased challenges of successfully performing navigational tasks in complex three-dimensional space (e.g. disorientation after vertical travel, less visual routing aid, deficient cognitive map creation) (Hölscher et al., 2009). In outdoor wayfinding research, a set of 'cognitive' algorithms (e.g. Duckham & Kulik, 2003; Grum, 2005) has already been created to deal specifically with increased wayfinding challenges by providing routes that are easier-to-follow, more intuitively correct, and in general more adhering to how people conceptualize routes to unfamiliar users (Tsetsos et al., 2006). Conversely, current research on indoor navigation and wayfinding is still mostly limited to Dijkstra (1959) or derived shortest path algorithms (e.g. Kwan & Lee, 2005; Thill et al., 2011). As a result, non-realistic paths (e.g. using complex intersections, avoiding main walking areas) are often proposed. Given the higher complexity indoors compared to outdoors, there is a considerable need in guiding unfamiliar users along 'easier-to-follow' paths. Chapter 5 has shown a first implementation of such an outdoor cognitive algorithm to indoor spaces, in this case the least risk path algorithm, minimizing the risk of getting lost.

In this paper we aim at improving indoor navigation by focusing on a different cognitive aspect of path guidance, namely the minimization of turns along a path. Over time, research has demonstrated the importance of minimization of the number of turns in providing less complex route instructions. For example, Golledge (1995) found that apart from time and distance, the amount of turns along a path is an important criterion in human route selection. Additionally, it was also proven that people familiar with their environment, when planning a route for someone else, provide different routes than those they would take themselves, with a significant lower complexity in the number of turns (Hirtle et al., 2010). Furthermore, Turner (2009) demonstrated, based on outdoor movement of familiar people, that the impact of turns on cognitive distance plays an important role in decision making, even when users have a good knowledge of the spatial network. Finally, the route of minimal deviations from a global direction may be perceived as optimal, because users feel more comfortable if they do not change the direction too much (Winter, 2002). This is also confirmed in Dalton's study (2003) where subjects attempt to conserve linearity throughout their journey provided that this choice approximates the direction of the final destination. As such, a minimization in number of turns has been demonstrated to be an important factor in both the selection of appropriate routes for guiding unfamiliar users as well as maintaining a feeling of comfort during the execution of those routes.

The remainder of the paper is organized as follows: Section 7.2 elaborates on the definition of turns in various research fields; in Section 7.3, several parameters causing difficulties with indoor turn calculations are identified; in Section 7.4 a new algorithm to accurately calculate indoor turns is proposed; and in Section 7.5 this algorithm is implemented in the fewest turns path algorithm. Finally, Section 7.6 elaborates on the conclusions from this study.

7.2 Defining the concept of turns

7.2.1 What is a turn?

In general, a turn can be defined as a directional change from the line of movement (Cambridge Dictionary). The angle is a central point in this definition, consisting of the corner between two distinct rays issuing from the same vertex. In case of wayfinding and concurrent route instructions, not every change in direction should be labeled as a turn. Indeed, turns are perceived as an enforced deviation from the current direction (Winter, 2002).

Evidence has also shown that some turns are more important than others to humans (Turner, 2001). For instance, a slight shift of 15° might not be considered a turn, while anything closer to 90° will be (Turner, 2001). At this point, there is no agreement on which angles form the boundary for deciding the significance of a directional change. For example, Mark (1986) describes in his simplest path algorithm that an angular change above some threshold incurs a maximal turn cost. However, the threshold itself has not been mentioned. In more recent wayfinding literature, a turn is defined as a decision to deviate from the straight ahead by more than 45° (Hölscher et al., 2011). The authors decide to concur with this definition and will describe a turn as any directional change deviating from the straight ahead by an angle of 45° or more. Obviously, there are possibilities to alter this threshold and calculate its impact on the results of the number of turns over various algorithmic tests.

7.2.2 TURN CONCEPTUALIZATIONS IN WAYFINDING RESEARCH

Over time, various researchers have proposed several definitions and measures for detecting turns, each embedded on a specific conceptualization of space and as such having different implications on turn calculations (Table 7-1). Turn calculations are most of interest in fewest turns path algorithms minimizing the number of directional changes on a route graph (Hillier & Iida, 2005). The simplest path algorithm extends this thought as it calculates paths with a minimal route description complexity based on the required amount of information at each intersection. Simplest path algorithms exist under multiple variants (Duckham & Kulik, 2003; Mark, 1986; Richter & Duckham, 2008), each focusing somewhat differently on the minimization criterion of route description complexity. However, all of them attach more cost to dealing with a turn, independent of the underlying intersection complexity and structure.

Winter (2002) proposes a line graph (maintaining the original topology of the road graph) to handle edge-edge relationships that describe a turn in response to the common more costly approaches of splitting up graphs in multiple nodes or adding turn penalty tables in nodes. Even though several interesting weight adjustments are suggested (e.g. semantic and human generalization), nowhere is mentioned what exactly is considered as turn. It can only be assumed from the construction rules of the line graph that every intersection gives occasion to turns when the edges of the outdoor street network are not aligned. Jiang and Liu (2010) compute fewest turn paths based on a natural routes concept, i.e. where various street edges are merged into a single road when they contain a sort of continuity in movement.

Author	Turn concept	Turn measure	Space concept
Simplest path algorithm (Duckham & Kulik, 2003; Mark, 1986; Richter & Duckham, 2008)	Classification of route instructions into frames depending on complexity for verbal description	Interplay of intersection complexity with directional changes	Road graph
Turn costs in route planning (Winter, 2002)	Edge-edge relations	- >0° - Human perception generalization: > threshold - Semantic turn concept: different street name	Line graph
Fewest turn algorithm (Jiang & Liu, 2010)	Change from one natural road to another (45° deflection angle)	Not every junction is considered decision point	Natural road graph
Space syntax research (Hillier & Hanson, 1984)	Visual transition (all turns equally treated)	Integration measure: average no. of turns to reach all streets	Axial map
Angular analysis (Turner, 2001)	Actual angle of visual transition	Cumulative angular cost incorporated in integration measure	Axial map
Indoor accessibility (Kim et al., 2008)	Visual transition	Impedances in integration measure. Impedances change depending on type and angle of movement	Axial map

Table 7-1 Classification of various approaches with different turn conceptualizations

Similar to traditional road graph conceptualizations, Space Syntax Community starts from the idea of breaking down space into a network of choices, which in turn can be modeled by graph theory. However, from there on it presents a highly different view on spaces, based on the internal visibility between locations. For example, their axial map is a graph of axial lines representing visibility relationships by drawing the fewest longest lines of sight (Turner et al., 2001). On this axial map, a spatial integration measure can be calculated, quantifying the number of turns to reach all street segments. As such, it forms a measure for the cognitive complexity of reaching a street and is found to predict pedestrian usage (Turner et al., 2001). The connectivity relationship present in the graph topology represents in this case turns as a visual transition instead of the pure connectivity of roads and edges in traditional road graphs. In its original definition, axial integration is a measure of depth in terms of number of turns, biasing all turns equally.

Turner (2001) proposes an improvement, termed angular analysis, by using the actual angle in the calculation instead of using binary turns as it was shown that people apparently move by considering a more subtle approach to turns. Kim et al. (2008) propose also an adaptation to the original axial integration calculation by adding impedances that allow diversification depending on the turn situation.

7.2.3 WHERE ARE TURNS COUNTED?

Decision points play a pertinent role in wayfinding as they segment routes into intermediate points where directional choices can be made (e.g. Klippel et al., 2005). This definition assumes an underlying network structure of space where the crossing of separate branches creates decision points. This coincides with the definition used in the simplest path algorithm (Duckham & Kulik, 2003; Mark, 1986). However, the fewest turns path algorithm of Jiang and Liu (2010) states clearly that not every junction is considered a decision point and turns are only counted when changing from one natural road to another, not the directional changes within a natural road. Winter (2002) inserted a similar idea in his line graph by merging semantically linked road segments. In the axial map conceptualizations, turns are also not counted at every physical intersection, but rather on the crossing of visual lines of sights. In this paper, it was decided to concur with the 'traditional' definition of intersections, i.e. turns will be counted at every intersection where path alternatives are available. This is extended by counting turns induced by the internal curvature, as these can also influence the cognitive feeling of wayfinding complexity. Applied to indoor environments, this means that any spatial unit having multiple doors can give rise to turns, as well as any curvature within the spatial unit.

7.2.4 TURN CONCEPTS IN ROUTE INSTRUCTION GIVING

The definition of a turn is tightly linked to the user's perception on making a significant change in direction, which is linked to how people verbalize navigational paths in line with their cognitive thinking of space. For example, the simplest path algorithm (Duckham & Kulik, 2003) is based on conceptualizations of essential elements of verbal route instructions into a cost model, of which the turn concept is one aspect (Streeter et al., 1985). As such, it is interesting to consider the structure and content of route instructions and their relation to turn concepts in both outdoor and indoor research.

The verbalization of route instructions can be modeled by three main components: (i) salient features, (ii) structure of decision points and (iii) the action itself (directional change or not) (Klippel et al., 2012). Turn actions at intersections are quite intertwined with the structure of decision points, hence influencing route instruction creation (Klippel et al., 2012). For example, Figure 7-1 demonstrates that with a similar angular displacement on different types of intersections, not necessarily all coincide with the same verbal description of 'go right'. However, at this point we choose to focus solely on the direction concepts as it is not important to know exactly the complexity of a turn, but merely the disambiguation of a turn versus no turn in the wayfinding experience. In future research, the integration with various intersection types in indoor environments will be considered, if only to enable a full implementation of the simplest path algorithm to indoor spaces.

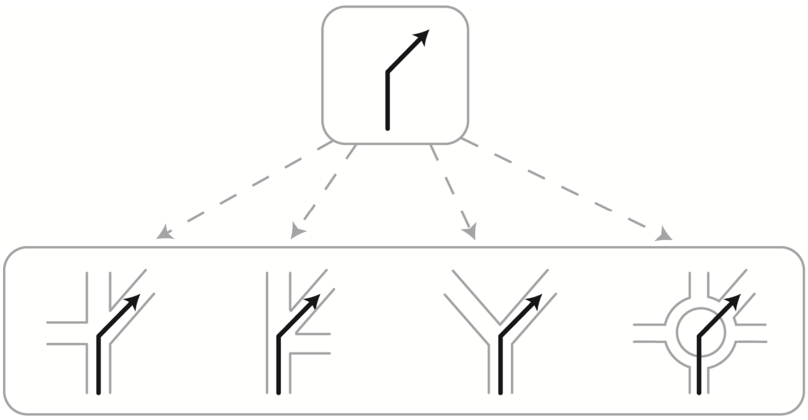


Figure 7-1 Relationship between turns and intersection types in route instruction giving (based on Klippel et al., 2012)

While previous authors all referred to research performed in an outdoor route instruction context, research on indoor route instruction creation is still in its infancy. To our knowledge, the work of Mast et al. (2012) forms one of the only papers on the topic, more specifically on the enhancement of indoor route instructions using descriptive generation strategies, i.e. without superimposing an artificial route graph on open space areas. Their work starts from the finding that generic route instructions (e.g. 'take first door on the left') do not always comprise the complexities of certain indoor situations (see also Section 7.3.1). As such, verbal route instructions require the detection of turns with a fine enough granularity, allowing for the disambiguation of the type of turn in reference to the underlying intersection type. In indoor environments, this process can become more complicated due to the difficulties with which a network can be modeled on top of open space areas (see also Section 7.3.1). That is why the procedure to automatically calculate turns based on a perceptive notion of turns (Section 7.4) will need to be closely linked to the translation of space models into verbal route instructions.

7.3 INFLUENCE OF THE CHOSEN INDOOR SPACE MODEL ON TURN CALCULATIONS

7.3.1 COMPARING INDOOR VERSUS OUTDOOR NETWORKS FOR TURN CALCULATIONS

In Chapter 6, a simple turn calculation algorithm was proposed using the coordinates of three consecutive nodes in the network and the slopes measured to the horizontal x-axis (Figure 7-2). If the angle formed in the middle node (N_{middle}) is larger than the defined threshold (in this case set at 45°), a turn is detected. In all other cases, no turn is accounted for. This algorithm was tested on outdoor street networks and five indoor networks, to examine the accuracy in calculating turns in both systems. Considering a further discussion on this topic, the main results of this research will be summarized briefly.

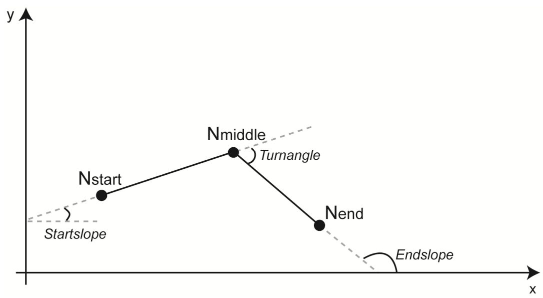


Figure 7-2 Node-coordinate based algorithm for automatically calculating turns

This study demonstrated that with current indoor models and a simple node-coordinate based algorithm, the exact number of turns could not consistently be deducted in indoor spaces, while the results in outdoor space were correct. The reason for these inaccurate indoor turn calculations was proven to be connected to differences in network construction between indoor and outdoor spaces, induced by a different definition in terms of what makes up a decision node. In outdoor networks, the creation of a decision node is based on the point where all road centerlines intersect. In indoor space, the various networks demonstrate a different creation of indoor decision nodes depending on varying abstraction rules of space (Table 7-2). For example, the center-node network models individual spatial units by single nodes (similar to crossroads in outdoor street networks), without taking into account the location of doors. On the other hand, in the visibility-based network, doors are considered to be the locations where choices are made for the remainder of the path and as such modeled by nodes. Due to this different theoretical decision node criterion, the turn calculation algorithm does not apply to indoor spaces. Even after applying outdoor network creation rules to indoor spaces, it was impossible to consistently create an indoor navigational network able to correctly handle and construct intersections similar to the outdoor case (Chapter 6).

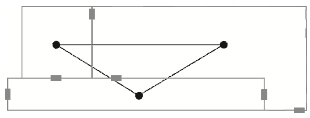
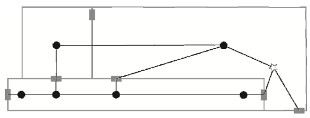
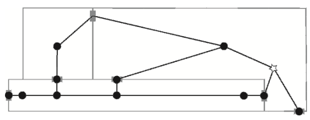
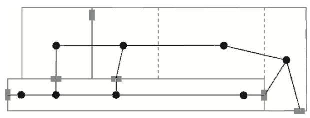
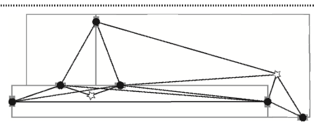
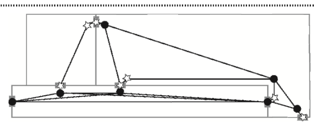
Network type	Decision node criterion	Visualization
Center-Node Network	Center of the room	
Geometric Network Model (GNM) (only room nodes)	Center of the room + door projections on corridor line	
GNM (room and door nodes)	Center of the room + door projections on corridor line + doors between all rooms	
Cell-decomposed model	Center of the room + door projections on corridor line + center of functional unit within a large room	
Visibility-based network model	Doors between all rooms	
Actual walking pattern	Doors between all rooms + intermediate nodes along the visibility path	

Table 7-2 Decision node criterion for several indoor networks (Chapter 6)

The core of this problem is essentially related to the existing structural differences between indoor and outdoor spaces. Over time, several authors (e.g. Li, 2008; Worboys, 2011) have tried to identify these differences with the aim of developing fully integrated indoor-outdoor applications. However, they mostly relate to intuitive visual and logical characteristics, and lack a theoretical foundation. Mast et al.'s vision (2012) on indoor spaces in this case appears to be more advanced as it is based on the distinction between network and scene space.

Network spaces are characterized by an inherent network structure, as such making graphs constitute an appropriate formalism for modeling these environments. Scene spaces on the other hand are built around the deliberately vague concept of scenes as local spatial configurations (Rüetshi & Timpf, 2005) and do not necessarily exhibit this network structure. For example, open spaces do not contain any clearly identifiable paths or decision points, which make it illogical to impose some kind of network. Mast and Wolter (2013) describe the influence of this distinction between spaces on indoor wayfinding experiences and route instruction creation. In indoor network space, the main question during wayfinding relates to determining the location of the decision point and its required action. In scene space, wayfinding consists of 'which' and 'where' questions such as 'Which door should I take?' and 'Where is the door that I need to take?' Although in both cases a determination of next possible directions is required, a clear delineation of 'decision points' in scene space is much harder (Mast & Wolter, 2013).

Although we agree with these inherent differences present in indoor spaces and the mistakes created by inducing a network on scene space objects, the practical implementation of scene versus network space into indoor wayfinding support is not applicable at this point. Indeed, indoor route instruction creation is still at its infancy due to a lack in definition and categorization of all possible semantic objects that make up indoor scenes (Mast et al., 2012). Furthermore, aiding wayfinding by providing appropriate algorithms requires selecting paths from a network (Golledge, 1999). These algorithms require a topology of connectivity, which cannot be provided by the strict containment hierarchy present in scene spaces. As such, we will continue modeling all indoor spaces, including scene spaces, by a network abstraction, realizing that this induces errors in space perception and possibly in indoor route instruction creation. The magnitude of this error will still have to be determined in further research.

7.3.2 Indoor spatial parameters influencing turn calculations

In the following paragraphs, several simple situations are introduced that cause problems with the automatic calculation of turns in indoor environments. These examples all show the circumference of the spatial units and their connecting door openings. A network is overlaid on top to help demonstrate the specific spatial parameters that induce problems in turn calculations. We opted to use the geometric network model and the visibility-based network as example networks, because they model the actual walking pattern the most realistically and as such should allow the closest result in automatic turn calculations. To make it clear when a turn is detected, triangles in the nodes designate the 45° turn angle zone which was previously set as threshold for the detection of turns.

7.3.2.1 Position of doors in the circumference of the spatial unit

In this section, we want to illustrate that the relative position of the entry and exit doors influences the results of turn calculations. Figure 7-3 shows two different situations: a first where the entry door to the spatial unit is located in the middle of the wall (left), a second where the same door is located at a more extreme position (right). Visualizations (a) and (b) represent respectively a geometric network and a visibility-based network. Visualization (c) shows an indication of the actual walking pattern as dashed line. The dark gray polygon shows the extension of the 45° turn angle zone, while the continuous black line shows the possible positions of doors through which no turn would be considered given the chosen network (referred to as 'no-turn zone').

Figure7-3 demonstrates that with different entry locations, different results in terms of turn calculations are obtained over the various network abstractions. With a central door position, the 'no turn zone' using the geometric network (a-left) contains the entire opposite wall and parts of the left and right side walls, while in a visibility-based network (b-left) almost the entire side walls will be categorized as 'no turn zone'. However, one can realistically assume that a wayfinder would consider every door that is on the opposite wall as being straight-ahead in this case. Obviously, this is a very simple example, leaving room for discussion in more advanced cases. With a more extreme position of the entry location, the wayfinder's perception of a left turn remains (c-right). However, using the geometric network (a-right), the entire top left corner captures the 'no turn zone'. In the visibility network (b-right), the right wall is almost entirely considered as 'no-turn zone' (and thus straight-ahead), while it only seems reasonable that a right turn is detected in those cases. A lower threshold could be proposed, but in more elongated rectangular spaces, the problem would remain. The position of the doors in combination with the location of the center point constitutes the key problem for a difference in turn accounting.

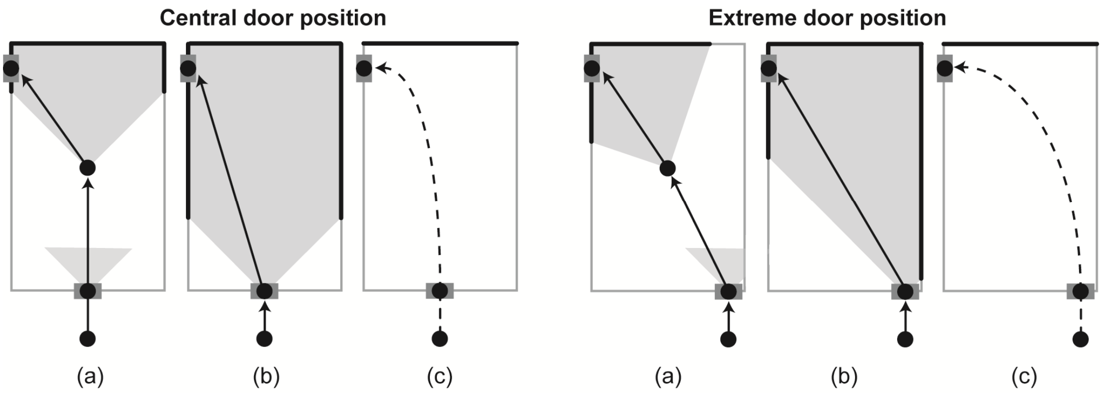


Figure 7-3 Influence of the position of doors in the calculation of turns using a (a) geometric network model and (b) visibility model against (c) an approximation of the actual walking pattern

One could assume from Figure 7-3 that whenever the exit door is situated on the opposite side of the wall through which is entered, no turn will be made. However, Figure 7-4 shows that for example when the edges are in each other's extension, this is not always the case. In both network models, not a single turn is calculated as all edges are located within the 45° turn angle zone, while the actual walking pattern will deal with two turns within this room: one right turn after the first door and a second more left turn to reach the destination. Also, determining the opposite wall is not always straightforward as often rooms have a more complex shape than a simple rectangle.

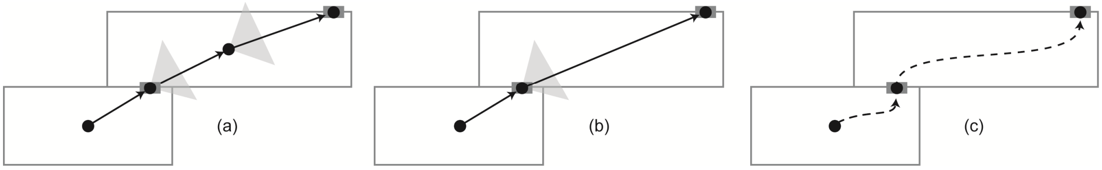


Figure 7-4 Door on opposite wall using a (a) geometric network model and (b) visibility model against (c) an approximation of the actual walking pattern

7.3.2.2 Geometry of the room

A second parameter important in the calculation of turns with respect to a chosen indoor network model is the geometrical shape of the room. In particular, the geometry defines the location of the center point, which is mostly of importance when using the geometric network, and also the direct visibility of a door due to the concavity or convexity of the room.

A problem occurs when the center point of a spatial unit is located at an extreme position compared to the location of both entry and exit doors (Figure 7-5). In a geometric network, two turns -respectively a right turn followed by a left turn- would be wrongfully calculated (continuous black line). The visibility model would not consider any turn as both doors are in line, which would coincide with the actual perceptive notion of turns.

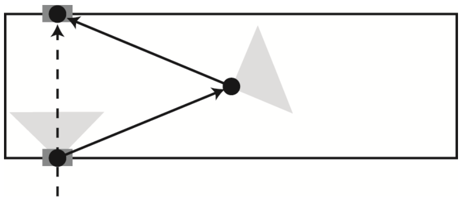


Figure 7-5 Effect of an extreme position of the center point on turn calculations

Often the geometric shape of the spatial unit contains concave corners, inhibiting direct visibility from door to door. The center point is thereby not always situated inside the shape of the polygon, resulting in unrealistic paths when using the geometric network model and inaccurate calculation of turns (Figure 7-6a). This situation can be solved by creating a subgraph using the SMAT transformation (e.g. Lee, 2007) (Figure 7-6b). However, Lee (2007) only proposes this transformation in case of spatial units that are labeled as 'corridors'. It requires also a computationally intensive process, making it unrealistic to model all concave units with this algorithm. Another solution makes use of visibility partitioning algorithms (e.g. Stoffel et al., 2007) where a concave spatial region is decomposed into smaller convex regions. The partitioning itself requires the creation of split lines where not mutually visible points are connected through intersections with these lines. But even this subdivision does not necessarily guarantee correct results as is shown in Figure 6c where in this case only a single turn is accounted for.

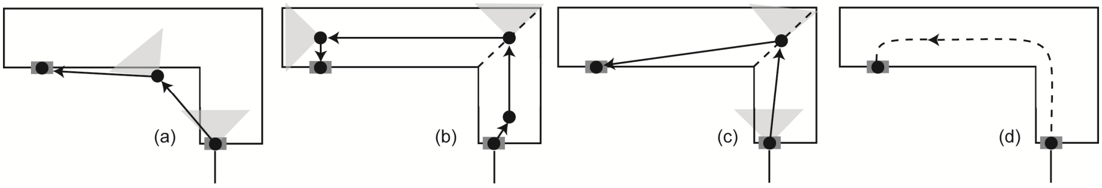


Figure 7-6 Effect of the geometric shape on turn calculations: (a) geometric network model, (b) geometric network model with SMAT transformation, (c) visibility partitioning, (d) actual walking pattern

7.3.2.3 Location before and after entering

The location of the nodes before and after entering a spatial unit are of importance in the calculation of turns as it determines the direction of the rays and as such the formed angle in the decision points. Previous algorithm takes the coordinates of both nodes before and after entering into account, while this results in wrong turn calculations. For example, Figure 7-7a shows that when using a geometric network (including door nodes) one turn in node A is returned. Similarly, the visibility-based network results no turns due to the fact that all nodes are almost located on a single linear section together with both door openings (Figure 7-7b). However, the actual walking pattern results in three turns: one to go right through door A, one before node C to go left and a third one immediately behind door C to go right to reach the final node. This is because of the fact that people always walk straight through doors, perpendicular to the wall that contains them.

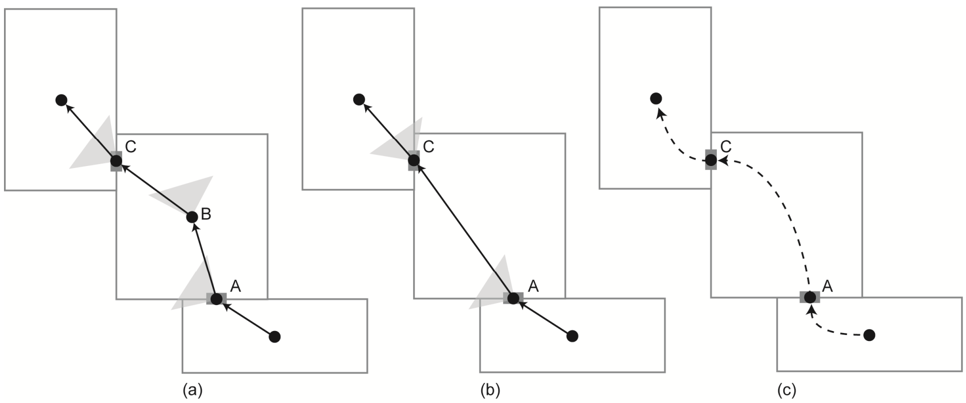


Figure 7-7 Influence of location before and after entering a spatial unit in various network settings: (a) geometric network, (b) visibility-based network, (c) actual walking pattern

7.4 PERCEPTION-BASED INDOOR TURN ALGORITHM

In Section 7.3, several key characteristics of indoor spaces were derived that inhibit a correct matching between actual perception of turns and their automatic calculation and this in relation to the underlying network structure. In the following section, a new algorithm is presented with the aim of accurately accounting for all turns, entirely based on the spatial structure of indoor environments without relying on any specific network abstraction.

7.4.1 RELATIONSHIP BETWEEN ACTUAL WALKING PATTERN AND INDOOR NETWORK MODELS

Theoretically, the walking pattern, determining the accurate number of turns in terms of a user's perception, is very similar to a visibility-based network as they both rely on the principle of walking on a direct line of sight. However, it was demonstrated that using only the visibility-based network is still problematic for calculating indoor turns in at least two cases. First, Figure 7-7 showed that the mismatch in number of turns using the visibility-based network is induced by the angle formed by the connection between the doors, which is too sharp to actually correspond to how people walk through those doorways. Second, when there is no direct line of sight, a subdivision as proposed in Figure 7-6c, is also not necessarily in accordance with the actual human perception of turns.

Conversely, an indoor network modeling the user's actual walking pattern, incorporates the visual door-to-door connections, but corrects for possible sharp angles. In other words, the network would have to account for a change in perception when walking through doors. Indeed, humans do not only rely on a visual line of sight between doors, they also have to be able to physically walk through them. Therefore, they rely on a path more perpendicular to the wall orientation itself. Such a perception-based network would incorporate nodes before and after each door as being the representative nodes for a single door (splitting up door nodes into two nodes). However, it is still an open question where exactly these nodes should be located (i.e. how far in front of the door). Also, the creation of such a network would result in many manual additions of nodes. Therefore, we do not have the aim to create such a network but merely use its construction rules as foundation for the development of a new perception-based indoor turn algorithm.

7.4.2 THEORY AND PARAMETERS OF THE ALGORITHM

The idea behind the perception-based indoor turn algorithm is the combination of visible view points at the decision points in doorways with the actual walking pattern perpendicular to the orientation of those doors. Therefore, we propose that the algorithm takes into account two variables: (i) the mutual orientation of both walls containing the entering and exit doors (α) and (ii) the angle between the line of walking pattern and doorway (β) (Figure 7-8). As such, this algorithm is not based on any kind of underlying network sturcture, but only uses the spatial structure of the individual rooms to determine the presence of indoor turns.

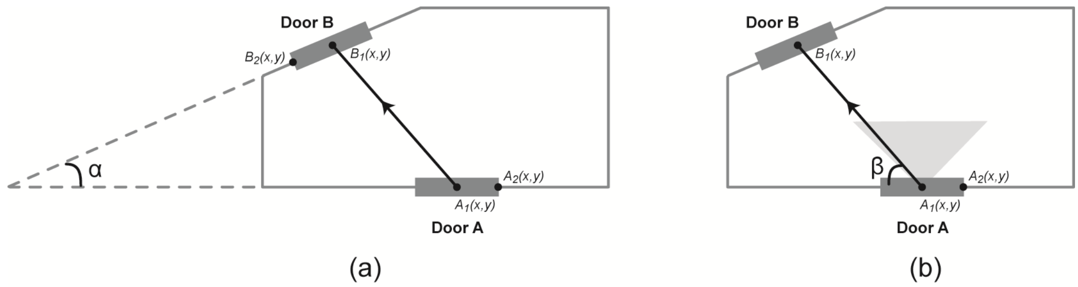


Figure 7-8 Parameters of perception-based indoor turn algorithm

To account for a turn, first the change in angle of walls containing both entry and exit doors is calculated. This is combined with a 45° threshold area drawn from the entry door opening as in this case the doors model as decision point for the actual walking pattern. This supports the idea that in a normal convex room only maximum two turns can exist. In concave rooms the number of turns is depending on the visibility between door nodes. Table 7-3 summarizes the various situations that give rise to a certain amount of indoor turns.

	Inside 45° threshold area (45° <= β <= 135°)	Outside 45° threshold area (β < 45° OR β > 135°)
α <= 45°	0 turns	2 turns
α > 45°	1 turn	1 turn

Table 7-3 Convention on the number of turns within a convex spatial unit

Both variables α and β require the calculation and comparison of the angle formed by two lines. For comparing the respective orientation of the walls containing doors (Figure 7-8a), the angle α between the walls with the entry (A_1-A_2) and exit (B_1-B_2) doors can be calculated using two coordinates of each door. The angle is then compared to the predefined threshold of 45° to distinguish between 1 turn or, 0 and 2 turns (Table 7-3). For the calculation whether the line of the walking pattern (A_1-B_1) falls into the threshold perpendicular to the orientation of the doorway, the angle β between both is calculated. If the angle has a value between 45° and 135°, it is considered that the user walks in a straight line from the door to the next node. If not, a turn is detected (Figure 7-8b).

Figure 7-9 illustrates in more detail this theory in two situations, with each example highlighting the number of turns, and the values for variables α and β. Situation b refers back to Figure 7-3 where none of the available indoor networks proved useful in accurately calculating indoor turns. The developed theory is able to correctly account for each situation.

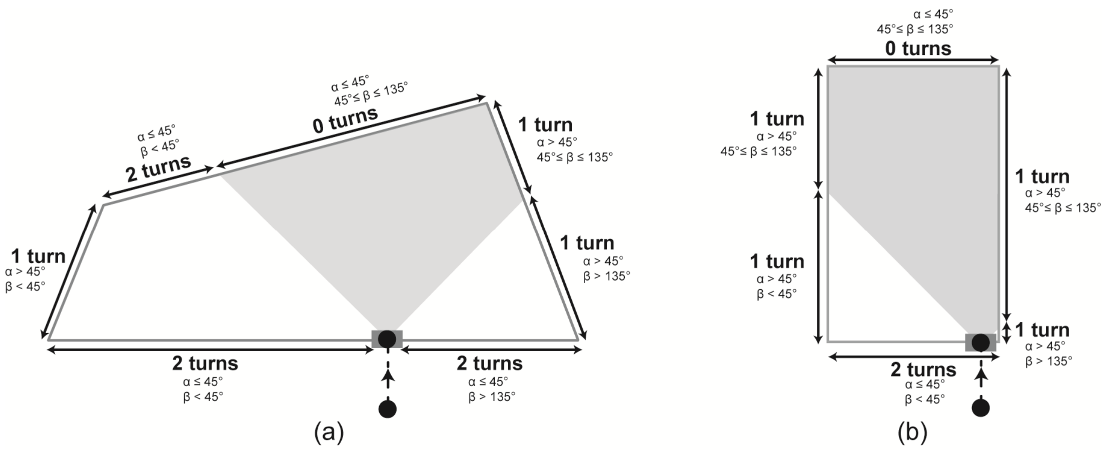


Figure 7-9 Examples of turn costs within a single spatial unit

With this theory, all issues previously highlighted as key parameters for inaccurate indoor turn calculations are solved (Section 7.3.2). Variable α links back to the idea of a direct line of sight of the walking pattern between both doorways, as this coincides with human's actual take on crossing spaces. Variable β prevents not only the infinite extension of the influence of a doorway to areas that are obviously required to be counted as turns (Section 7.3.2.1 – Figure 7-3), but also supports a rectilinear view on the walls with door openings (which solves the problem highlighted in Figure 7-7). With regard to the geometry of the spatial unit (Section 7.3.2.2), the use of center point nodes is avoided and replaced by solely using door nodes. Only in cases of non-visibility are intermediate nodes used, while being similarly treated by the algorithm as door nodes. Because we consider each room unit by unit, previous and next nodes do not influence the results of the turn calculations as was the case in Section 7.3.2.3. As such, the door points are considered as decision points for the continuation of routes, and possible mistakes caused by the location of intermediate nodes are limited to a single spatial unit. The exact location of doors also becomes less important (in contrast to Figure 7-7) as we account for a combination of wall angle and threshold zone variables.

7.4.3 Structure of the Perception-Based Indoor Turn Algorithm

The perception-based indoor turn algorithm (Algorithm 7-1) has the specific aim of using the previously defined theory to calculate the number of turns on a list of predefined paths (pathlist). The data requirements for the algorithm consist of a network of nodes and edges, the coordinates of the door openings and door wall orientations, and any intermediate curvature nodes.

```
FOR (all paths in pathlist)
       Select the next path from pathlist
       WHILE (Nodes in path){
           1. Select 1st door and 2nd door
           2. Check direct visibility between 1st door and 2nd door and
              create visibleNodeList
           3. Determine number of turns between each node couple in the
              visibleNodeList
           4. Change parameters for next rotation
```

Algorithm 7-1 Perception-based indoor turn algorithm

The algorithm consists of a loop over all nodes in the selected paths, with four consecutive steps. Each step is discussed in greater detail below.

7.4.3.1 Determination of spatial unit: select 1st door and 2nd door

The entire order of nodes of a path is passed through one by one and doors or openings on an edge between nodes are selected. This is done because our theory started from doors being the start position for turn calculations. As such, any kind of indoor network type can be supported in this algorithm. This is done as follows (Figure 7-10).

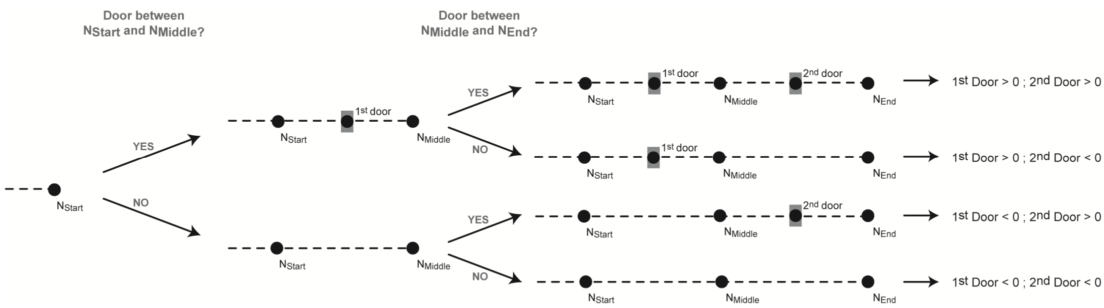


Figure 7-10 Algorithmic steps in determining 1st door and 2nd door elements

In a first step, it is examined whether there is a door (termed 1st door) between the start vertex (N_{Start}) and the next node in the path (N_{Middle}). The second step examines the relation between N_{Middle} and the next node (N_{End}) on containing an intermediate door (termed 2nd door). Figure 7-11 presents several options depending on the presence of 1st door and 2nd door variables, which determine the required turn cost calculations (Section 7.4.3.3). Indeed, the theory in Figure 7-8 calculates turns on a unit-by-unit base. As such, depending on whether all 3 subsequent nodes are in the same spatial unit or not, will influence which turn cost calculations will have to be made.

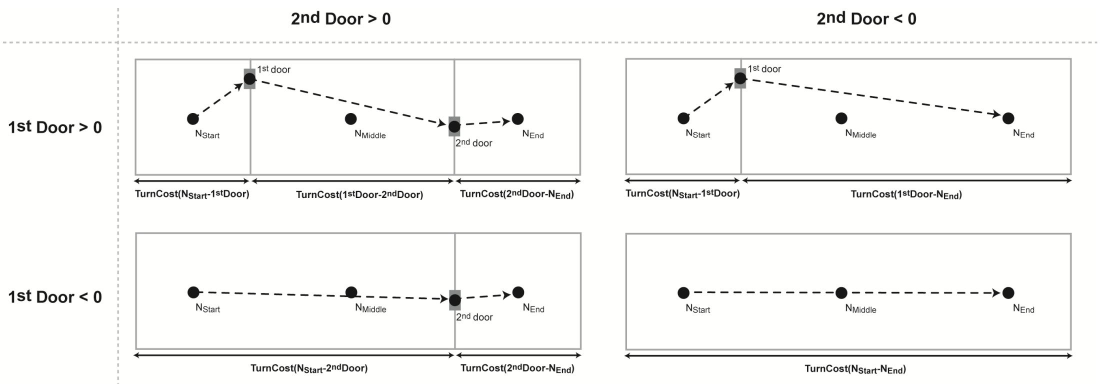


Figure 7-11 Separate turn cost elements depending on the relationship between N_{Start} and N_{End}

In case of the start node, the initial orientation does not induce a cost as is assumed that the user is oriented to its chosen door. As such, the startup-turn cost is only influenced by the visibility between start vertex to 1st door and 1st door to node (Section 7.4.3.2).

7.4.3.2 Check direct visibility between 1st door and 2nd door and create visibleNodeList

Subsequently, the visibility between 1st and 2nd doors is tested and in case of concave units, several intermediate nodes might need to be created. The resulting pairwise-visible nodes are stored in a visibleNodeList. This is a list of all nodes between (and including) 1st door and 2nd door objects that are pairwise mutually visible. For example, in case of immediate visibility between 1st door and 2nd door, the list will only contain a single row with nodes 1st door and 2nd door.

The method for checking the direct visibility between two points is based on finding the number of intersections between the direct line of sight of both points, and the circumference of the spatial unit. If no intersections are found, both points are mutually visible. However, if there are intersections, a further sub-partitioning of space is required to create intermediate 'break' points. Section 7.3.2.2 mentioned several such methods for doing so. However, we decided to partition space based on the existing intermediate nodes of the original network and in a second step, using nodes part of the natural curvature of the original edges. Although we are aware that using the original network can induce mistakes when the intermediate nodes are positioned to an extreme location, it appears that indoor networks often contain a quite realistic subdivision of the spatial units, created with visibility rules in mind (e.g. no crossing of walls). Also, the use of intermediate nodes and internal curvature nodes is restricted to a minimum, making the amount of possible mistakes limited even when the network would not be very realistic. In this paper we have not deeply examined the impact of possible network mistakes, but it should be done later on. Note that the possibility to use previously discussed partitioning methods still remains, making our algorithm completely network-independent.

When a sub-partitioning of space is required, an algorithm searches for an intermediate node furthest located from the 1st door, but still visible. For example, in Figure 7-12 nodes N_1 through N_4 are all intermediate nodes of a certain spatial unit of which N_3 satisfies the criterion of being still visible from 1st door. If this node is also directly visible from the 2nd door, no additional intermediate nodes are required. If not, a recursive algorithm finds again the node furthest from the previous intermediate node while still being visible. The algorithm will recursively keep selecting new intermediate nodes that are mutually visible to the last node in order to obtain a realistic final door-to-door walking pattern for the concave spatial unit.

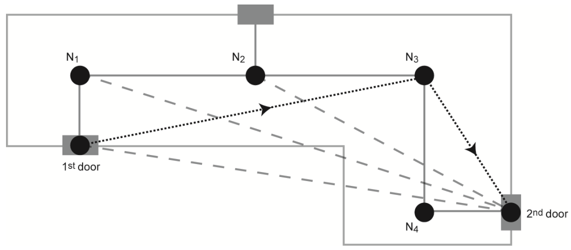


Figure 7-12 Example of the applicability of the algorithm in a concave spatial unit

7.4.3.3 Determine number of turns between each node couple in the visibleNodeList

This method begins by calculating the slopes of each wall containing a door or opening based on a second point in the same plane. For nodes in the visibleNodeList that are not an opening or door (i.e. intermediate node or curvature node), the slope is defined to be the perpendicular to the walked segment from node to node (as this corresponds to the slopes of doors being perpendicular to the walking pattern). These slopes are compared with each other and define the mutual wall orientation (angle α). In a second step, it is checked if the node is situated inside the threshold area drawn from the previous door opening (angle β). As such, the total number of turns on a segment can be determined using the theory in Figure 7-11. However, not every relationship between certain node types in the visibleNodeList requires a similar treatment in the calculation of number of turns (Table 7-4).

Visibility in spatial unit	Connection type	Parameters	Number of turns
Immediate visibility between Doors	Door-Door	Threshold + wall orientation	0, 1, 2 turns
Non-immediate visibility: intermediate nodes	Door-Node	Threshold	0, 1 turn
	Node-Node	Threshold	0, 1 turn
	Node-Door	Threshold + wall orientation	0, 1, 2 turns
Non-immediate visibility: single intermediate node	Door-Node-Door	α<= 45°	2 turns (merge in visibleNodeList)

Table 7-4 Possible relationships between node types and turns in a single spatial unit

In the case of immediate visibility between two doors that are part of a single spatial unit, the general rules can be applied as explained in Section 7.4.2. Both parameters are of importance, with possible detection of 0, 1 or 2 turns within that spatial unit. With non-immediate visibility, the visibleNodeList will contain several connection types. For Door-Node connections, the only item of importance is whether the line of walking is inside or outside the 45° turn angle zone constructed from the Door node. This will find either 0 or 1 turn, because the user will always walk straight to the Node, similarly to the perpendicular crossing of Door nodes. When dealing with Node-Node connections, the threshold is drawn in continuation of the line of walking pattern and can give rise also to at most 1 turn. For Node-Door connections, the turn angle zone, again in line with the walking pattern, can decide over the presence of an additional single turn only. Finally, the angle between the walking pattern and the Door can give rise to an additional turn as well if outside the 45° turn angle zone and this because of the sharp angle with which that Door node would be entered. This is the reason why Node-Door connections can also give rise to 2 turns.

A special case occurs when two successive elements in the visibleNodeList consist of a Door-Node connection followed by a Node-Door connection. This means that all nodes are part of the same spatial unit, but there is no direct visibility between both doors. As such, a single intermediate Node has been created, in our case by using the original network structure. As mentioned in Section 7.4.3.2, this can induce certain mistakes, given the extremity of some intermediate nodes. As such, one cannot necessarily rely on the quality of this node to be on the path of visibility (e.g. often the centroid of a spatial unit is the only available intermediate node, which has been proven to often lay to the extent of the geometrical spatial unit as in Figure 7-5), therefore possibly leading to incorrect turn calculations (Figure 7-13). As a solution, we propose to merge both elements in the visibleNodeList and act like both Doors are mutually visible. This allows us to compare the walls of both doors (variable α). If $\alpha > 45°$, two turns are attached. If not, the elements from the visibleNodeList are kept in the original way and previously discussed rules are applied (Table 7-4 – middle part).

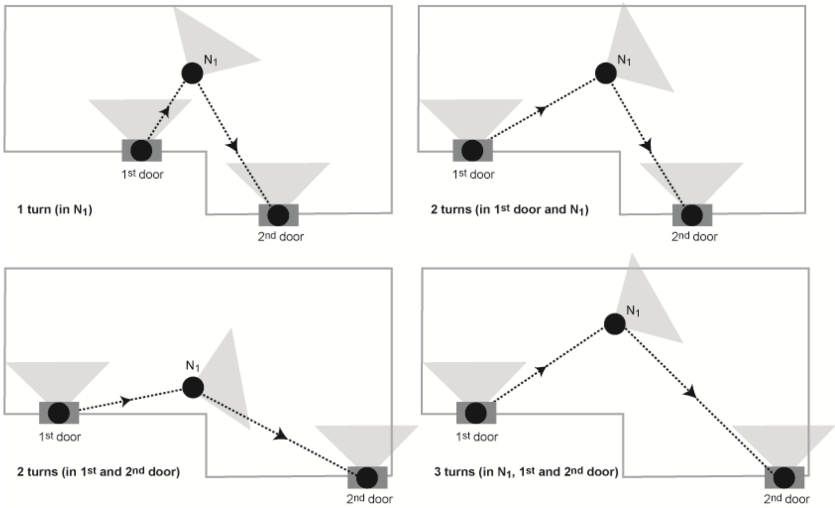


Figure 7-13 Example of a special case where 2 turns are not necessarily accounted for

7.5 INDOOR FEWEST TURNS PATH ALGORITHM

To illustrate the usage of our perception-based indoor turn algorithm, we applied it in the implementation of the indoor fewest turns path algorithm, i.e. an algorithm calculating paths between two points that contain the fewest amount of turns.

7.5.1 STRUCTURE OF THE INDOOR FEWEST TURNS PATH ALGORITHM

The main structure of the fewest turns path algorithm (Algorithm 7-2) is based on the structure of the simplest path algorithm (Duckham & Kulik, 2003). This structure is similar to the well-known Dijkstra algorithm structure, except for the fact that instead of calculating node costs, costs are stored and compared in the edges. Required input data is: a graph with nodes and edges, start vertex and intermediate curvature nodes. Notice in particular that the type of indoor graph does not matter as long as it is possible to derive the connecting doors or openings from the dataset. The output is a list of turn costs per edge (ListCs(e)). The threshold area for detecting a turn is again set to 45°.

```
Initialize cs(s,v)

WHILE (E\S)>0 do
      Find e part of E\S such that cs(e) is minimized
      Add e to S
      FOR all e' part of E\S do //Recalculate cs(e')
         IF(e,e') part of Ɛ //If e and e' share a middle vertex
            Set  cs(e')=  MIN(cs(e'),cs(e)+w(e,e'))  //Change  cost  for
            connected edge e' if smaller than previous cost

Initialization:
•  Calculate nr of edges starting from startvertex
•  Find first doorID → either doorID or -1 (if none)
•  Calculate cs(s,v) → Figure 7-11

Recalculate cs(e'):
•  Calculate nr of edges sharing vertex met endnode of selected edge (=
   Nmiddle)
•  IF(nextedgeid !partOfSelected){
     1. Find first doorID → either doorID or -1 (startvertex)
     2. Find second doorID → either doorID or -1 (if none)
     3. Calculate cs(e') → Figure 7-11
•  Compare and update cost cs(e') in Cs list

Variables:
Cs(e):    Turn cost for edge e from start vertex s
Cs(s,v):  Turn cost for edge (s-v)
S:        List containing already calculated edges
E:        List containing all edges
e:        Selected edge
e':       Edge connected to selected edge
```

Algorithm 7-2 Indoor fewest turns path algorithm

To calculate the individual turncostElements, the separate nodes that are intermediately visible are stored in a visibleNodeList, which is then used to assign a certain number of turns, in accordance with our theory for turn calculations (Table 7-4). The steps used are similar to the algorithm in Section 7.4.3 with the only difference that in the current algorithm, the order of nodes in the path is not known ahead of time.

7.5.2 APPLICATION OF ALGORITHM TO VARIOUS NETWORK SITUATIONS

It is our belief that the presented perception-based indoor turn algorithm and its implementation in the fewest turns path algorithm can be applied to any indoor network modeling structure. This is in stark contrast with the original node-coordinate based turn algorithm, where every node gives rise to possible new turns (Chapter 6). When multiple nodes are part of the same convex spatial unit, the common spatial unit is deducted to compare wall orientations. As such, all network type paths can be transformed to find the doorways that are traversed and are required in the algorithm. The algorithm only requires the coordinates of two consecutive door openings that are passed, independent of how the spatial unit is modelled. In this section, several examples will be given of situations that exhibit a wrongful turn calculation when using the node-coordinate based turn original algorithm, but an accurate turn calculation when using the perception-based turn procedure.

Figure 7-14 highlights a path from node 499 to node 13, passing by doors 240 and 243. The underlying network is a geometric network model, while the black lines show the used nodes in the perception-based turn algorithm. Using a simple node-coordinate based algorithm, turn angles would consecutively be calculated in nodes 499-501-510-509-507. This would result in a left turn (in node 510) followed by a right turn (in node 508). However, applying the perception-based turn algorithm, results in accurate turn disambiguation. Since doors 240 and 243 are not mutually visible, an intermediate node, part of the original network model is selected (in this case node 507 as it is the node furthest away from first door 240 while still being visible). As such, only a single right turn is calculated in node 507 coinciding with the actual perception of turns along this path.

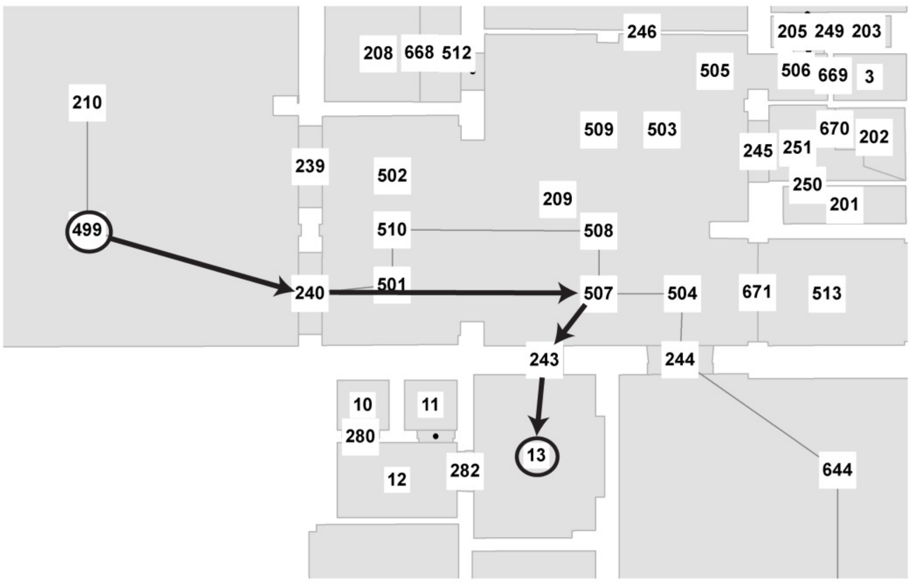


Figure 7-14 Example of a correct turn calculation on a geometric network model

A second example highlights the improved application of turn calculations when using a visibility-based network model (Figure 7-15). A path going from node 17 to node 38 passes respectively by doors 286, 297, 293 and 291. Using a node-coordinate based algorithm on this path results in no accounting of any turns, as the location of previous nodes before a certain door inhibits sharp angles (similar to Figure 7-7). When using the perception-based indoor turn algorithm, the angle from door 286 to door 297, perpendicular to the wall containing door 286, is just contained within the 45° turn angle area, inducing no turn in this spatial unit. The next spatial unit with a path from door 297 to door 293 creates rightfully a right turn, where in the node-coordinate based algorithm, this turn was neglected.

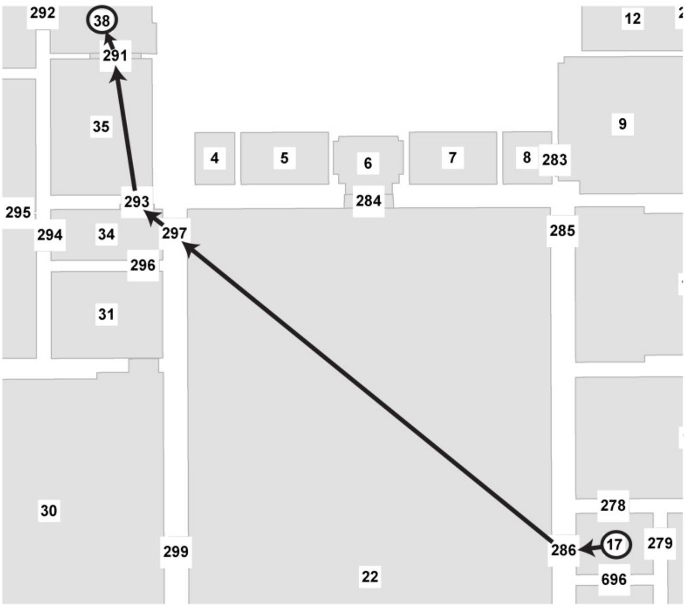


Figure 7-15 Example of a correct turn calculation on a visibility-based network

7.6 DISCUSSION AND CONCLUSION

In this paper, a new procedure for accurately calculating turns in indoor spaces is proposed. This is important for providing better cognitive support for indoor wayfinding through the implementation of fewest turn path and simplest path algorithms. The need for the development of this procedure for indoor turn calculation stems from the highly differing spatial structure of indoor spaces, compared to outdoors, which resulted in the creation of various indoor network models, with each having their own decision point definition. As such, it can be very challenging for any one algorithm to calculate turns accurately on these different network structures. However, the newly presented algorithm showed to be independent of the underlying indoor network structure, and as a result can be used in any indoor modelling situation. The procedure is based on a direct door-to-door walking pattern combined with the perceptive notion of turns. Furthermore, the algorithm is applied in the implementation of the fewest turns path algorithm indoor, which will also allow future applications in indoor simplest path algorithms.

As mentioned, our algorithm's main advantage is its network-independence for turn calculations in indoor spaces. However, we are aware that the algorithm presents several drawbacks which will be addressed in our future work. First, the data requirements for calculating indoor turns with the new procedure are quite strict, as they require availability of the polygon circumferences of each spatial unit with two coordinates of each door depicting the door orientation. Second, even though it is stated that the algorithm is network-independent, this assertion silently assumes that the given network respects the visibility principle and avoids the crossing of walls. Although we also relied on using the original network structure as approximation of the user's walking pattern when dealing with non-mutually visible door nodes, other methods are available that break up concave units independently of the underlying network. The accuracy of these methods in indoor turn calculations will have to be examined in more detail. Note that at this point, the use of intermediate network nodes is kept to a strict minimum by relying in the first place on door nodes and the execution of turn calculations occur also unit-by-unit.

The presented algorithm was applied to several examples, displaying its applicability for indoor spaces. However, at this point the fewest turns path algorithm is not yet tested for application to outdoor spaces or combined indoor-outdoor environments. It is important to connect and extend the indoor algorithm with the outdoor variant in order to provide a seamless wayfinding aid. Furthermore, the definition of turns as put forward in this paper refers back to literature on wayfinding and route instruction creations. However, we will have to confront this turn definition with the actual perceptive opinions on making a turn of wayfinders in indoor space. Did the person moving along a path really considered their change in direction as turning? How is this related to the spatial context, type of turn, type of building and user's experience? Luckily, the turn threshold can easily be altered, for example by introducing a more gradual cost change. A final improvement in further research should be the accounting of turns during vertical movement. For this paper, the analysis was restricted to a 1-level indoor environment. However, we do realize further research will have to reveal how turns should be counted when changing floor levels. In summary, it can be concluded that with the presented algorithm for indoor turn calculations and its implementation in the indoor fewest turn path algorithm, a significant contribution and first start is made in providing more cognitive algorithms to indoor spaces.

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8

GENERAL DISCUSSION

Over the last decade, various researchers have increasingly developed systems based on situation awareness and smart environments using LBS (Gartner et al., 2007; Huang et al., 2009). In line with these developments, applications for navigation and wayfinding also began extending their focus from the outdoor to the indoor world. As a result, developers have to acknowledge the fact that users deal with more complex cognitive challenges during navigation in indoor environments, induced by specific differences between indoor and outdoor space. In addition, because users walk seamlessly between indoor and outdoor, they expect their guidance tools and analytical support to work similarly. In order to fully accommodate navigation, an accurate connection between indoor and outdoor applications supporting navigation must be made.

As a first step towards this integration, this dissertation is focused on the complexities of indoor spaces, their differences versus outdoor environments, and how all of this shapes indoor navigation and evacuation applications. We argue that space, and as such the models and analyses supporting them, should be seen as a holistic environment where a distinction between indoor and outdoor parts is not necessarily useful. As such, this dissertation aims at initiating further discussion on the complete integration of indoor and outdoor environments, by mainly focusing on indoor aspects. This has lead to the following research objective:

> **Study and improve models, analyses and algorithms for navigation and evacuation scenarios in indoor spaces by linking them to similar outdoor concepts.**

From this general research objective, five research questions were distilled.

- RQ 1: What is the current state-of-the-art on the integration of indoor and outdoor environments for pedestrian navigation?
- RQ 2: What is the current state-of-the-art of indoor navigation and evacuation research?
- RQ 3: Can analytical procedures from outdoor space be directly applied to indoor spaces?
- RQ 4: Can cognitive outdoor navigation algorithms be directly extended to guide unfamiliar users in indoor spaces?
- RQ 5: Do the different indoor space models have any noticeable effect on the operation and on the results of navigation and wayfinding algorithms?

In Table 8-1, an overview of the separate chapters, their topics and main results is given. Section 8.1, organized by research question, summarizes and discusses the results of the various chapters linked to that research question. In Section 8.2., a broader discussion is given on several more general topics together with some recommendations for future research.

Table 8-1 Overview of main results within each chapter

Chapter	RQ	Topics and methodology	Main results
CH2: Integrating indoor and outdoor spaces for pedestrian navigation: a review	RQ1; RQ2	- State-of-the-art on integrating indoor and outdoor environments for pedestrian navigation - Comparison of 36 scientific studies within the framework of available models, data requirements, algorithmic and context support	- Very few applications support an integrated concept of indoor-outdoor navigation - Many challenges due to large variety in models, data and context parameters in both I and O space - Further research required on algorithmic support, 3D and more general requirements for pedestrian navigation
CH3: Combining indoor and outdoor navigation: the current approach of route planners	RQ1; RQ2	- State-of-the-art on navigation in indoor and combined indoor-outdoor environments - Study of the use of indoor infrastructures for navigation in currently available route planners in terms of data, algorithms and model support	- Indoor-outdoor integration is problematic mostly due to problems with indoor context, leading to sub-optimal routing - Data constraints (mostly indoor) prevent the optimal use of all navigation routes - Indoor address matching is hampered due to a lack in indoor methodology, reference dataset and standards
CH4: Measuring the exitability of buildings: a new perspective on indoor accessibility	RQ2; RQ3	- Extension of traditional spatial analysis tools to 3D indoor environments - Development of *exitability*, a new indoor accessibility measure which quantifies the level of access to exits from every room by modeling the movement of occupants	- Overview of relationships between navigation research (focusing on evacuations) and fire simulation research - Case study demonstrates capabilities of *exitability* in analyzing built environment - Indoor extension of outdoor concepts is proven feasible but requires more research
CH5: Evaluating suitability of the least risk path algorithm to support cognitive wayfinding in indoor spaces: an empirical study	RQ4; RQ5	- Extension of outdoor guidance algorithms to 3D indoor environments - Least risk path algorithm, minimizing risk of getting lost, is duplicated and tested indoor by comparing results with shortest path alternatives	- Tests revealed non-stable results in terms of selecting the least risky edges in indoor environments - Algorithm has to be adjusted to the specificities of indoor space - Improvements: weight adjustments, changing underlying network topology, changing risk value definition
CH6: Comparing indoor and outdoor network models for automatically calculating turns	RQ4; RQ5	- Extension of outdoor guidance algorithms to 3D indoor environments - Comparison of indoor and outdoor network models for wayfinding, on their suitability for automatically calculating turns	- Different indoor networks are not able to return the accurate number of turns compared to outdoor networks - This is due to differing definitions of what makes up a decision point between indoor and outdoor spaces - Adjusting indoor network to follow the outdoor construction rules appears not possible
CH7: Automating turn calculations for the indoor application of the fewest turns path algorithm	RQ4; RQ5	- Extension of outdoor guidance algorithms to 3D indoor environments - New procedure for automatically calculating indoor turns - Application of fewest turns path algorithm indoor	- Overview of turn concepts in research and relationship with verbalization of route instructions - Delineation of parameters linked to indoor space influencing turn calculations - New procedure works independent of underlying space model, resolving problems with indoor turn calculations

8.1 SUMMARY AND DISCUSSION OF RESEARCH QUESTIONS

8.1.1 RQ 1: WHAT IS THE CURRENT STATE-OF-THE-ART ON THE INTEGRATION OF INDOOR AND OUTDOOR ENVIRONMENTS FOR PEDESTRIAN NAVIGATION?

With people moving seamlessly between indoor and outdoor environments, systems that integrate navigation and wayfinding in both spaces have been identified as the next challenge in navigational research (Huang & Gartner, 2010). Chapters 2 and 3 both focused entirely on the state-of-the-art in integrating indoor and outdoor environments for pedestrian navigation. While in Chapter 2 a theoretical reflection was made on integrated pedestrian navigation approaches by comparing 36 scientific studies, Chapter 3 showed a more practical focus by studying the integration of indoor and outdoor data in current, well-known route planners.

Both chapters demonstrated that research on combined indoor-outdoor navigation is currently still in its early days. Chapter 2 highlighted that, at this point, few applications can be found which support a fully integrated approach to IO pedestrian navigation. Those that do exist appear to be limited to small geographical areas, and include only certain high-level information on the indoor sections of the navigational paths. The restricted availability of extensive pedestrian IO navigation applications can be attributed to a current absence in data. Similarly, route planners show a lack of integration of indoor sections with outdoor street networks in their shortest path queries. The indoor parts of those integrated pedestrian approaches are often the least detailed, or simply do not exist (e.g. only entrance information available, without specifications on the indoor route). In the latter case, route planners provide accurate route information up until the entrance points of the indoor section, after which textual information explains further indoor movement. As such, while it seems that integration between indoor and outdoor environments is technically possible, at this point consistent IO pedestrian navigation support is largely inhibited by a fragmentary coverage of accurate indoor data.

A further elaboration on this data problem in Chapter 2 showed that pedestrian navigation applications rely on a large variety of highly different data sources. Some of these sources consist of an inherent combination of indoor and outdoor spaces (e.g. CityGML, BIM), but all of them show specific problems largely related to accuracy, feature definitions, and application level specifications. These sources are also mostly too complex for immediate navigation support, given their specific development for other research fields than navigation. However, they can still be valuable in the IO integration as long as they are simplified and supplemented with additional data sources (e.g. road network data, user constraint data ...). Nonetheless, most data sources used in current IO navigation applications are strictly limited to either the indoor or outdoor context. Information on indoor spaces is commonly available through 2D floor plans, while outdoor sources range from road network data to cadastral datasets to imagery. As such, it seems that not a single data source is readily available covering both indoor and outdoor space at a sufficient level for pedestrian navigation applications.

Apart from a large variety of available data sources and formats, developers are also dealing with highly different models, containing a vast diversity of context descriptions at multiple levels of detail (Chapter 2). These different models are all developed for valid reasons based on the needs of individual applications. For example, outdoor road networks are widely available and used in car navigation applications and are often used as data source for outdoor pedestrian navigation applications. However, while they might largely cover the same space, they do not necessarily account for pedestrians' specific needs.

In general, when developing integrated pedestrian navigation applications, a choice is made between two space model options: namely, network and polygonal approaches. Networks offer the advantage of easily being extendable and connected to indoor environments, while polygons cover pedestrians' degrees of freedom better and also provide a more unified concept of space. Within route planners, only network approaches are used as the model of space. This is not surprising given the inherent relationship between algorithms and networks. However, applications seem to be sometimes stuck to set, static networks, narrowing their flexibility in making adjustments to dynamic events and overall data changes. To this end, Becker et al. (2009) proposed a general framework for modeling indoor spaces by combining multiple data sources into the same space structure. This multi-layered space representation allows for, for instance, the existence of multiple networks of the same environment with varying constraints and decompositions, as such anticipating dynamic usage (e.g. different user types, different applications, time changes). The additional advantage is that all layers are connected through inter- and intra-layer connections, creating a coherent and flexible structure. As this framework is currently only available for indoor environments, the question is raised how something similar can be developed for integrated indoor-outdoor environments, especially given the existing variety in data sources, context, granularity and scale level of both indoor and outdoor spaces.

Both of the papers in Chapters 2 and 3 have clearly demonstrated that part of the reason for the discovered variety in data sources and models is rooted in the fundamental differences between indoor and outdoor spaces. For example, indoor data availability is lagging behind compared to its outdoor counterpart. This is not surprising given that outdoor urban space has been historically analyzed and modeled for a long time. Conversely, indoor building infrastructures are just recently being opened up, along with new methods for indoor data gathering. Also, indoor data availability is often linked to a specific, small geographic area given the importance of a specific building for mapping. Indeed, companies and data providers developing navigation services will put most effort into areas with the highest commercial value. Indoor acquisition techniques are also not yet automated in the same way as outdoor data gathering, with for example mobile mapping vans and widespread collaborative mapping efforts such as OpenStreetMap. However, recently, similar achievements have been noticed with respect to public participation in indoor routing applications (e.g. Google Maps indoor allows for importing floor plans yourself), which can aid in removing the boundary between indoor and outdoor data coverage.

The existing structural, environmental and cognitive differences between indoor and outdoor environments also show up in the array of objects available for querying and navigation support. Indeed, we noticed in Chapter 2 that the objects that are mapped for indoor and outdoor pedestrian navigation are widely diverse, with indoors mostly consisting of objects related to the building structure, while outdoor aspects are more limited to generic road, distance and time-related parameters. At this point, no agreement has been made on which objects should be mapped, and at what level of detail, within both indoor and outdoor space to be able to support pedestrians' wayfinding tasks on a sufficient level. This is demonstrated by the fact that the available indoor data within route planners currently covers a wide scale in level of detail, ranging from very rough to quite detailed (Chapter 3). The outdoor pedestrian objects are also commonly deduced from car navigation applications, inducing problems of not accounting for specific pedestrian routes, and path descriptions (e.g. car directions are just too basic to coincide with pedestrians' navigation needs). Therefore, we recommend a further investigation of pedestrian navigation context requirements in an integrated indoor-outdoor environment is urgently needed. Studies like those by May et al. (2003), and Millonig and Schechtner (2007) try to shed light on the information requirements needed by pedestrians to navigate successfully, but both are currently limited to an outdoor pedestrian context. For instance, their research highlighted that pedestrians, to explain navigational paths, mostly rely on landmarks, but that the existing variety in possible types of landmark information complicates the implementation into actual navigation applications. Note also that indoor and outdoor landmarks might differ in structure, availability and types. Thus, additional understanding of pedestrians' needs for personalized navigation information is highly necessary, especially in indoor and combined indoor-outdoor environments. Considerable challenges in this realm involve the development of richer navigable databases, containing the specific types of objects relevant for pedestrian navigation (compared to car navigation requirements). These objects must be accurately located and correctly labelled, but should only be included within navigation instructions if they are readily visible from the pedestrian's direction of approach, and easily recognizable (May et al., 2003). This has to be accompanied by the definition of quality criteria for context objects and data mining methods to provide a mechanism to automatically extract objects of importance to pedestrian route instruction giving (Millonig & Scherchtner, 2007).

With regard to the current state-of the-art on integrating indoor and outdoor spaces for pedestrian navigation, we can conclude that this research field is still far away from ubiquitous availability of such applications, although small applications (in terms of coverage and purpose) have proven to be possible. This is due to practical issues (e.g. limited data availability) but also more theoretical questions that are still unanswered (e.g. What is required for pedestrian navigation? How can you model IO space together given their differences in structure, constraints, usage and perception?). It is our belief that a sort of integration process, both in models and data sources, will be required to handle the specific needs of pedestrian navigation in indoor-outdoor space. This inherently means dealing with delineation processes, merging operations, data quality and semantic differences, deduction processes for gathering the required objects, and transformation into a certain model of space. In addition, the quality of integration and connection is found to have a direct influence on the possibility of accurately calculating routes, as several examples in Chapter 3 demonstrated sub-optimal routing due to a lack of complete entrance data. In Chapter 2, several important questions in this regard were already raised.

We want to suggest a solution on the feasibility of data gathering and integration, especially with respect to the indoor context, as it seems unrealistic to gather and maintain all indoor data accurately from all building structures. We pointed out in Chapter 3 that even small enhancements in indoor data can have a huge influence on routing (e.g. identifying solely connection points between indoor and outdoor environments, without the actual indoor network, would make address matching more accurate and would also provide possibilities to have more optimal routes). More accurate information will of course result in more optimal route calculations, although significant developments are similarly required in the area of algorithmic support, model definitions and route instruction content.

Therefore, the development of a minimum set of requirements for combined indoor-outdoor navigation is deemed useful as it can help in for example determining whether certain data sources comply with these requirements, as well as facilitating the development of transformation processes depending on the type of data source. Studies like Li et al. (2011) might serve as an example as they investigated the minimum set for visualizing indoor multi-level buildings during wayfinding tasks. Questions requiring answers are: What should be provided in terms of context and semantic objects? What is the required minimal algorithmic support? How should visualization and route instructions be communicated to the pedestrian user? In general, the aim should be on getting a better view on what people want and need from integrated pedestrian IO navigation applications.

8.1.2 RQ 2: What is the current state-of-the-art of indoor navigation and evacuation research?

RQ1 demonstrated that although integrated navigational applications are still in the early development phase, the outdoor part is largely sufficiently developed. Problems with integrated pedestrian navigation applications mostly arise from specific difficulties with regard to the indoor aspect of space. In this research question, the specific indoor navigation developments with respect to indoor models, algorithms and analyses are considered in more detail in order to grasp the specific challenges ahead for dealing with indoor environments in a navigational setting. Apart from research focusing on indoor navigation, an investigation of indoor evacuation research is also elaborated on, as evacuation and navigation are quite closely related concepts (Section 1.1.1) and evolutions in one application field can help resolve problems in the other. The following discussion on RQ2 is based on Chapters 2, 3 and 4.

The models containing aspects of indoor environments have been broadly shaped by over 20 years of development in 3D geo-information data structures, creating both purely geometric representations such as IFC, CSG, voxels and TENs, as well as a series of topological models, mostly as variations on the Boundary Representations (Lee & Zlatanova, 2008). Over time, city models have been generated in order to respond to an increasing demand for more realistic and detailed representations of urban environments (Lee & Zlatanova, 2008). Notwithstanding the creation of those elaborate 3D models, practically, most approaches for indoor navigation applications make use of indoor navigational networks in various forms and shapes. Indoor networks originated from pure 1-on-1 connectivity models, with variations and adjustments over time to deal with specific problems caused by the indoor situation. As such, corridor derivation, visibility partitioning, cell decomposition models and eventually hierarchical graphs all took a place in the indoor navigation setting (Chapter 2).

However, more recently, research environments have come to the conclusion that using only connectivity models does not necessarily satisfy all requirements set within indoor navigation applications (Brown et al., 2013; Isikdag et al., 2013). For example, indoor spaces benefit from linking a semantic classification with geometrical features, to identify ‘navigable spaces’ for different modes of locomotion. Additionally, semantic information with regard to the function and usage of spatial units is desirable as it allows for more accurate and appropriate route planning (e.g. no walking through a room when a meeting is ongoing) (Brown et al., 2013). As such, the idea of solely relying on topological connectivity information for route planning has evolved to more mature and multi-purpose models. These should contain all geo-information necessary for indoor navigation applications, being geometry, topology and semantics (Isikdag et al., 2013). This can be achieved by integrating several domain-specific models into more harmonized and comprehensive hybrid data structures (Becker & Dürr, 2005; Breunig & Zlatanova, 2011, Afyouni et al., 2012). Possible examples for such a hybrid data model in navigational applications consist of integrating different topographic space models to comply with the various functionalities of navigation applications (e.g. 3D building model for visualization combined with a network for navigation and additional properties and information on structural building elements for querying (Isikdag et al., 2013)). Additionally, it can be beneficial to include models covering the same physical area but containing richer and more expressive and interpretative attributes on different aspects (e.g. the multi-layered space representation of Becker et al. (2009)). Indeed, navigational applications demand a much-needed link between the pure topographic representation of space and the cognitive perspective of the user (Giudice et al., 2010) as navigation should be tuned to the natural wayfinding methods of familiar and unfamiliar building occupants to simplify the overall navigation task. Note that the topological quality of connectivity still forms the core characteristic within indoor navigation modeling.

At this point, most attention in indoor navigation research has been focused on the models and their requirements. However, further algorithmic, analytical and contextual support forms a major lacuna in current indoor navigational research. Indeed, not only the representation of exact indoor space, but also a deeper understanding of 3D space models should be pursued in order to exhaustively query indoor environments. This requirement pushes the need for a uniform unilateral description of all objects and attributes within the indoor domain. However, so far no consensus has been reached on the amount, exact content or structure of the data needed to support indoor navigation and at the same time on the usage of salient clues in indoor environments (Giudice et al., 2010). This immediately links to the large variety in context attributes that can possibly be added to the specific models. At this point, few researchers have addressed this specific issue of determining which attributes are required related to user and environmental context in indoor navigation applications (Afyouni et al., 2012). This is also visible in the currently available indoor navigation algorithms, which are still mostly restricted to typical outdoor algorithms, such as shortest or fastest path calculations, thus taking only distance and time aspects into account (Chapter 2 and 3). Some researchers (e.g. Millonig & Schechtner, 2007; Hagedorn et al., 2009) have highlighted the importance of providing different routes to pedestrians as they can benefit from, for example, simpler or safer path proposals. It seems that the development of these more elaborate algorithms goes hand in hand with the recognition and availability of richer, semantic object definitions in line with pedestrians' requirements for route instructions.

Furthermore, in Chapter 3, a very specific and practical problem related to indoor navigation was discovered: the lack of appropriate methodologies for indoor address matching and geocoding. Several examples in Chapter 3 have proven that the availability of an indoor network is not necessarily a guarantee for accurate route guidance, as sometimes the exact location of destination or start points could not be established. Reasons for problems with indoor address matching were tied back to a lack of available indoor data, data formats that cannot deal with the common geocoding methodologies, no reference data set, and a large variety in semantic addresses and location information structures influenced by the geographic context (Chapter 3; Goldberg, 2013). This last point is especially closely linked with the differences and problems between outdoor and indoor geographic spatial reference systems. Indeed, one point in space in the outdoor world (e.g. one address or one set of coordinates), potentially represents entire sets of points in the three-dimensional indoor world (Kolodjiez & Hjelm, 2006). Additionally, where in outdoor space a geographical position can be easily translated from address information into (x, y, z) coordinates, indoor spatial coordinates do not make any sense at all. Users rely more on a relative positioning related to contextual surroundings (e.g. room B2.75 is assumedly located in wing B and level 2). The availability of comprehensive semantic and context information in navigational models is thus of even more importance indoors than outdoors. The available outdoor reference systems can also not easily be extended into indoor environments. Note that address matching is not solely a problem for indoor navigation; it also influences results of integrated indoor-outdoor queries. Several examples in Chapter 3 have demonstrated that queries linked to buildings with multiple exits only use one address point for route planning, no matter what the destination of the query is. This sometimes results in sub-optimal or inaccurate path planning. The accuracy of the semantic and locational description of addresses is thus of major importance for several aspects of navigation services.

A second part of this research question encompasses the state-of-the art on indoor evacuation research. From our discussions in Chapter 4, it was found that evacuation of indoor environments is largely tackled from two divergent angles of research: (i) geospatial research and (ii) fire simulation research. First, geospatial research consists of typical indoor navigation research, which slowly widened its focus to integrate emergency and evacuation aspects, mostly by adding specific parameters on graph networks (e.g. Gilliéron et al., 2004; Karas et al., 2006; Jun et al., 2009; Lee & Zlatanova, 2008). Furthermore, in line with increased computational abilities, several pedestrian simulation models (e.g. agent-based models, cellular automata), modeling the behavior of pedestrians on polygons and networks, were also applied to an evacuation context (e.g. Hajibabai et al., 2007; Park et al., 2007; Koh & Zhou., 2011; Kneidl et al., 2013). Second, fire simulation research groups initiated much work on modeling building egress during emergencies by using flow- and force-models. From there on onward, a number of fine-grained crowd simulation models (Gwynne et al., 1999; Santos & Aguirre, 2004), have been developed to predict emergency situations and evaluate interior design for planning purposes.

Despite a shared interest in analyzing evacuation situations, geospatial models and fire simulation models have been developed largely separate from each other. By originating from different points of view, models in each field are incomplete in one or more particular interests of urban planning. For instance, existing indoor navigation models are often limited to networks without a connection to the actual building structure, while evacuation simulation models lack a thorough semantic model of urban space. Models also differ with respect to the incorporated level of granularity, from macro-scale to more detailed grids. More recently, fire simulation models applied a 2-level modeling approach to accurately simulate the dynamics of travel while also taking the larger framework into account (e.g. Kneidl et al., 2013).

As mentioned in Chapter 1, the actual movement of occupants to an exit is determined by both user and environmental context parameters, which are differently implemented in evacuation versus navigation applications. This is also visible in the developed evacuation algorithms, with mostly modifications of common shortest path algorithms with time as edge weight (e.g. indoor navigation models) (Meijers et al., 2005; Lee, 2007; Lee & Zlatanova, 2008). Conversely, more-advanced simulation models (both pedestrian simulation and fire simulation models) include more sophisticated impedance variables - related to the individuality and physical state of human beings (gender, age, queuing, leadership, ...)- in their evacuation algorithms (Pu & Zlatanova, 2005). However, even then, there is still a major ongoing discussion on the required type of parameters to be included and how they should each be modeled. This difference in parameter inclusion is related to the original goal of the models: while simulation models aim at modeling the exact behavior of pedestrian flows and their dynamics, navigation models typically focus on pedestrian guidance for navigation and evacuation. Research should compare these approaches in more detail to possibly merge them, or at least identify which aspects could be beneficial in order to expand context parameter definition and general algorithmic support. This can not only prove useful for improved evacuation support, but also in a wider navigation context.

8.1.3 RQ 3: Can analytical procedures from outdoor space be directly applied to indoor spaces?

Our results of RQ2 acknowledged that indoor environments currently lack a significant analytical backbone support system. This is in stark contrast to the abundance of analytical tools available for outdoor spaces. Thus, this research question specifically focuses, as a first step towards more integrated analyses, on extending certain existing outdoor analytical features that would be of benefit to the indoor and later on integrated indoor-outdoor environment.

To address this research question, we specifically focused within Chapter 4 on one type of analysis - accessibility analysis - because of its strength in analyzing how space structures can affect the possibilities of human movement. Indeed, accessibility measures form a handy tool with which urban settings can be valued and improved, and their results are commonly translated into performance measures by which policies can be evaluated (Church & Marston, 2003). It is especially interesting to evaluate building design as this allows answering various questions such as: are the occupants within the building well distributed? What is the best location to have a meeting? How well is the structure adapted to host physically disabled persons?

To this end, a new indoor accessibility measure was proposed, quantifying the level of access to exits and the occupant’s ease of reaching them, from within each spatial building unit, given distance, time and cost constraints. This was termed *exitability*. The measure builds upon traditional outdoor person-based accessibility concepts and extends those to the three-dimensional indoor environment. The impedance function portraying the attraction of exit locations is modeled by linking it to the individual movement of groups of people.

Our methodology stands in direct contrast with other indoor accessibility measures that use gravity-based distance decay functions, solely relying on distance and geometry of the building as accessibility model (Kim et al., 2008; Thill et al., 2011). However, it was demonstrated that distance alone does not necessarily represent the complexities of outdoor human spatial behavior and is found to be of declining importance as an organizing principle of urban form (Kwan & Weber, 2003). This is also true for indoor environments where, for example, indoor three-dimensional distances alone tend to not account for the implications of the added effort for walking up and down floor levels, and more in general for measuring the occupant's ease of movement within a building (see also the results in Chapter 3). Therefore, our *exitability* measure incorporates a more individual movement-based definition by taking the average exit times per room, based on the movement of every occupant in that room to an exit. The speed of movement is thereby determined by the group density (depending on time and location), and the maximum capacity on an edge (depending on spatial structure, location and time). They are calculated using widely applied formulas for modeling pedestrian flows, but with additional accounting for congestion and the formation of queues. As the ability to reach an exit is most demanding during evacuation scenarios, the implementation of *exitability* is specifically focused on pedestrian movement in emergency situations. As such, it serves as an example of the inherent relationship between evacuation and navigation modelling, with time being the largest constraint.

The development of *exitability* was complemented by an extensive case study to demonstrate its capabilities for spatial analysis of indoor environments, more specifically for evaluating the efficiency of the building design in enabling evacuation of building occupants. For example, in the base scenario, the maximum *exitability* of all occupants within our case study building was demonstrated to be just over 10 min, with more than 50% of occupants theoretically being able to leave within 5 min. As expected, distance does play a role with low floors having lower *exitability* values due to their physical closeness to the building exits. A flocking effect near staircases could be observed slowing down the *exitability* values of higher floors. We claim that those stairs can be seen as intermediate exit points. However, these general results get more nuanced when taking into account large population densities resulting in queuing and even a continuing delaying effect on subsequent groups following the queue. Modifications to this base scenario were tested through lowering the availability of exits and decreasing the population occupancy. This allowed for more extensive analysis of inter-room differences and variations in *exitability*. It especially demonstrated the complex interrelationships which one has to consider when analyzing human movement in buildings, taking into account the spatial location of the specific exit (and as such the average distance increase or decrease in exit paths), limiting factors on the paths towards those exits (e.g. small doors of the specific exit, or most exit routes pass by tiny corridors) and the general population distribution in relation to the chosen exit routes.

With the development of an accessibility measure in indoor environments, it was proven that it is possible to extend outdoor analyses into an indoor world. The main advantage of applying analyses is to find certain patterns and anomalies that are not necessarily visible or known at first sight. This is especially interesting for indoor environments, considering the three-dimensionality of the built environment. For example, our case study demonstrated that in worst case scenarios, more unfavorable *exitability* values can be found for lower floors of a building, than what would be expected from their closeness to the exit, compared to those from higher floor levels. This is due to the initial congestion for the lower floors and less hindrance from predecessors when occupants from higher floors arrive. This highlights once more the importance of implementing *exitability* as a movement-based model compared to the typical distance-based accessibility values. Furthermore, it also underlines the importance of taking accessibility into the three-dimensional urban world and using the full scale of variation in vertical and horizontal direction, which can result in surprising findings on the infrastructure and its use. This was also recognized by Thill et al. (2011), who discovered that top floors of a centrally located building might not have a better accessibility compared to buildings at the periphery. It is, however, hard to compare our exact results and findings on the applicability of indoor accessibility measures with those of other researchers. This is partly due to the different context of research (e.g. Church & Marston (2003) only focus on blind person accessibility) and different methodologies (e.g. gravity-based accessibility measures used by Thill et al. (2011)).

In general, a large void in available indoor analytical methodologies was found, especially compared to the multitude of techniques, even simple ones, available in common GIS environments. This is kind of surprising since we can imagine applications such as indoor buffer creation, diffusion analysis and location planning all being of potential interest for understanding and opening up the indoor world. In any case, the real question remains whether those common techniques are all immediately transferable into an indoor context. An important remark here is that in order to support general analysis of and within indoor spaces, a set of modeling principles that fit the properties of indoor spaces should be identified and would ideally be as generic as possible to support the development of various applications at different levels of granularity (Li et al., 2010). For example, Thill et al. (2011) advocate using 3D networks as models of space for urban analytical functionalities, as they argue that for understanding complex spatial and functional relationships within complex urban environments, a 3D representation of both indoor and outdoor environments enhances analysis. Methods for network-constrained spatial analyses are, however, completely different than those built on top of Euclidean space (Okabe & Sugihara, 2012). Li et al. (2010) advocate for a more continuous take on space, by specifically choosing a grid-graph based model where the scale level of the grid can be adjusted depending on the required analysis. They do state that their approach needs to be extended to incorporate 3D units, as currently their work is restricted to single-level building infrastructure. As such, when considering analyses that are based on displacements of agents or robots perceiving their environment, the question that arises concerns the identification of the appropriate modeling paradigm, either continuous or discrete, and with which spatial structure (Li et al., 2010). Since it was essential in our accessibility measure to take into account the actual movement of users, a network model of 3D space seemed the best space model. However, we should examine if the results of our analyses change when varying the network. In general, we call for approaches that are sensitive to the complexities of urban form and differences among individuals across multiple axes (Kwan & Weber, 2003). How exactly this should be done requires further research. In line with our approach, one can make a start by examining the direct implementation of certain analytical projects in indoor space and their response in dealing with the indoor particularities.

8.1.4 RQ 4: Can cognitive outdoor navigation algorithms be directly extended to guide unfamiliar users in indoor spaces?

The results of both RQ1 and RQ2 revealed that, next to a void in indoor analytical methodologies (addressed in RQ3), the algorithmic support for indoor and combined indoor-outdoor navigation is also quite limited, with most algorithms restricted to Dijkstra (1959) or derived shortest path algorithms. The results of those algorithms often exhibit non-realistic paths (e.g. selection of complex intersections, avoiding main walking areas) in terms of what an unfamiliar indoor wayfinder would need to navigate a building comfortably. Cognitive algorithms are found more useful in this realm as they are closer connected to actual wayfinding strategies. They can provide routes that are more intuitive to follow and adhere better to how people describe paths to unfamiliar users. Until recently, these algorithms were only implemented in outdoor spaces, although indoor environments have proven to consist of even more context difficulties that complicate wayfinding endeavors. As such, similarly to RQ3, this research question aims at investigating whether those cognitive outdoor algorithms for path guidance can be extended into an indoor and integrated indoor-outdoor environment.

This RQ is addressed in Chapters 5 and 6. In Chapter 5, the focus was on the least risk path algorithm, which has the aim of minimizing the risk of getting lost. We investigated whether the least risk path algorithm has the same connotation and importance in indoor spaces as in its original outdoor setting by comparing the results of shortest paths with their least risk paths counterparts in a case study building. In Chapter 6, the focus moved to turn minimization as a key aspect of the fewest turns path and simplest path algorithms. We tested a simple algorithm for automatically calculating the number of turns on networks using the position of the nodes as input. This was done both on several indoor networks and compared with known efforts in outdoor space.

Both Chapter 5 and Chapter 6 demonstrated major challenges with the 1-on-1 extension of the existing algorithms into indoor spaces as the tests displayed unsatisfactory results. In Chapter 5, it was concluded that the least risk path algorithm does not return stable results in terms of selecting the least risky edges in indoor environments. The results of our case study showed that most indoor least risk paths were similarly long or slightly longer compared to their respective shortest paths. Although this seems in line with the theoretical definition of least risk paths, the increased length should be supported by the provision of less risky paths. This was proven not to be the case, with paths deviating from the shortest path, by choosing equally or more complex intersections while also avoiding main corridors in favor of paths through smaller rooms. As this is counterintuitive to what in indoor wayfinding research theoretically comprises riskiness of paths, we argue that, in its current form, the least risk path algorithm is not reliably applicable to indoor and integrated indoor-outdoor environments. In Chapter 6, it was demonstrated that the exact number of turns could not consistently be deduced on any of the indoor networks models. This is in stark contrast with the results on outdoor networks, where the number of turns could accurately be obtained independent of the level of detail and consistent with user's perceptive notion of turns in outdoor space.

As such, both our findings within Chapters 5 and 6 contribute to our conclusion that outdoor algorithms cannot be simply copied into indoor environments. Several parameters were identified as being of major influence to this outcome, discussed hereafter.

First, we argue that the ability of obtaining accurate results following the algorithmic implementation in indoor space is hampered by a changed interpretation of algorithmic concepts due to structural and environmental differences between indoor and outdoor spaces. For example, the key idea behind the least risk path algorithm, discussed in Chapter 5, is choosing paths with a minimum risk of getting lost. The original risk definition depends on the number of edges converging at an intersection and their respective lengths. However, as discussed in Chapter 5, some aspects in the definition of risk might not be as profoundly present as what might actually be necessary for wayfinding. Indeed, instead of selecting purely the longest edge at every intersection, selecting an edge with a slightly shorter length but with other parameters that reduce navigational complexity (e.g. a long line of sight, wide and open corridors) might often be of more importance for overall risk reduction. Additionally, even though having a slight increase of the number of edges at an intersection might not add much more discomfort to the wayfinder itself, his chance of picking the right option does actually decrease. It should be noted that these aspects (e.g. openness, line of sight, complexity of intersections) might equally apply to the outdoor implementation of the least risk path algorithm. Although the idea of the algorithm is quite appealing in aiding unfamiliar users through complex environments, we want to point out that the outdoor implementation is at this point still unsatisfactorily tested. Further analysis of the risk value definition, both indoor and outdoor, is therefore required.

Besides the merely structural aspects influencing algorithmic implementations, more important is that the definition of a certain algorithmic concept might need to be altered given the cognitive interpretation and use of the specific environment in which the algorithm is implemented. For example, the risk of getting lost indoors has a different meaning and interpretation compared to outdoor risk, because of the fact that our cognitive perception of space, and as such risk, is changed. Indeed, it is widely acknowledged that many have wayfinding problems in indoor environments due to the typical architectural structures (e.g. corridors with single rooms compared to outdoor integrated city environments) that only rudimentarily account for human spatial cognition (Hölscher et al., 2006). Additionally, wayfinding in indoor environments is hindered by its 3-dimensionality, inducing specific problems ranging from orientation loss after vertical travel to incongruent floor plans (Hölscher et al., 2012). These additional complexities within the spatial structure of an indoor environment put a high strain on understanding and simplifying space, which is important in the creation of cognitive maps (Carlson et al., 2010). It is found that the risks of getting lost are higher when dealing with such incomplete cognitive maps. Wayfinding research has also demonstrated that the interpretation of the various cognitive factors contributing to the risk of getting lost are different indoors compared to outdoors, and thus should also be differently implemented in the least risk path algorithm (Carlson et al., 2010). However, the precise extent of differences and their impact on guidance algorithms still has to be examined more precisely.

A second example showing the influence of the perception of space on the definition and interpretation of guidance algorithms came up in Chapter 6. It appeared that given the general theoretical definition of a turn as a directional change from a reference line, the indoor application for counting the number of turns did not return accurate results. This is caused by an unclear definition of what exactly makes up an intersection indoor, and as such where turns should be counted in indoor environments. Leaving the underlying network model aside, not all indoor spaces always contain clearly identifiable paths or decision points, in comparison to typical road intersections. For example, in an entrance hall of a building, where exactly does a user take the decision for the continuation of his path? One might think this happens on entering the new spatial unit (as such putting the decision point in the doorways), but this indirectly assumes that the person already knows where to go next. If the user is still trying to find his way, he might first be wandering around more before taking an actual decision. This is just a simple example of the complexities of indoor environments with respect to how people use them in wayfinding tasks. Note also that the definition of a turn is tightly linked to how people verbalize navigational paths. These verbalizations of turn actions in route instructions are even more challenged since they are largely influenced by the underlying intersection type at the decision point. Indeed, participant's strategies for verbalizing route instructions are found to change along with the complexity of the intersections (Klippel et al., 2012). It is obvious that generic path instructions like 'go left at the 1st intersection' do not necessarily apply to an indoor context and a further understanding of how people perceive indoor space areas is required.

In this context, we also want to urge for real-life testing of proposed improvements to guidance algorithms. Indeed, it is hard to know what the best weight distribution within the definition of risk value is, if you don't have a reference dataset to compare it with. Equally, it is only logical that the exact meaning of what is defined as turn and when they occur in indoor environments should be held against the light of how people actually perceive them. Indeed, one can compute turns easily, but did the person moving really make a change in direction, at which point did this happen and did he perceive it as such? This touches upon one of the current major problems in indoor research, namely that there is a separation between cognitive wayfinding studies and navigation studies. While wayfinding research largely focuses on how people behave when entering a building for the first time or when performing certain search tasks, navigation research produces many algorithms for navigation guidance. There seems to exist a disconnect between both, as the developed guidance algorithms are not widely tested in wayfinding tests and at the same time when developing guidance algorithms, the results of previous cognitive wayfinding research are often not taken into account. It is our belief that ultimately the quality of these models and algorithms in aiding users has to be tested and examined in the field.

Our main conclusion within this research question is that the setting, whether indoor or outdoor, has been proven to influence the theoretical definition of algorithms, but more importantly the setting influences the cognitive meaning and perception of the algorithmic concepts. This demonstrates that differences in indoor and outdoor spaces are not just structural, but are also highly influenced by cognitive perception of space, especially considering applications focused on human movement. This complicates the understanding of how exactly algorithms should deal with, and be adjusted to, the user's perceptual interpretation of space, hence our appeal for more empirical tests.

8.1.5 RQ 5: Do the different indoor space models have any noticeable effect on the operation and results of navigation and wayfinding algorithms?

The results in RQ4 illustrated difficulties with a 1-on-1 application of outdoor concepts in indoor environments. An important aspect in this context is the influence of the chosen model of indoor space can have on the results of given guidance algorithms. This topic first emerged in Chapters 5 and 6.

In Chapter 5, the unsatisfying results of the indoor implementation of the least risk path algorithm were partly caused by using a geometric network model. This network models corridors as sub-graphs introducing synthetic hallway nodes directly in front of each doorway leading to that corridor. This results in a large amount of intersections, each adding more weight to the total risk value of a particular path, which does not necessarily comply with the wayfinder's notion of risk when traversing a corridor in comparison to a room. On the contrary, it is sometimes much harder to instruct a person on how to cross a specific open space (often consisting of a number of obstacles) than to guide them through a straight corridor. The confusion with these hallway nodes comes from the changed functionality of nodes: from formal decision points to merely morphological nodes. Indeed, adding additional nodes in a corridor does not mean that they are true decision points, especially when traversing the entirety of the corridor. This was also substantiated by wayfinding experiments where participants explicitly stated not requiring any landmark checkpoints in a corridor when no choices had to be made (Viaene & De Maeyer, 2013). Conversely, when a user would have to turn away from the main corridor, the created sub-node can indeed be seen as decision node, but an added challenge arises as it might be harder to determine at which point this turn should be taken.

The confusion with what exactly makes up a decision node in indoor space also emerged in Chapter 6. As stated in RQ4, it was identified that inaccuracies in indoor turn calculations were caused by the unclear definition of what a user considers as decision point in indoor environments. This issue gets even more complicated given the fact that guidance algorithms rely on a network modeling of space and as such we have to deal also with differences in how the various indoor network models capture the user's movement and perception in the network nodes. No single indoor network model is at this point all-encompassing in dealing with turns; with every network posing new challenges to the turn calculations. For example, the visibility-based network might be the closest in modeling walking patterns indoors, as it relies on similar concepts as during actual locomotion (visibility aspect, decision points in doorways), but turn calculations were wrongfully returned due to the sharp angles with which some doorways were entered. As such, the criteria with which decision nodes and edges were created in indoor space proved different than the rules for outdoor network creation (e.g. Table 6-2). Overlaying the rules of outdoor intersection creation on indoor principles did not culminate in any useful results due to several problems: linkage to the spatial units creating a loose relationship between graph and how people reason about indoor space, and decision point creation outside the actual geometry of the rooms. It is not clear when, how and which type of indoor network can serve as equivalent to its outdoor counterpart.

Because the results of turn calculations are completely influenced by the chosen indoor network of space, a new procedure for indoor turn calculations was developed and presented in Chapter 7 that works independently of the underlying network. Our new procedure for indoor turn calculations is based on the idea of combining the visible viewpoints at the decision points in doorways with the actual walking pattern perpendicular to the orientation of those doorways. The algorithm takes two parameters into account: (i) the mutual orientation of the walls containing entering and exit doors and (ii) the angle between the line of walking pattern and the doorway. Depending on the relationship between both parameters, 0, 1 or 2 turns are determined within a single convex spatial unit. To illustrate the accurate working of the algorithm, the fewest turns path algorithm indoor was calculated on the exact same examples that previously lead to significant miscalculations in the number of turns. These examples showed that the algorithm is space-model independent and as such can be used in any indoor modeling situation. This is a noticeable improvement to the problems identified in Chapter 6.

In conclusion, the results presented in Chapters 5 through 7 underline the difference between outdoor urban networks and their indoor equivalents: in outdoor space each network node represents both a formal decision point and intersection, while this is not necessarily the case in indoor environments. Indeed, the various network proposals could and should be further investigated with regard to how the results of wayfinding algorithms change with changing underlying network. Is a certain network better suited for calculating algorithms? Are the results of running the algorithms biased by the underlying description of the data? Is this the case for all algorithms, or just for specific types? Additionally, it might be useful to connect the choice of indoor network with the development of more sophisticated algorithms in line with wayfinding strategies. For example, by using a hierarchical or a dynamically changing network, the least risk path algorithm could select routes that are more preferred or contain higher classified edges to be in line with users' hierarchical spatial reasoning. The main questions here are which hierarchical structure should be used and how it should be defined. While in outdoor navigational research, the road classification often serves as a natural hierarchy, indoors this hierarchy is much harder to define. A possibility could be to discover the latent natural hierarchy of the indoor graph by using the reach metric introduced by Gutman (2004). However, given our results in Chapters 5 and 6, we do not expect that there would be a single indoor network model that is able to rule out its structural influence in the results of guidance algorithms. That is also why we developed Chapter 7's space-independent model for turn calculations.

8.2 FURTHER DISCUSSION AND RECOMMENDATIONS

The aim of Section 8.2 is to critically reflect upon the results presented throughout this dissertation and previously summarized. In doing so, it serves as a compilation of the most important points addressed in the discussion sections of the separate chapters, supplemented by additional global insights after four years of research on integrating indoor and outdoor pedestrian navigation applications.

8.2.1 Influence of open versus closed space on the chosen modeling paradigm (continuous or discrete) in pedestrian indoor-outdoor navigation guidance

In this section, we want to elaborate further on the importance of identifying an appropriate modeling paradigm, either continuous or more discrete, for running pedestrian navigation guidance algorithms, in a more general context. In RQ4 and RQ5, it was demonstrated that issues with transferring outdoor guidance algorithms into indoor spaces were related to (i) the inherent structural differences between indoor and outdoor space, and (ii) their perception by users as open versus closed space. Both these aspects influence the choice of the underlying model of space.

Navigation and evacuation are typical situations that revolve around humans; how they move, behave, and interact. The locomotion aspect within navigation and evacuation is defined as the movement of one's body around an environment (Montello, 2005). During locomotion, humans recognize the existing obstructions and boundaries of that space and (try to) avoid them. As such, their movement is restricted to the open areas in between the set boundaries of space, independently of whether the user is situated in an indoor or outdoor environment. However, throughout this dissertation it has become clear that structurally, indoor and outdoor spaces differ in the way their boundaries are defined and as a consequence how free movement is inhibited. For example, indoors, rooms are mostly completely surrounded by walls, with only small openings for doorways. Outdoors, the boundaries are more rectilinear and limited on only two sides (e.g. a street has mostly two open ends). At first sight, this difference is rather small, still it interferes significantly with how space is perceived and how space can be modeled.

When humans 'perceive' an environment, they add new knowledge to their cognitive map. In turn, this cognitive map influences how they act and behave in the environment and as such also how they react to external guidance. Navigation guidance services have to take into account differences in perception, induced by the specific environment, in order to be of any use (Section 1.1.2.2). This came across in specific problems such as: how is a turn perceived in indoor space? What is the complexity of an intersection indoors versus outdoors? How do I verbalize routes in indoor environments? As such, although the setting (both indoor and outdoor) influences the theoretical definition of algorithms, more importantly it also influences the cognitive meaning and perception of the algorithmic concepts within that setting. This means that, even though indoor environments can be considered as one continuous space, they are also bounded by multiple impenetrable boundaries. Depending on the purpose of analysis, these boundaries need to be acknowledged. For example, humans navigating in an indoor environment cannot walk through walls, making that indoor space in navigation applications is considered non-Euclidean. Conversely, analyzing the distribution of air or sound within a building is far less or not restricted by the physical boundaries, making their view on the same environment more continuous and open.

Apart from the complexities of the environment and its perception, navigation applications require a modeling concept to run on. The choice of modeling paradigm prolongs the open versus closed space discussion even more, as choices have to be made between discrete versus continuous models of space. Mast et al. (2012) are one of the only researchers mentioning explicitly this open versus bounded aspect of environments by relating it to definitions of scene space versus network space. Scene space is defined as open areas which are characterized by the absence of clearly identifiable nodes and edges, while network space contains clearly identifiable nodes and connected by edges (Rüetschi & Timpf, 2005). Applied to indoor environments, corridors are typically envisioned as being networks, while larger rooms are considered open, scene space areas with internal obstacles. However, within our research, it appeared that corridors cannot always be considered as network edge, following the user's perception (e.g. taking a turn in a corridor versus traveling straight through them are highly different navigation tasks in terms of difficulty of verbalization, perception and algorithmic support). Similarly, one can consider outdoor environments as mainly being network spaces, except for situations like open car parking lots where a more free movement is possible. As such, the choice of modeling a certain space as either a network or a scene within navigational applications is not necessarily only linked to the spatial structure, but more importantly to the perceptive use of that space. Both indoor and outdoor environments consist of scene and network space elements, depending on the scale of focus and the application at hand. The consequences of this for navigation implementations will be discussed in Section 8.2.3.

In RQ5, it was demonstrated that just by choosing a certain indoor network, mistakes are induced. This is not surprising given that, while in network space wayfinding consists of selecting a path at each decision point, in scene space, wayfinding is characterized by activities such as searching, exploring, and matching as there are no clear paths to choose from (Mast et al., 2012). However, we argue that for navigation and wayfinding support in indoor environments, using network-based models still seems logical, and this for several reasons. First, algorithmic support requires selecting paths from a network (Golledge, 1999). Second, networks simplify analysis of space as they describe a topological relationship between similar objects by downgrading their geometrical dimension into point and line structures. For example, for indoor buildings, using the Poincaré duality principle, one can easily map the separate three-dimensional units into one-dimensional points in topological space. The connections between those points can designate adjacency relationships with possible extensions to describing various other topological relationships based on the included contextual information. This has the added advantage of being scale-independent, which is a very nice feature for integrating indoor-outdoor spaces for navigation. Indeed, it is often said that the indoor and outdoor world consist of different scale levels that prevent integration on multiple levels. While the density of networks might be different, their theoretical foundation is universal across space concepts allowing complete integration and connection.

While networks at first sight seem logical in supporting navigation and evacuation scenarios, modeling spaces by networks introduces several inaccuracies because of the transformation and simplification process from space (open or closed) into a network of nodes and edges. All spaces do contain some inherently open areas. Simplifying them to point and line structures thus means ignoring the continuity, geometry and internal structures of space. This is especially true in the context of indoor environments. The multitude of different indoor networks available demonstrates that there are several possibilities to downgrade geometry from 3D to 1D. As such, different networks emerge based on the way the objects are chosen, which relationship needs to be identified and simplified, and how their boundaries are represented (OGC, 2014). At this point, it is not clear how one should decide which objects should be transformed into nodes as it apparently has a significant effect on the results of analyses (RQ5) and the user's perception of those analyses (RQ4). This might also be the reason why still no model has been developed for subdividing 'open' areas into multiple sub-cells.

In conclusion, we discussed the complex relationships between indoor versus outdoor spaces, its perceptive influence as being open versus bounded and the modeling on top by discrete or continuous models. Navigation applications need to acknowledge the inherent boundaries of space. Networks seem to be well-suited for this, but one needs to be aware that the specific choice of network can have a major influence on the supported methodologies and analyses. In Sections 8.2.3 and 8.2.4, we discuss this topic in more detail and make several recommendations for the implementation of navigation applications in indoor and combined indoor-outdoor environments based on the found differences between indoor and outdoor space.

8.2.2 Three-dimensionality of indoor and outdoor spaces

One key aspect of indoor environments which is often described as being highly different from outdoor spaces is its three-dimensionality. Since this issue did not show up very often in Section 8.1, we aim to investigate here the importance of the 3D aspect in supporting indoor-outdoor connections.

Following the results of our route planner analysis (Chapter 3), it was demonstrated that not taking into account the full three-dimensional structure can result in sub-optimal path calculations and route instruction support. Indeed, given that little to no data on underground sections was available, the shortest path calculations were based on the shortest path above ground in two dimensions, neglecting the actual movement up and down staircases in three dimensions. This obviously does not support wayfinding well in a pedestrian context, as humans do care about the added effort of vertical travel.

Research on cognitive wayfinding in indoor environments is well-aware of the effect the third dimension can have on the execution of wayfinding tasks (e.g. orientation difficulties after vertical travel, assumption of congruent floor plans over the various floor levels). However, the translation of these wayfinding problems into navigation guidance algorithms is not yet facilitated. For example, no differentiation is made between horizontal and vertical travel in the current definition of the least risk path algorithm. Going up or down a staircase has such a profound impact on a user's perception of space that it can only result from a deliberate wayfinding choice. In that case, the risk of getting lost might be considered lower when traveling on such a vertical edge compared to other edges. On the other hand, the definition of risk value accounts for the effect of taking the wrong edge at an intersection by counting his length twice (as the idea is that a user recognizes his wrong choice at the first intersection and returns on his path). In the situation where the wrong choice was actually up or down a staircase, the effect of returning along the same path is much larger due to the added effort involved for the vertical travel. Also, it is not very clear when exactly a floor level change is perceived as profound enough to account for actual three-dimensional travel (e.g. does going up 10 stairs count as 3D travel and a floor level change?). It is clear that the specific environmental context comes into play (e.g. different buildings constitute different ways of being subdivided into multiple floors).

Not only does the three-dimensional aspect have an influence on the algorithmic support available, it also affects more generally data and model requirements. An example is the continuing strict separation between developments of 2D and 3D models currently impeding integration of both, especially in navigational applications (Breunig & Zlatanova, 2011; Chapter 2). Some data sources do try to integrate 2D and 3D aspects of the environment (e.g. CityGML's integration of 2D terrain surface models with urban building 3D models), but this results in problems with level of detail definitions and varying semantic definitions of the same object (Gröger & Plümer, 2012). Requiring all data in three-dimensions would put a huge strain on data collection, maintenance and route calculations. It is also not clear if the user of navigation applications actually expects and requires such fully-supported 3D route guidance aspects (e.g. is 3D route visualization preferred over 2D maps?). Note also that outdoor environments consist of three-dimensions as well, but on a different scale and in a different structure. Navigation in an integrated indoor-outdoor environment has to not only account for the multiple floor levels, but also for the natural and man-made level changes in the outdoor terrain.

8.2.3 Implications of our research on indoor navigation developments

Our main research objective aimed at studying navigational and evacuation applications in indoor spaces, by linking them to equivalent outdoor situations. In this section, we want to relate the different results of our research to this general research objective and make several recommendations with regard to the study of indoor and outdoor spaces.

8.2.3.1 Which aspects of the difference between indoor and outdoor space mostly affect indoor navigation applications and analyses?

In Section 1.1.2, we discussed the generally recognized differences between indoor and outdoor spaces. However, in this part, we relate back to the results of Chapters 2 through 7 in order to make more specific suggestions on which aspects have proven to be most affecting both indoor analyses as well as indoor guidance algorithms.

First, with respect to indoor analyses, and more specifically indoor accessibility analysis, the main difference between indoor and outdoor space that emerged from our results in Chapter 4, is the explicit three-dimensionality of indoor environments. Accessibility, and the ease of reaching a certain location in indoor environments, needs to take into account the restrictions and extra effort of movement in three dimensions. As underlying model of space, we used the Geometric Network Model (GNM), as it served our purpose of delineating accessibility differences between the spatial units based on their mutual connectivity relationships. However, the three-dimensional aspect does not specifically emerge from this network graph, since it merely models the topological aspect of connectivity and not the extra effort of three-dimensional movement. That is why in our analysis a flow-based movement model was applied on top of this general connectivity network. The advantage of using a flow-based movement model is that we are able to model the actual human movement and its restrictions, while also dealing with congestion aspects created by the interaction of human movement in the specific spatial unit.

Although we were able to apply the outdoor accessibility concept into indoor space, the indoor application of accessibility analyses is still limited on several levels. First, by using the GNM with rooms modeled by a single network node, the destinations and origin zones of the indoor accessibility analysis are linked to those spatial units themselves. In contrast, if one wants to analyze more detailed accessibility relationships between locations within every indoor spatial unit, the used network will have to be more fine-grained as well. A grid-based model might serve this purpose, as long as the methodology on top accounts for actual human movement in 3D space. Second, with regard to the attribute density, our indoor accessibility measure contains at this point less detail compared to developments in outdoor space (e.g. inclusion of user opportunities along paths, time of day influence...). With that being said, although more extensions and attributes can always be added to our indoor accessibility measure, it currently already takes into account the congestion aspect, which is a common, highly influential, outdoor technique that applies to, and shows the effect of, three-dimensional movement as well.

During the implementation of cognitive outdoor guidance algorithms into an indoor environment, the specific differences between indoor and outdoor space also emerged multiple times. We decided to apply all our implementations on top of a Geometric Network Model, as networks are typically chosen to support guidance algorithms (see Section 8.2.1). With regard to the general algorithmic structure, indoor versus outdoor implementations of the algorithms are quite similar. However, the differences between indoor or outdoor implementations do come into play when considering the required cognitive attributes to be part of the algorithms. We can distinguish between three different cases here that one has to be aware of when developing indoor navigation guidance applications:

- Algorithms that rely purely on geometric aspects of space (e.g. path with widest roads, path with least level changes, shortest or fastest paths ...): for these algorithms, it does not matter whether the implementation is in indoor, outdoor or combined indoor-outdoor space. The network can be connected easily from outdoors to indoors (a GNM works fine in this case, as it is similar to the outdoor road network). The only requirement with using this network is that the requested geometric aspects for the specific algorithm are attached to the separate edges and nodes (e.g. information on path level changes needs to be linked to the edges in order to calculate the path with the fewest level increase). Even for modeling more open space areas, either indoor or outdoor, a simple geometric network will be applicable. However, in that case one might benefit from using a visibility based type network, as the resulting paths will align better with the actual lines of movement. Both networks will allow accurate and correct indoor algorithmic implementations.

- Algorithms containing a perceptive component (e.g. riskiness, ease, simplicity, most beautiful paths …): these algorithms have to deal with the fact that cognitively indoor and outdoor environments are differently perceived by users, due to differences in spatial structure and the presence of certain landmarks (e.g. Section 1.1.2.2). The algorithmic structure indoors requires different parameters and/or a different ratio of influence of certain parameters (RQ4). The choice in network also interferes with the indoor algorithmic implementation because of differences in decision point criteria. Implementing algorithms with such cognitive components in indoor environments not only requires a different underlying network structure (e.g. more hierarchical networks being able to model differences in perception of intersection nodes), but also a different and more dynamic algorithmic structure that differentiates between global travel (e.g. following a general direction to the destination by taking high-level routes with fewer intersections) versus a more local focus (e.g. when coming closer to the destination). Further research on the exact implementation of such algorithms is highly recommended.
- Algorithms containing a geometric cost heuristic based on the relationship between network edges (e.g. minimization of the number of turns or intersection complexity): the heuristic of those algorithms, although at first sight similar to common geometric algorithms, interferes when implementing them in indoor environments with the architectural indoor building structure (e.g. the number of turns on an indoor path is influenced by the doorways through which humans move in a straight line). This is due to the fact that the cost calculation relies not on an attribute attached to every edge (as is the case when typically using a network approach), but rather to the relationship between several edges and nodes. As such, the type of indoor network chosen to simplify open space determines the results of the indoor calculations of these types of algorithms. We recommend that such indoor implementations should be replaced by a network-independent variant, as suggested in Chapter 7.

In conclusion, when developing more and better cognitive algorithms, one has to be aware that the indoor context adds significant difficulties, differing parameters, and many restrictions. Furthermore, the choice of network will highly influence the results of those algorithms. Thus, while a simple geometric network indoors can work in most use cases, it is not necessarily always the best choice to support robust indoor navigation applications. Independent of the type of algorithm that one wants to apply, an important aspect here is that the algorithmic structure is required to be carefully tested in outdoor space to understand if all parameters are correctly implemented.

8.2.3.2 How does the choice of locomotion affect indoor navigation support?

In the discussed research, only pedestrian, non-disabled navigation as mode of locomotion was considered and modeled to navigational networks. With respect to other modes of locomotion that occur in both indoor and outdoor space, we can only make suggestions based on the findings of our research. In the following paragraphs, two types of locomotion aspects that can appear in indoor environments will be discussed in light of our findings of pedestrian navigation.

First, facilitating wheelchair use in an indoor environment will, in our point of view, not be highly different indoor versus outdoor. The main requirements for facilitating wheelchair-friendly navigation guidance relate to the data availability with regard to slope restrictions, width of doors and openings, accessibility of elevators, etc. These parameters can easily be added to any network graph. Again, the more detailed the network graph is, the more detailed the results of guidance support can be. Note that data requirements at a high enough level of detail still form the biggest bottleneck for wheelchair friendly navigation, and this both in indoor as well as outdoor environments (e.g. slopes and obstacles in outdoor space affect locomotion similarly to indoor space). The previously discussed cognitive aspects and differences between indoor and outdoor space do come into play here as well when providing more cognitive guidance support on top of the movement restrictions of wheelchair users.

Second, when considering robot movement, typically this occurs on grid networks or raster models as the movement is more step-to-step related. The most stringent requirement for guiding robots indoor and outdoor is the recognition of obstacles that need to be avoided (walls, tables, stairs....). As such, algorithms for robotic movement in indoor space will rely on different context variables compared to human indoor movement because of a different type and speed of movement (evaluating each step at a time).

8.2.3.3 How does the context (emergency versus normal movement) affect indoor navigation support?

Section 1.1.1.4 discussed the different aspects that need to be considered in case of emergencies, with those often containing more unpredictable parameters, versus navigation under normal circumstances.

The indoor cognitive guidance algorithms (discussed in Chapters 5-7) have been developed to guide unfamiliar people in their wayfinding endeavors in case of normal situations. When dealing with emergencies, some of these algorithms make much less sense to be used as guidance algorithms, because of the stringency of an emergency situation. For example, while an algorithm that minimizes the numbers of turns is a nice feature for unfamiliar users, in an emergency, everyone just wants to get out of a building as fast as possible without spending much attention to the number of turns along the way. Conversely, the algorithm minimizing the risk of getting lost could be useful in an evacuation context. However, during emergency situations, people in buildings do not necessarily want to spend extra time on calculating the least-risk path route and tend the follow the general direction of the crowd. Also, the least risk path might have a different connotation when used in normal situations (e.g. focused on avoiding difficult intersections) versus evacuations (e.g. focused on avoiding dangerous paths). As such, although the algorithms can be implemented in both context situations, the used parameter support and their connotation might have changed.

Also, we believe that a more appropriate algorithmic support would be to guide people (e.g. firefighters) into indoor environments while being aware of other emergency personnel and building users. Such implementations have the difficulty that there is often not a clear view or idea on the extent and location of the emergency which makes it harder to stay up to date and accurately guide people in such situations. As such, the context parameters to be included in the algorithms are completely different in this case and focus more on getting everybody out of the building or getting to the location of the disaster as fast and safe as possible. That is also the reason why evacuation and navigation have been largely separately developed so far (see RQ2), and probably will remain so in the near future.

Note that in all cases, the underlying indoor network models can be used in both emergency and non-emergency situations, as the spatial and algorithmic structure is similar. However, in emergency situations, the networks might have to be much more dynamic, in order to anticipate on sudden blockages or movement restrictions due to the emergency situation.

8.2.4 CLOSING THE GAP BETWEEN INDOOR AND OUTDOOR SPACE: RECOMMENDATIONS FOR FUTURE COMBINED INDOOR-OUTDOOR RESEARCH

Following our research results on indoor environments, the next step would consider integrating indoor and outdoor space in combined analyses and applications. Although we did not specifically implement combined indoor-outdoor applications, we do want to comment on the problems that can occur when closing the gap between indoor and outdoor space in terms of analyses, algorithms, networks, data etc. based on our previous discussion of indoor-outdoor differences, locomotion types and context variables. We will first discuss the indoor–outdoor integration for navigation support, and afterwards the possibilities for indoor-outdoor analytical integration.

First, it is clear that the integration of indoor and outdoor space for navigation guidance applications will have to occur on several levels:

- Routing support: For integrated navigation applications, it seems fair that one can connect a typical outdoor network (either car network, or a separate pedestrian network) with a basic geometric indoor network. With such a combined indoor-outdoor network model and general attributes of importance to wayfinding attached to the individual edges and nodes (e.g. length, time, width, height ...), basic pedestrian navigation guidance can be quite easily accomplished. When aiming for more extensive or specific guidance, the previously discussed differences between indoor and outdoor spaces arise and will have to be taken into account (Section 8.2.3.1). This might bring about different internal implementations for indoor and outdoor algorithms based on the challenges that the specific environment poses.
- Representation issues: With regard to representation and visualization models, as mentioned in RQ1, when integrating indoor and outdoor space, one has to integrate several data sources with different content, scale level, attributes, etc. Apart from network models for calculating routing algorithms, there is not yet a consensus on what the user might require as space representation. Especially with regard to the indoor sections, a

simple floor-by-floor representation might not be enough to capture the three-dimensionality of a building; while a full 3D representation might become very complex, both to understand by the user, and to consistently update and use as visualization tool. The requirements for space representation will also have to be weighed against what is actually feasible in terms of data acquisition, cost and time efficiency. At this point, basic indoor mapping might be the only commercially feasible solution, until indoor data acquisition techniques improve further.

- Coordinate system: Facilitating the integration of indoor and outdoor spaces also means that every location in indoor space also gets coordinates attached to each individual unit. In a strict sense, transformation of indoor local coordinate systems to outdoor more global coordinate systems might be quite simple as long as the connections between the two are correctly and accurately determined. However, the main problem occurs when address matching and routing descriptions need to rely on more semantic data, especially in indoor sections where global coordinates do not have much meaning for a wayfinder's navigation experience.
- Evacuation applications: The context of evacuation and navigation has already proven to be widely diverse within indoor space. The indoor-outdoor integration during evacuation situations seems most of relevance when considering indoor emergencies that extend to the immediate outdoor vicinity of a building complex. For example, the evacuation analysis of *exitability* is easily extendable to outdoor space, as people often have to evacuate further away from the building than just the main exit. The outdoor component will then have to be modeled at the same scale level as its indoor parts. In contrast, emergency situations that affect solely outdoor space, often occur due to environmental situations (e.g. tsunami, earthquake, floods, and fire) and affect a larger scale environment. When modeling such large scale residential evacuations, the focus is not on the individual building units itself, but more census-block oriented. The methodologies for modeling and calculating this will also have to take into account other parameters, (e.g. traffic incidents, topography, weather) and at a more global level of focus (e.g. not just population distribution within a building, but rather the distribution of people across multiple areas).

- Context differences: When integrating indoor and outdoor space, we will always have to deal with context differences between indoor and outdoor environments (similar to the differences between the evacuation versus navigation context). Some applications benefit from combining both spaces, but most will probably remain quite separate because of the inherent difficulties for merging (e.g. data problems, model differences, different semantics and context, locomotion differences ...). For integrated navigation applications, visibility aspects will always largely influence the ease of wayfinding and as such also the need for more cognitive algorithms.

For navigation guidance, the integration of indoor and outdoor environments is proven to still be hampered by several issues. However, if we look even further, a more methodological problem might arise in further analyses in the integrated context of indoor-outdoor spaces. If we develop two separate methodologies (each one adapted to its own space environment) for performing the same analysis, can they still be merged into a single application support? For example, as we want to extend the fewest turns path algorithm into integrated indoor-outdoor environments, we should have an integrated methodology for calculating turns. However, we demonstrated that the indoor and outdoor interpretation of turns is highly different in both spaces, making the methodologies also different. Should they remain separate or can a generalized principle be developed that also fits the common schemes of indoor and outdoor? Is their maybe a more general underlying concept that encompasses the main idea for a certain analysis/algorithm, independent of implementation issues related to particularities of space environments? In Thill et al.'s (2011) indoor-outdoor accessibility analysis, two separate methodologies, one for outdoor and one for indoor accessibility, were developed. We would have to compare exact values with such a model but at this point we question those separate implementations for indoor and outdoor space. Indeed, when do you find yourself at the boundary of indoor-outdoor space and as such when do you make the switch between methodologies? At this point, we can only underline that there is still a gap between indoor and outdoor geospatial research that requires further research. Our research however, gave a first glance of the difficulties and problems that can occur when extending navigation applications from outdoor into indoor space.

8.2.5 Future research possibilities

Every dissertation is linked to a number of limitations, largely due to the methodological choices made during the specific research execution. In this dissertation, although our research objective encompassed understanding the differences between indoor and outdoor space, we were not able to exactly quantify all of them. We have determined conclusively that the environment largely affects the results of navigation and analyses; but more research should be dedicated to adequately state and understand the exact differences between indoor and outdoor environments.

Additionally, by limiting our research to solely indoor pedestrian navigation, it is not easy to extend the observations and recommendations made in this dissertation to a more general context of indoor navigation and analyses. Although we tried to discuss them in the previous sections, we are aware that navigation guidance for pedestrians under normal conditions is a specific type of context. Several aspects do require more extensive research in this realm. For example, what is the impact of the indoor network choice on the result of guidance algorithms? What are the minimal data requirements to support indoor and integrated indoor-outdoor navigation? How to generate indoor and indoor-outdoor route instructions?

With respect to guidance algorithms, we highlighted the importance of cognitive algorithms in indoor space. Aspects like the risk of getting lost (Chapter 5) and minimization of the number of turns (Chapters 6-7) will have to be combined to provide a more complete cognitive algorithm. Additionally, other aspects like the complexity of intersections, availability of landmark information, the ease of movement, alignment to common wayfinding strategies ... should be investigated for possible implementation into indoor and combined indoor-outdoor cognitive algorithms.

With respect to indoor analyses, much more extensive research is required, as we only discussed indoor accessibility analyses (Chapter 4). As such, broader indoor analyses should be tested and examined with respect to the underlying model of space, user requirements and attribute context. Overall, we are at the beginning of fully understanding the importance of context (indoor versus outdoor) on navigation applications and analyses. With this dissertation, a first start is made into examining those topics.

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9

GENERAL CONCLUSION

This dissertation revolved around the study of indoor spaces in navigation and evacuation applications. With the increased interest in Location-Based Services and applications, a shift from outdoor towards indoor environments is becoming more and more important. By studying the modeling and analytical support available within indoor navigational applications by relying on similar outdoor concepts, we aim at closing the gap between indoor and outdoor space research.

By investigating the state-of-the art of navigation and evacuation scenarios in combined indoor-outdoor environments, it was demonstrated both theoretically (Chapter 2) and practically (Chapter 3), that research environments are still in the early days of providing combined indoor-outdoor navigation services. A huge variety in spatial models and data structures, along with a multiplicity in data sources with varying accuracies, coverage and semantic context support, currently hampers the availability of fully integrated pedestrian navigation applications. At the same time, this abundance in variables aligns with the existing differences between indoor and outdoor characteristics, the chosen mode of locomotion, and user's perception of space.

Indoor navigation research still requires much attention as a research field. Although aspects of modeling indoor spaces through networks, 3D city models and polygonal approaches show the widening interest in the field, it appears that the algorithmic and analytical support in indoor space is currently lacking. This led to our interest in examining navigational applications in more detail. In Chapters 4 through 7, our research focused on examining whether commonly available outdoor concepts for analysis and path guidance could be extended into indoor building structures without any hindrances. More specifically, in Chapter 4, we implemented an accessibility tool, measuring the occupant's ease of reaching exits during evacuations, which demonstrated the ability to extensively analyze three-dimensional indoor urban environments in a way that has never been attempted before by taking into account the specific movement behavior of people in indoor space. However, it also questioned the lack of knowledge about the importance of the underlying modeling paradigm in the execution and performance of indoor analyses and the general void in comparative analytical research in indoor spaces.

Chapters 5 through 7 sought to implement outdoor cognitive algorithms in indoor environments to provide a more appropriate wayfinding support with easier to follow routes. In Chapter 5, the indoor implementation of the least risk path algorithm, minimizing the risk of getting lost, was executed, while in Chapter 6 the focus was put on algorithms that aim at minimizing the number of turns along a path. Not only was it demonstrated in both chapters that the meaning of algorithms outdoor can be completely changed when implementing them in indoor spaces, the specific modeling principle of networks seemed to be a major cause of this. That is why in Chapter 7, a (network) space-independent model was developed for performing turn calculations in indoor spaces aligned with the indoor perception of turns. This showed that it is possible to extend the idea behind outdoor algorithms and analytical tools into indoor space, but that adaptations are called for to deal with the specificities of indoor spatial characteristics (e.g. non-Euclidean space), movement of users, and their perception of space during wayfinding.

The ensuing discussion reflected on a selection of some important issues that occurred in our research and which require further attention in the future. It was made clear that navigation applications have to deal with several complex relationships between (i) indoor versus outdoor space and their characteristics; (ii) open versus closed perception of space; and (iii) discrete versus continuous modeling paradigm. Developers need to be aware that the specific choice of these aspects can have a major influence on the quality and accuracy of supported methodologies and analyses. Specifically for indoor navigation guidance support, the chosen algorithm will define the preferred type of indoor network and context parameters. For example, for geometric-based navigation guidance, an indoor geometric network will satisfy the needs and can easily be extended to common outdoor networks as well. When applying more cognitive-based algorithms, it is proven that either the network or the algorithmic implementation will have to be adjusted to model the perceptive differences of indoor versus outdoor space. At this point, it is not yet clear whether in such cases, the indoor and outdoor algorithmic and analytical support will remain largely separate or whether they can be integrated to provide in combined indoor-outdoor analyses. It is clear though that more research is still required to close the gap between indoor and outdoor geospatial research. Our research however, gave a first glance of the difficulties and problems that can occur when extending navigation applications and analyses from outdoor into indoor space.

10

NEDERLANDSE SAMENVATTING - SUMMARY IN DUTCH -

Mensen voeren bijna dagelijks verplaatsingen en bijhorende navigeringstaken uit, en doen dit binnen een bepaalde omgeving en context. Navigatie kan hierbij gedefinieerd als een tweeledig proces bestaande uit, enerzijds het doelgericht en gemotiveerd nemen van beslissingen over het te volgen pad ('wayfinding' of wegbepaling), en anderzijds de eigenlijke voortbeweging langs het gekozen pad van begin- tot eindpunt ('locomotion' of voortbeweging) (Montello, 2005). Evacuatie wordt vaak verbonden met navigatie, aangezien het dezelfde componenten van 'wayfinding' en 'locomotion' heeft, hoewel bij evacuatie alles in een meer tijdsgelimiteerde context verloopt. Tijdens het 'wayfinding'-proces interageren aspecten van positionering, oriëntatie, en routebepaling met elkaar met als doel een mogelijke route of het vervolg van een route te kunnen bepalen (Nagel et al., 2010). Om dit proces te vergemakkelijken, worden 'wayfindings'-taken vaak ondersteund door externe hulpmiddelen zoals routebegeleidingssystemen en kaarten. Dergelijke routebegeleidingssystemen zijn immers bedoeld om de cognitieve kaart van de gebruiker te verbeteren en te vervolledigen. Hierdoor kan de gebruiker gemakkelijker passende 'wayfinding'-beslissingen nemen, wat vooral belangrijk is voor gebruikers die zich in een nieuwe of weinig vertrouwde omgeving bevinden (Golledge, 1999).

Navigatie en evacuatie zijn complexe processen die reeds veelvuldig bestudeerd werden binnen meerdere onderzoeksdomeinen, zowel in cognitief en psychologisch onderzoek, als in ruimtelijk-geografisch en architecturaal onderzoek. In dit proefschrift ligt de nadruk op het ruimtelijk domein. De afgelopen jaren is de populariteit van navigatie- en evacuatietoepassingen binnen geospatiaal onderzoek, in navolging van ontwikkelingen binnen Location-Based Services (LBS), significant toegenomen. De ondersteuning van routebepaling vormt daarbij een essentieel onderdeel, aangezien LBS informatie en diensten verschaffen aan gebruikers, door gebruik te maken van allerhande ruimtelijk gelocaliseerde data (Kolodziej & Hjelm, 2006). Tot voor kort speelden LBS voornamelijk een rol in een breed gamma van outdoor contexten (bijvoorbeeld gezondheidszorg, reclame, gaming, en transport). Mensen besteden echter het overgrote deel van hun tijd binnen gebouwen (Jenkins et al., 1992), wat betekent dat een aanzienlijk potentieel van mogelijke consumenten wordt genegeerd door de LBS markt te beperken tot outdoor omgevingen (Kolodziej & Hjelm, 2006). Recentelijk hebben belangrijke ontwikkelingen in enerzijds indoor positionering (ontwikkeling en integratie van verschillende sensoren zoals WiFi, Bluetooth, RFID) en anderzijds indoor mapping (bijvoorbeeld door Google Maps Indoor) voor een verschuiving gezorgd van outdoor- naar indoor-LBS toepassingen. Dit wijst erop dat de industrie het commerciële belang van indoor omgevingen nu toch langzaam aan erkent.

Dit proefschrift richt zich op het bestuderen en verbeteren van navigatie- en evacuatietoepassingen in een indoor context. Vanuit theoretisch oogpunt kan men aannemen dat routebepaling in indoor omgevingen vrij gelijkaardig is aan het outdoor equivalent. Vanuit een cognitief perspectief echter blijkt het vinden en berekenen van een pad binnen gebouwen en ondergrondse constructies erg te verschillen van de routebepaling op een wegennet. Dit is te wijten aan een aantal belangrijke structurele verschillen tussen indoor en outdoor omgevingen, bijvoorbeeld een ander schaalniveau en -gebruik, verschillende objecten, en een verschillende perceptie van de ruimte. Deze verschillen hebben alle een invloed op de gebruikte data, modellen en algoritmes binnen navigatiesystemen. Zo zijn de gebruikte navigatiestrategieën binnen gebouwen of ondergrondse tunnelcomplexen grotendeels verschillend van deze op wegennetwerken (Hölscher et al., 2006). De uitvoering van navigatietaken in complexe gebouwen leidt ook tot een hoger risico op desoriëntatie door de verschillende niveaus en trappen, en het vaker verloren lopen door een gebrek aan visuele herkenningspunten (bijvoorbeeld omdat oriëntatiepunten minder duidelijk herkenbaar zijn) (Hölscher, et al., 2006). Daarnaast spelen bij navigatie in gebouwen, fysieke en psychologische eigenschappen van de gebruiker (invaliditeit, claustrofobie

....) een grotere rol. Bovendien heeft de manier van bewegen ook een grote impact op navigatie. Zo zijn automobilisten vooral geïnteresseerd in de kortste of snelste route, terwijl voetgangers misschien liever eenvoudige (Duckham & Kulik, 2003) of betrouwbare routes (Haque et al., 2007) volgen. Dit alles maakt een vlotte implementatie van navigatie en 'wayfinding' in indoor omgevingen ingewikkeld. Bijkomend zorgt de evacuatiecontext met een grotere tijdsdruk en veranderende menselijke reacties voor nog meer beperkingen aan het 'wayfinding'-proces. Het is dan ook van uitermate groot belang om aangepaste routebegeleidingssystemen te ontwikkelen die in staat zijn met deze specifieke complexiteiten binnen gebouwen en ondergrondse infrastructuren om te gaan.

Daarnaast streeft dit proefschrift ook na een beter zicht te bieden op de verschillen tussen indoor en outdoor omgevingen om een uiteindelijke integratie van beide in navigatietoepassingen te faciliteren. Een naadloze integratie van de indoor en outdoor context maakt het immers mogelijk een goed inzicht te krijgen in de echte verplaatsingen van mensen in een stedelijke omgeving.

Dit alles leidt tot de volgende onderzoeksdoelstelling:

> De studie en het verbeteren van modellen, analyses en algoritmes ter ondersteuning van navigatie- en evacuatietoepassingen binnen gebouwen en ondergrondse infrastructuren door gebruik te maken van gelijkaardige outdoor concepten.

Deze vrij algemene onderzoeksdoelstelling wordt meer gespecificeerd in de volgende vijf onderzoeksvragen:

- OV1: Wat is de stand van zaken rond het integreren van indoor en outdoor omgevingen voor de ondersteuning van navigatie voor voetgangers?
- OV2: Wat is de stand van zaken rond het onderzoek van navigatie- en evacuatietoepassingen in indoor omgevingen?
- OV3: Kunnen analytische procedures, wijdverspreid en aanvaard in een outdoor context, zomaar worden vertaald naar en toegepast worden in een indoor context?
- OV4: Kunnen cognitieve routebepalingsalgoritmes uit autonavigatiesystemen onmiddellijk worden uitgebreid om routebegeleiding te bieden aan mensen in indoor omgevingen?

- OV5: Hoe beïnvloeden de verschillende indoor ruimelijke modellen de werking en resultaten van toutebepalingsalgoritmen?

Deze onderzoeksvragen komen aan bod in hoofdstukken 2 tot en met 7 van dit proefschrift.

De hoofdstukken 2 en 3 zijn volledig gewijd aan het in kaart brengen van de huidige stand van zaken rond de integratie van indoor en outdoor omgevingen voor voetgangersnavigatie. Hiermee wordt ook getracht een antwoord te bieden op OV1 en OV2. In hoofdstuk 2 wordt een theoretische reflectie gemaakt rond die integratie door 36 wetenschappelijke studies met elkaar te vergelijken. Uit dit onderzoek blijkt dat op dit moment de integratie van indoor en outdoor omgevingen in toepassingen van voetgangersnavigatie nog steeds in zijn kinderschoenen staat. Integratie wordt bemoeilijkt door een grote verscheidenheid aan beschikbare ruimtelijke modellen en datastructuren, gecombineerd met een overvloed aan mogelijke databronnen, elk met zijn eigen specificaties qua nauwkeurigheid, ruimtelijke dekking en semantische context. Deze verscheidenheid is te wijten aan de verschillende aspecten die het onderscheid tussen indoor en outdoor omgevingen voor navigatie kenmerken, de gekozen wijze van voortbewegen, en de perceptie van de gebruiker van zowel zijn omgeving als de gekozen wijze van voortbewegen.

Hoofdstuk 3 beschrijft een meer praktijkgerichte aanpak waarbij specifiek het gebruik van indoor infrastructuren voor navigatie in verschillende routeplanners wordt geëvalueerd. Uit de resultaten van diverse case studies blijkt dat momenteel meestal databeperkingen een gebrek aan accurate indoor-outdoor navigatieroutes veroorzaken. Daarnaast zijn er problemen met de indoor ondersteuning van outdoor 'address matching' methoden als een gevolg van andere adresstructuren, afwezigheid van een indoor referentie databestand en verschillende netwerken. Dit leidt in vele gevallen tot sub-optimale routebepaling of zelfs een compleet gebrek aan routebepaling in indoor en geïntegreerde indoor-outdoor omgevingen.

Vanuit de antwoorden op OV1 en OV2 blijkt ook dat vooral de algoritmische en analytische ondersteuning voor navigatie en 'wayfinding' binnen indoor omgevingen op dit moment nog onvoldoende ondersteund wordt. Daarom is ons onderzoek binnen hoofdstukken 4 tot en met 7 specifiek gericht op het verlengen van outdoor concepten voor analyse en routebepaling naar een indoor context.

In hoofdstuk 4 is een nieuwe bereikbaarheidsmaat, genaamd *exitability*, ontwikkeld, die het gemak kwantificeert waarmee gebruikers de uitgang van een gebouw kunnen bereiken. De analyse is specifiek gericht op een evacuatiescenario als voorbeeld van de intrinsieke relatie tussen navigatie- en evacuatieprocessen. Daarvoor worden eerst de verschillende ontwikkelde modellen voor gebouwen evacuaties vergeleken vanuit zowel geografische studies als simulatie-onderzoek van noodsituaties (OV2). De ontwikkeling van *exitability* toont de mogelijkheden om uitgebreide analyses van de structurele verschillen binnen driedimensionale stedelijke omgevingen te evalueren door rekening te houden met het specifieke voortbewegingsgedrag van mensen in indoor omgevingen. Ondanks het feit dat met de implementatie van *exitability* is aangetoond dat het mogelijk is om outdoor analytische methodologiën te vertalen naar een indoor omgeving (OV3), rijzen tegelijkertijd vragen over de gebrekkige kennis van de relatie tussen het gekozen modelleerparadigma en de resultaten van indoor analyses. Het is -gezien het gebrek aan relevant vergelijkingsmateriaal- ook duidelijk dat onderzoek rond indoor analyses zich nog steeds in een pril stadium bevindt.

In hoofdstukken 5 tot en met 7 wordt geprobeerd om outdoor cognitieve algoritmen naar een indoor context te vertalen om een betere ondersteuning van 'wayfinding'-processen te bieden aan gebruikers die zich in een omgeving bevinden waarmee ze niet of nauwelijks vertrouwd zijn.

Het is al veelvuldig naar voor gekomen dat indoor omgevingen vaak moeilijker en complexer zijn om te navigeren dan outdoor ruimten. Een algoritme dat gericht is op het minimaliseren van het risico op verloren lopen - het minste risicopad-algoritme van Grum (2005) - kan dus zeer waardevol blijken in de 'wayfinding'-begeleiding van gebruikers in een onbekend gebouw. Daarom wordt in hoofdstuk 5, het oorspronkelijk in outdoor omgevingen ontwikkelde minste risicopad-algoritme in een indoor context geïmplementeerd en uitgebreid getest. De tests worden uitgevoerd in een complex studiegebouw en vergelijken de kwaliteit van de berekende minste risicopaden met de kortste pad alternatieven. De resultaten wijzen meestal op een niet nauwkeurige selectie van paden wanneer het gaat over het risico om verloren te lopen. Het geeft aan dat het algoritme zelf waarschijnlijk dient te worden aangepast aan de specifieke kenmerken van de indoor omgeving. Daarom worden verbeteringen zoals onder andere netwerkaanpassingen, een aangepaste definitie van risicio en aanpassing van de onderlinge verhouding tussen risicofactor en padlengte voorgesteld.

Een tweede algoritme dat is bestudeerd in een indoor context, is het eenvoudigste pad algoritme van Duckham en Kulik (2003). In dit algoritme wordt getracht de complexiteit van route-instructies te minimaliseren door rekening te houden met zowel het aantal bochten als de verschillende types van kruispunten langsheen een pad. In het artikel in hoofdstuk 6 worden verschillende indoor en outdoor netwerkmodellen beoordeeld op hun geschiktheid voor het automatisch berekenen van bochten. Daarvoor wordt een eenvoudig algoritme geïmplementeerd dat gebruik maakt van de coördinaten van de netwerkknooppunten om de hoek tussen drie opeenvolgende knooppunten te bepalen. Uit dit onderzoek blijkt dat de huidig beschikbare indoor netwerkmodellen niet toelaten het correcte aantal bochten langsheen een pad automatisch te bepalen, terwijl dit in outdoor netwerken wel mogelijk is. De oorzaak hiervoor ligt in een inconsistente definitie van wat exact een beslissingspunt in indoor omgevingen is, wat op zijn beurt opnieuw verbonden kan worden met de verschillen in ruimtelijke structuur tussen indoor en outdoor ruimten. Daarenboven wordt aangetoond dat het incorrect berekenen van het aantal bochten ook een grote invloed heeft op het genereren van accurate indoor route-instructies.

Zowel de resultaten in hoofdstuk 5 als hoofdstuk 6 tonen aan dat de betekenis van algoritmen volledig gewijzigd kan zijn door de indoor context (OV4). Het blijkt dat de specifieke netwerkmodellering van de indoor omgeving daarvan een belangrijke oorzaak vormt (OV5). Dat is de reden waarom in hoofdstuk 7 een model-onafhankelijk algoritme is ontwikkeld voor het berekenen van het correcte aantal bochten in indoor omgevingen. Het aantal bochten is daarbij in overeenstemming met de eigenlijke perceptie van de gebruikers. De relevantie van dit algoritme wordt ook aangetoond door de implementatie van het minste aantal bochten pad algoritme indoor. Dit onderzoek illustreert zo ook dat het mogelijk is om outdoor algoritmische concepten naar indoor omgevingen uit te breiden, maar dat aanpassingen essentieel zijn om te voldoen aan de specifieke ruimtelijke en cognitive verschillen van de indoor versus outdoor context.

Ter conclusie, dit proefschrift heeft aangetoond dat navigatietoepassingen te maken hebben met meerdere complexe relaties tussen (i) indoor versus outdoor omgevingen; (ii) open versus gesloten perceptie van de ruimte; en (iii) discrete versus continue modellering van deze ruimte. Ontwikkelaars moeten zich terdege realiseren dat de specifieke keuzes betreffende deze aspecten een grote invloed hebben op de kwaliteit en de nauwkeurigheid van de ondersteunde methoden en analyses. Zo zal het gekozen algoritme bij indoor routebegeleiding, de specifieke structuur van het gebruike indoor-netwerk definiëren, tesamen met de bijhorende parameters. Voor routebegeleiding gebaseerd op geometrische aspecten van de ruimte, is een veel voorkomend geometrisch netwerk model geschikt. Bij toepassing van meer cognitieve algoritmen blijkt dat ofwel het netwerk ofwel de algoritmische toepassing zal moeten worden aangepast aan de perceptieve verschillen die voorkomen binnen indoor omgevingen. Op dit moment is het nog niet duidelijk of in dergelijke gevallen de indoor en outdoor algoritmische en analytische ondersteuning grotendeels gescheiden moeten blijven of dat ze kunnen worden geïntegreerd om te voorzien in geïntegreerde indoor-outdoor analyses. Het is wel duidelijk dat er meer onderzoek nodig is om indoor en outdoor ruimtelijk onderzoek dichter bijeen te brengen.

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CURRICULUM VITAE

Ann Vanclooster was born in Sint-Niklaas (Belgium) on March 9th, 1987. In 2004, she graduated at the Sint-Lodewijkscollege in Lokeren and subsequently started her academic career at Ghent University. She obtained a Master's degree in Geomatics and Surveying (*magna cum lauda*) in 2009 at the Department of Geography. Immediately following her graduation, she received a grant of the Research Foundation Flanders to pursue a PhD. Ever since, Ann has been part of the CartoGIS research unit of the Department of Geography (Ghent University). Her research on indoor navigation has resulted in several participations in major international conferences, a research stay in Korea and the publication of several articles in international academic journals.