GIS TECHNOLOGY

Space subdivision for indoor applications

Sisi Zlatanova, Liu Liu, George Sithole, Junqiao Zhao and Filippo Mortari

GISt Report No. 66

TU Delft

OTB Research Institute for Housing, Urban and Mobility Studies

Delft University of Technology

Space subdivision for indoor applications

Sisi Zlatanova, Liu Liu, George Sithole, Junqiao Zhao and Filippo Mortari

GISt Report No. 66

Summary

This report makes an overview of 2D, 2,5D and 3D approaches for indoor space subdivision for the purpose of indoor navigation. The report starts with a conceptual framework for indoor space utilisation. We introduce and elaborate on the concepts of indoor space (navigable and non-navigable), agent, activity, resource and modifier. Using these concepts, we investigate navigation cases and discuss information requirements for space subdivision. Two sections make review of 2D and 3D research for sub-spacing. We classify 2D and 3D approached in three groups with respect to the subdivision (partial or complete) and the type of navigation (grid or graph), and provide analysis of the approaches against the user requirements for indoor navigation. Section 6 concludes on challenges and future developments.

This research was supported by a grant (11 High-tech G11) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

ISBN: 978-90-77029-37-4
ISSN: 1569-0245

OTB Research for the Built Environment
TU Delft
Julianalaan 134, 2628 BL Delft, the Netherlands
Tel.: +31 (0)15 278 4548; Fax +31 (0)15-278 2745
Websites: http://www.otb.tudelft.nl
Http://www.gdmc.nl

E-mail: s.zlatanova@tudelft.nl

This publication is the result of the research programme Sustainable Urban Areas, carried out by Delft University of Technology

Contents

1 Introduction

Indoor modelling has rapidly gained the interest of researches and developers. According to the Environmental Protection Agency 75% of the world's population lives in cities and nearly 90% is spend indoors (EPA, 2009). Humans perform many activities indoors related to work, shopping, leisure, dining, sport, etc. The buildings and the large variety of associated spaces such as underground passages, sky bridges, metro lines, garages, stations, yards, gardens, and roof terraces are becoming elaborated conglomerates of enclosed spaces. This complexity poses many challenges for building managers, occupants and visitors.

Navigation (finding path to a certain location) and location-based services are some of the most important services indoors. How to calculate the most appropriate path? How to convey the path instructions in the most understandable way? How to quickly instruct management teams for needed maintenance and localisation of failures? How to evacuate people in the case of emergencies, etc.?

Indoor spaces differ significantly from outdoor and complicates the human orientation:

- Many of the clues used to orient outdoors (sun position, shadows, size of streets, residential, vs. business areas) are missing in indoor environment.
- The orientation is complicated by the existence of multiple levels, relatively smaller spaces and the more difficult overview of the entire indoor environment.
- The way of movement differs. Indoor environments have less structured lanes for movement such as streets and paths. Agents have larger number of options to go from point A to B.
- Indoors spaces tend to have many obstacles (furniture, columns, podiums, etc.) which can be avoided in various ways.
- Points of interest are difficult to identify as the furniture may have many different appearances (e.g. 'coffee machine' used as a point of interest might be left behind because was not recognized as such)
- The speed of movement is relatively slow, which affects the perception about space

To facilitate human activities, to provide comfort, safety and security, to ensure the necessary infrastructure is available, the enclosed spaces have to be represented by semantically and geometrically rich models to be able to reflect the personal profile of an individual or a group of individuals.

The management and navigation of indoor spaces has to be supported by digital virtual representations of the indoor environment. Broadly, the creation of such virtual representations involves (i) digital acquisitions of the spaces, (ii) structuring of acquired data, (iii) formalisation of the structured data to establish the relationships between the sub-spaces, and (iv) imprinting of application or user requirements onto the formalised structured data.

This report presents a formalisation of indoor spaces and first ideas for establishing of a formal approach for subdivision with respect to the user perception/need of space, user profile and/or user activities. The ultimate goal is developing guidelines for automatic partitioning of indoor spaces for various indoor navigation applications.

The report is organised into four sections. The next section introduces a framework for navigation. Section 3 presents indoor navigation cases and corresponding information requirements. Section 4 and 5 make review and analyses of 2D and 3D approaches. The aim is to identify what kind of subdivisions are applied and if the method comply with the identified indoor requirements. Section 6 concludes with a discussion future research on space subdivision.

2 Conceptual Framework

A definition of space can be found in several sources. Encyclopaedia Britanica (http://www.britannica.com/EBchecked/topic/557313/space) gives a very general definition which explicitly names the dimension: 'a boundless, three-dimensional extent in which objects and events occur and have relative position and direction'. Wordnet (http://wordnet.priceton.edu) defines space as 'an empty areas usually bounded in some way between things'. Direct hyponym of space is then compartment (a space into which area is subdivided) and cell (any small compartment). More specialised ontologies such as OmniClass (http://www.omniclass.org, a classification for Architecture, Engineering and Construction in North America) distinguish between *spaces by form* and *spaces by function*. 'Spaces by form are basic units of the built environment delineated by physical or abstract boundaries and characterised by physical form'. 'Spaces by function are basic units of the built environment delineated by physical or abstract boundaries and characterised by their function'. The spaces can be both 2D and 3D. For example, space by form can be a 3D room or a 2D walking path. An interesting example is a wall (interior, exterior), which is considered a space by function, which implies that spaces can be filled with some material, i.e. not just air.

Indoor spaces are artificial constructs designed and developed to support human activities. Virtual representations of indoor spaces have to be able to support these activities. Therefore, the way in which space is partitioned in a virtual model has to accommodate the conceptual construct of the space, i.e., the partitioning of space should be informed by spatial arrangements alone, but also the activities that take place in the spaces.

In this section a conceptual framework is offered to describe indoor spaces, the agents that operate in these spaces and the activities that take place in these spaces. Later the partitioning of spaces is used as a basis and motivation for the partitioning of indoor spaces.

For the purposes of the framework, *space* is conceived as being made up of *sub-spaces* that are occupied by *resources*, and *agents* who perform activities subject to varying levels of access. In this paper *sub-spaces*, *resources*, *activities*, *modifiers* and *agents* will collectively be referred to as elements of indoor space.

Space is treated here as environments in which all activities and resources that are associated with that environment take place. For example a shopping mall is a space in which activities associated with business, trade, and entertainment can be found.

2.1 Space and sub-spaces

In the context of this paper and for presenting the framework, we will use the term *indoor space* to indicate enclose of space.

In daily life, humans *commonly perceive indoor space* as a closed volume, which is bordered by physical unmovable elements. The spaces have a sematic meaning (room, corridor, stairs, which corresponds largely to the definition of space by form). People can move within the space. The spaces are non-overlapping and share one neighbouring element (e.g. wall). Space is the environment in which humans store resources and engage in activities. A logical compartmentalisation of resources and activities requires the creation of sub-spaces. Sub-spaces are commonly used for living space, work space, leisure space, access and storage.

Indoor Subspace is any subdivision of an indoor space in into smaller parts, which might be partially or completely bordered by virtual (abstract) boundaries. The sub-spaces may or may not have semantic meaning. People can move freely inside such sub-spaces. The sub-spaces are non-overlapping and share one neighbouring element (virtual or concrete boundary). Depending on its use a sub-space can be *navigable* or *inert* (*non-navigable*). Navigable spaces can be used to perform activities, e.g., foyers, corridors, etc. Inert sub-spaces or non-navigable spaces are those spaces in which no activity can take place, e.g., walls.

Continuity of space: Space is treated as being continuous. The creation of sub-spaces discretises space. However, sub-spaces are themselves still treated as being continuous. In this paradigm, the inert sub-spaces act as hard boundaries between the sub-spaces.

To realise the conceptual models, particularly in an automated fashion, the acquired data of indoor spaces has to be partitioned. The partitioning has to be done in a manner that supports the conceptual models and importantly the needs of agents (moving, staying) in the space.

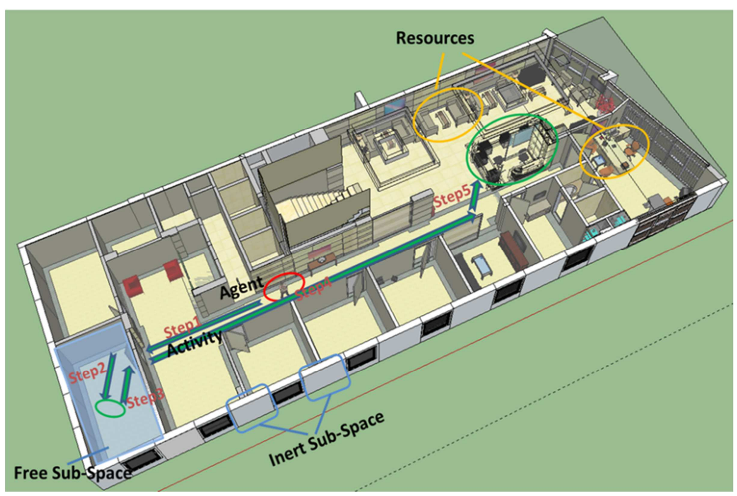

Figure 1: Example of static partition with agents, resources, navigable (free) and non-navigable (inert) spaces.

Static partitions: In this paradigm space is partitioned with assumption the agents experience space in the same way or have the same conception of space. Because of this agents are not involved in the choice of partitions. Typically activities will also not be involved in the partitioning, leaving resources and modifiers as the only determinants of the choice of partitions.

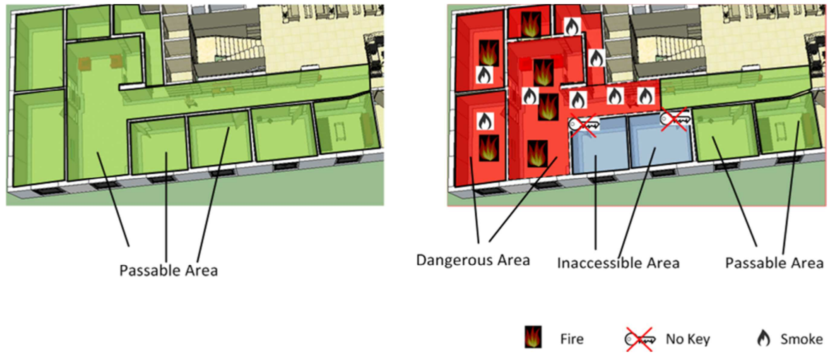

Figure 2: Dynamic partition due to modifier *fire*: dangerous, inaccessible and passable areas.

Dynamic partitions: Unlike static partitions, dynamic partitions (i) accommodate all elements of the space, and (ii) accommodate the changes that the elements will go through (Figure 2). Essentially as elements change space is repartitioned, but importantly it is partitioned for the agent, i.e., each agent receives a partitioning of space that fits their conception of space. In such a paradigm the navigation model (and its accompanying partitioning) of an able bodied and a disabled person may be different. This model also allows agents to be involved in the partitioning of other agents.

Hybrid partitions: Dynamic partitions may become complex. Therefore, hybrids of both partitioning schemes maybe required to balance the complexity and facility.
Spaces and subspaces can change their function.

Figure 3: Time as global modifier (left): the office is closed, i.e. the sub-spaces are aggregated to one new space named 'inaccessible'. Renovation as a local modifier (right): room is accessible for construction company only.

Modifiers are properties of a sub-space and they alter the usability of the space. They promote or inhibit activities, resources and agents within a sub-space. The scope of a modifier can be global (Figure 3) or local. Modifiers define the environment (ambience) of the partition, e.g., friction/drag coefficient, lighting, etc. Examples of modifiers can be also extreme events as fire, flood, etc. (Figure 3).

Because of the complex nature of indoor spaces, the conceptual framework cannot be represented in one model. Rather various co-operating models will be required such that have to represent geometric, topological and semantic properties of framework elements. These models cannot individually satisfy the indoor requirements; therefore hybrid models should be envisioned.

2.2 Agents

Agents are clients that use or engage in activities or use resources offered by a sub-space.

The nature of agents: While agents will typically be humans, they can also be human proxies (for example robots programmed by humans). However, a proxy's use of sub-spaces is defined by human needs therefore human and proxies can be treated as indistinguishable. Agents can also from time to time serve as resources within a sub-space (**Error! Reference source not found.**).

Figure 4: Examples of agents that have become resources.

The movement of agents: Unlike activities and resources, agents are able to move between sub-spaces. The movement of agents between sub-spaces is through inert sub-spaces. Broadly the movement of an agent within sub-spaces will be for the purpose of entrance, exit, or passage. Entry and exit points will be defined in the inert sub-spaces. The ease of passage will be determined by modifiers of the sub-space.

Figure 5: Computers in a monitoring centre and tables in a design studio as resources.

Resources are the permissible things that an agent can store in a sub-space or take from a sub-space (Figure 5). Types of resources will not be unique to a sub-space but instances of a resource will be specific to sub-space. Resources act as attractors of agents. This attraction can be specific to certain agents and its scope can be local or global.

Activities are the permissible actions that an agent can perform within a sub-space. Types of activities will not be unique to a sub-space although specific activities may be unique to the sub-space. The scope of activities is large: working, playing, reading, shopping, cleaning, walking, sitting, etc. Activities also serve as attractors of agents to a sub-space.

2.3 Characteristics of spaces, agents and resources

Indoor spaces, agents, resources and modifiers influence each other and determine the partitioning of space. As mentioned previously, mobility, shape and size of agents result in different navigable spaces. Size, location and shape of resources can also require partitioning of indoor non-navigable space to provide a better localisation of the resource (e.g. a lamp in a ceiling). Modifiers may influence navigable or none-navigable space, which will require a new space subdivision.

For the scope of this report, indoor spaces have the following characteristics:

- Dimension: 2D or 3D geometry
- Thematic semantics, which refers to identified meaning of the space,
- Attributes, i.e. characteristics of space/sub-space (navigable and non-navigable), which provide further information. An important attribute in the context of navigation is *accessibility* of space or existence of other non-navigable spaces within the navigable space, which form *obstacles*.
- Change in time, i.e. if dynamic changes take place
- Relations between indoor spaces in terms of *adjacency* and *connectivity*. These relations combined with other properties of spaces (e.g. accessibility) determine the navigation graph/grid (see Section 3), which is used to compute a path (shortest, safest, fastest, etc.)

Agents are characterised by their *dimension* (2D, 3D), *individual characteristics* (size, age, gender, locomotion mode) and *preferences (e.g.* shortest path).

Resources are characterised by their *dimension* (2D, 3D), *location* (within a navigable or non-navigable space) and their *dynamics* (static, movable)

3 Indoor applications and indoor requirements

To be able to perform correct navigation several components have to be available: (3D) indoor localisation, a (3D) model that represents the space subdivision, (3D) algorithms for path computation (on a topological model or a grid), guidance (Points of Interest, Landmarks), guidance (visualisation) of the path and finally tracking/correction (if the path is not followed). While much research exists on 3D localization and tracking, the research on models (geometrical and topological) and guidance (giving directions) is still very fragmented. Commercial systems make use of predefined models (topology is extracted from 2D floor plans and make assumptions that the rooms are empty (i.e. there is no furniture). Some examples of such navigation applications are Google maps (for smart phones, Figure 6), or the Yamamoto modelling tool (Figure 7).

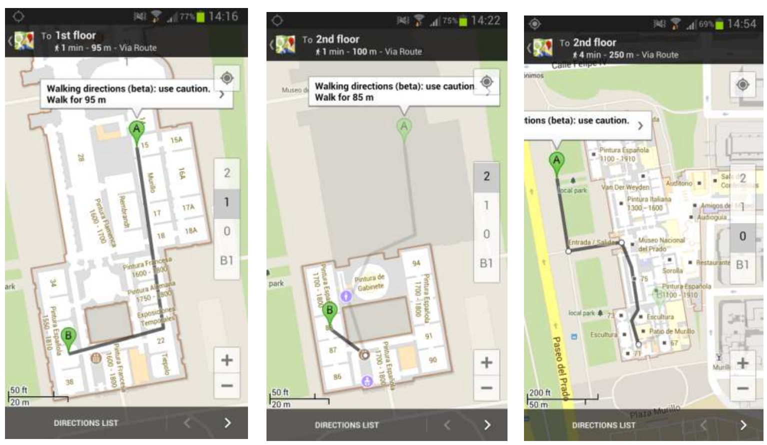

Figure 6: Google maps 2D indoor/outdoor navigation in Prado (floors are represented as layers).

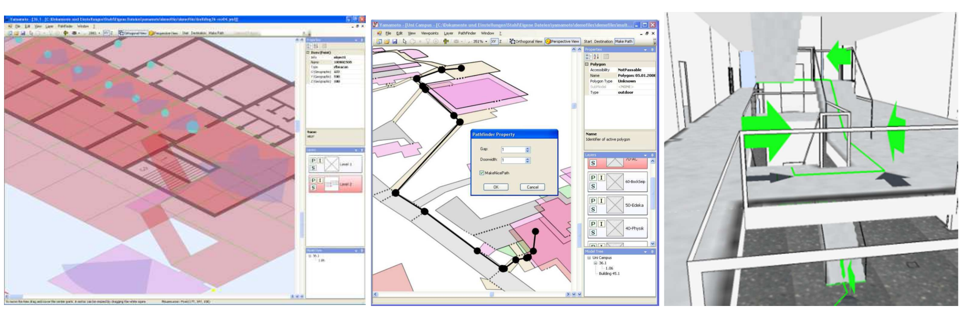

Figure 7: Yamamoto 2,5D modelling tool (internet).

Such approaches are quite acceptable for basic use and common navigation to places of general interest in relatively simple buildings. In more complex buildings as airports, museums (Figure 8, Figure 9), concert halls, shopping malls, airports (Figure 10) or for some application that need resources attached to vertical components, layered 2D floor plans might create confusion and misinterpretation.

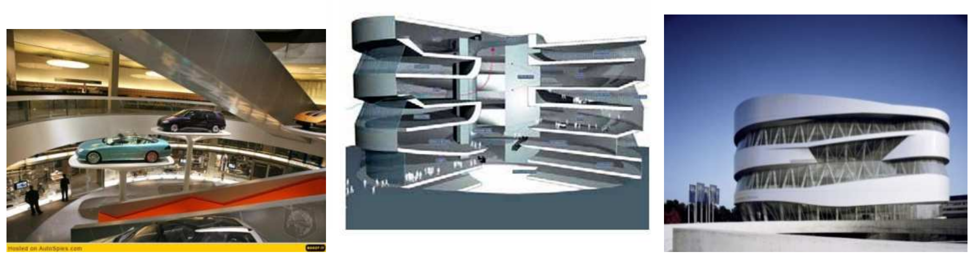

Figure 8: Mercedes Benz Museum, Stuttgart: the building is organized as a spiral (internet).

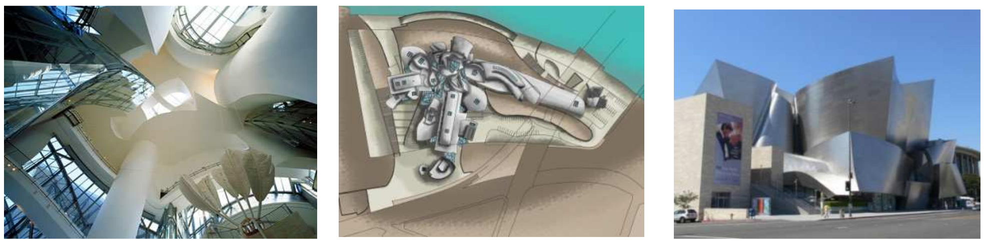

Figure 9: Guggenheim Museum Bilbao: complex non-rectangular spaces with internal bridges (internet).

Figure 10: Schiphol Airport, Amsterdam: large open spaces with shop and food corners (internet).

3.1 Inventory of navigation applications

To be able to estimate whether subdivision of spaces is needed, an inventory of possible applications has been made. The classification is derived by analysing existing applications and research in indoor navigation (mostly for humans) and by discussing with various users. The following cases have been identified:

1. *Find navigable space*: This is the most common navigation case in daily life. People visiting an unfamiliar institution, museum, shopping centre, etc. need to be guided to a specific room. The subdivision of space follows the construction subdivision of a building. Symbolic notations of rooms and a connectivity relations would be sufficient to perform routing. Semantics can be very simple indicating only the type of the room and room numbers. If space partitioning is performed, it is only to make the path fit different agents (e.g. locomotion modes). Such sub-spaces do not receive sematic identification.
2. *Find navigable space within navigable space*. For example, the point of interest is a specific area in large halls, specific items/booths in museums (permanent exhibitions) distribution centres, food corners in shopping centres. Such cases need more information about both the including space (as exhibition hall) and the specific item and its location. The original building spaces (halls) need to be subdivided to be able to identify the sub-space of interest. The

sub-space of interest will be semantically identifiable (e.g. food corner) and will have attributes. Examples of such attributes are open hours (for food corners), historical facts (for museum items), etc.

3. *Find navigable spaces with specific (restricting) attributes*. Examples of such cases are navigation to restricted areas at airports and other secured buildings or to infrastructure and facilities for cleaning and utility management. Similar situation may be observed in shopping centres, building offices, food corners, exhibition halls, stores, etc., where goods have to be delivered to different parts of building, which are not accessible to general public. These cases will require subdivision of rooms/halls to be possible to accurately locate the area of interest (e.g. passing though security portals) (Figure 11). Information indicating accessibility of spaces would be compulsory attribute.

Figure 11: Security gates at airports (internet).

4. *Find non-navigable spaces within navigable space*, such as windows (for cleaning), walls (for painting) and ceilings (change blubs). The navigation will require detailed identification and information about the spaces representing walls and all objects attached to them. While the above cases can commonly be performed in 2D dimensions, this case will require 3D space and corresponding semantics. Shape and size of the room (walls, windows) becomes of critical importance in two directions: 1) for calculating needed materials (in case of cleaning, painting) and 2) for transporting necessary equipment (e.g. ladders).
5. *Find resources in/on non-navigable spaces* (Figure 12). Examples are finding books books, medicines, items etc. in cupboards, shells. This kind of guidance will require information (geometric and semantic) about furniture in rooms and items within the furniture. 3D shape and size of all the objects might be needed as well. A record of personal preferences will be useful as well. The navigation can be seen as extension of case 4. After the non-navigable space is found, the resource have to be identified.

Figure 12: Visualisation of books in library (UbIcom., Zlatanova and Heulel, 2001).

6. *Find non-navigable space within non-navigable space*. This case aims to reflect utility and facility management. Installations in walls, floors and ceiling are typical example of it. According to our framework, utilities cannot be seen as resources but rather as spaces. This case is slightly different than case 5 as it would require references between different 3D models (one related to the

geometry of the building and another related to the utility network. In case of failure in a network even a more complex case could be created, that the switch location differs from the location of the defected segment to be changed. Figure 7 illustrate failure in water network that effects part of the floor and several stores in a building (Figure 13).

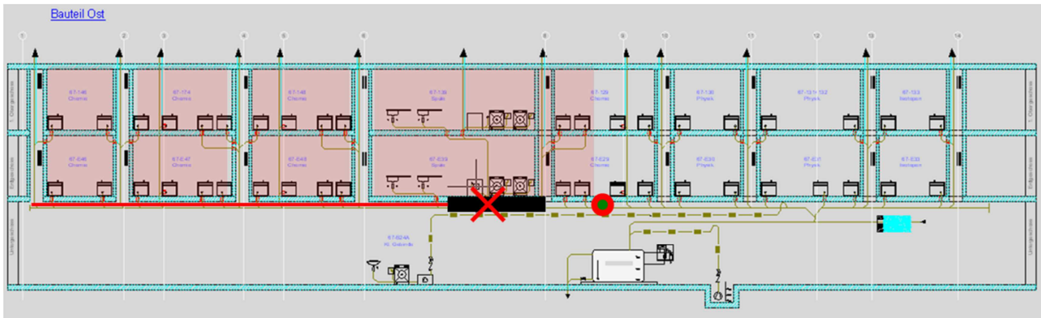

Figure 13: Schematic view of failure in utility network that effect several sections of the building (Hijazi et al, 2012).

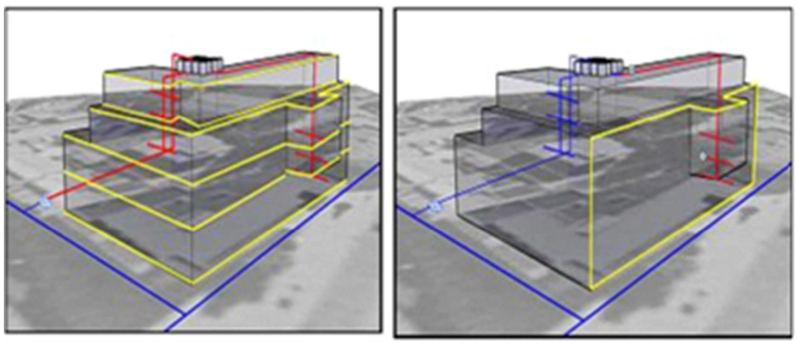

Figure 14: Utility networks and their distribution within buildings (Hijazi et al 2012).

7. *Find dynamic navigable spaces within navigable spaces.* This case refers to temporary spaces such as info desks/booths in exhibitions, airports, museums, which arrangement changes in the time (depending on the type of exhibition, maintenance activities, arrangement of furniture, etc.). This case is similar to case 2 as it requires subdivision of large rooms into smaller areas but attributes much be extended information about existence in time.
8. *Find dynamic navigable spaces.* Many companies that participate in large civil engineering projects, often need to relocate their offices to adapt the better to the development of the project. In this case, the indoor structure changes, navigable spaces are modified, added or removed. This case is more complex than case 7, as the changes are not limited to one dedicated space and affects navigable and non-navigable spaces. Time attributes are needed to be assigned to all spaces.
9. *Find mobile resources in navigable spaces* e.g. free wheelchairs in hospitals, trailers in shopping malls. This task is similar to case 5, but requires localization of the mobile unit all time.
10. *Find way among non-navigable spaces in a navigable space.* This case reflects navigation considering furniture or other interior objects that may disturb the navigation. Often navigation of human does not consider obstacles as humans can take decision on spot how to avoid them. However, robot navigation or navigation for transporting large items (ladders, equipment) cannot be completed without knowledge clearance between obstacles. Obstacles can be further classified as static, movable and dynamic.

11. *Emergency navigation*, which may be a combination of all cases. It might require using unusual way of moving through the environment such as using windows as exits, walking over furniture, crawling under tables or investigating the environment with UAV. In such cases not only connectivity but also adjacency relations between spaces will be needed.

The cases above are analysed with respect to some of the characteristics of spaces, agents and resources (Section 2.3). The last row indicates which cases will require space subdivision. Space subdivision is needed is all cases.

Table 1: Summary of information requirements for the uses cases mentioned above.

Criteria/use cases	1	2	3	4	5	6	7	8	9	10	11
Space: Dimension	2d	2d	2d	3d	3d	3d	2d	3d	2d	3d	3d
Space: Thematic Semantics	0	+	+	++	++	+	+	+	+	++	++
Space: Change in time	-	-	0	-	-	0	+	+	+	-	++
Space: Attributes	0	+	++	++	++	+	+	+	+	++	++
Space: Accessibility	-	-	++	-	-	-	-	+	0	+	++
Agent: Personal preferences	-	-	-	-	++	-	-	-	-	-	++
Resource: Movable	-	-	-	-	-	-	-	-	++	-	++
Space: Connectivity	+	+	+	++	++	++	+	++	+	++	++
Space: Adjacency	-	-	-	-	+	+	+	+	0	0	++
Space: Obstacles	-	-	-	-	+	+	-	-	-	+	++
Space subdivision	**0**	**+**	**+**	**+**	**++**	**++**	**+**	**++**	**+**	**+**	**++**

--not needed, 0-basic, +needed, ++ very much needed

Table 1 clearly shows that the information requirements strongly depend on the application. Emergency response naturally poses the highest requirements. To be able to perform navigation geometrical, topological (connectivity and adjacency) and semantic information shell be available. Many applications need time component (indicating that spaces are changing in time). All applications need space subdivision to be able to address the destination point in the best possible way. Although not of general interest, obstacles (indoor furniture) are critical for transporting equipment and in emergencies. The table cleary show that not all applications need 3D, i.e.

3.2 Indoor requirements

Brown et al, 2012 completed a compatible study on indoor navigation requirements. It concentrates on information requirements for navigation of agents (humans) but considers mostly Cases 1, 3, 10, 11 of Section 3.1, i.e. find navigable space and find navigable space considering accessibility. The study distinguishes between navigation of users with different profiles (personal abilities and task or taking part in different scenario) in a room, on a floor, between floors, in parts of buildings (with different types of access), to exits, between buildings. The use cases identified aim to categorize the possible movements in the building regardless the application or the final goal. The authors identity a set of 15 generic requirements:

1. An indoor environment shall capture the general semantic information for a specific building and be represented by all spaces belonging to this indoor environment.
2. All spaces belonging to an indoor environment shall be represented both semantically and geometrically, defining spatial properties of physical spaces. Navigable space can be decomposed for different modes of locomotion (e.g. user in a wheelchair).
3. Spaces belonging to an indoor environment shall be categorized according to specific pre-defined space types depending on the user, scenario and the tasks he/she is performing.

4. All spaces belonging to an indoor environment shall be able to be decomposed into smaller space parts for the definition of start and end points for a route and most appropriate path.
5. All spaces belonging to an indoor environment shall be able to be extended with additional semantic attributes.
6. Storeys within an indoor environment should be represented and associated to all spaces belonging to a specific storey within an indoor environment.
7. All indoor spaces and sub-indoor space parts will be able to be geo-coded.
8. Storage of semantic information for the function, usage and occupants of an indoor space.
9. Specialised types of indoor space shall be used to differentiate levels of connectivity of indoor spaces, i.e. only the spaces that connect together multiple spaces, must be considered in a routing algorithm.
10. Specialised types of connecting space with specific semantics shall be used for vertical and horizontal and fixed, assisted and transfer connecting spaces, as vertical spaces might be quite complex.
11. Transfer spaces shall be separated into both physical (e.g. door or window opening spaces) and virtual opening spaces (e.g. airport security gate) for which specialist attributes can be defined.
12. Indoor obstacle spaces should be semantically categorised as fixed, movable and dynamic obstacle spaces, with physical attributes representing the spatial extent, supporting weight, persistency, current state and scenario type.
13. Fixed position obstacle spaces will have semantics defining the surface material and specialist semantics defined for interior and external walls, floors, ceilings, stairs, ramps and general fittings (e.g. light fittings).
14. Movable obstacle spaces will have semantics including physical weight and specialist semantics defined for windows, doors, furniture, and construction work.
15. Door and window should have specialist semantics allowing constraints to be defined according to the type, opening mechanism, sub-parts, directionality of opening, current state, accessibility and usability in scenarios

These requirements reflect very well the characteristic of spaces, agents, activities and resources as defined in Section 2.3 and correspond largely to the information requirements as given in Table 1. Requirement 4 concentrates specifically on space partitioning. It refers to partitioning with respect to the actor (start, end location, scenario and task). But the concept of resource is not taken into consideration. Requirement 4 can be extended to cover use cases 2, 4, 5, 6, 7, 8, 9 by specifying more explicitly, what the end location would be. For example, to be able to get a book from a shelf (Case 5) the agent should be navigated to a space which is the closest adjacent navigable sub-space to the non-navigable space which contains the resource of interest..

3.3 Navigation taxonomy

The above requirements has been derived under the assumption that one person has to be navigated to one destination. For simplicity, the 11 use cases are also developed for individual cases, i.e. one agent finds one space or recourse. However, some applications require simultaneous navigation of many agents to multiple resources or spaces. Zlatanova and Baharin, 2008 and Wang and Zlatanova, 2013, provide examples of navigation in which many agents need to cooperate and negotiate how to go to many end destinations. Such cases will not affect the space partitioning, but they will influence the path computation algorithms. Wang and Zlatanova, 2013 present taxonomy of navigation of multiple users avoiding multiple obstacles. They identify four criteria to distinguish between different cases:<X1,X2,X3,X4>, where

X1 {o, m} is the number of users (one or many)
X2 {O, M} is the number of destinations (One or Many)
X3 {S, D} is the type of destinations (Static or Dynamic)
X4 {s, m} is the type of obstacles (static or moving)

A case denoted by <o,M,D,m> means one moving object has to be routed to many dynamic destinations, avoiding many moving obstacles. The authors have completed an elaborated investigation on which cases are covered by what kind research and what kind of navigation problems are applied (Table 2). Three 'Problem Types' are identified: shortest path problem (SPP), pursuit-evasion problem (PEP) and traveling salesman problem (TSP). The column 'Environment Type' distinguishes between the two types road network and free space and indicates whether any investigation has been conducted. The last column 'Application Domain' summarizes if any relevant research has been performed. As visible from the table, there only 4 navigation cases where the well-known and widely used shortest path routing is applicable. Totally 8 navigation cases associated with dynamic one/more destinations can be seen as generalizations of the PE problem and have been intensively applied in robotics. The other 4 cases with multiple static destinations can be considered as extended TSP problems.

As mentioned previously, there are many methods developed for routing with obstacles for robots. These methods make a large use of space partitioning for the purpose of tracking and navigating. The space id subdivided into grids sufficiently small to be able to localise the robot. Only a few obstacle-avoiding routing focuses on humans. Amongst the 16 cases presented in the table, only two of these cases, i.e. $<o,O,S,s>$, have been developed for grids (network).

Table 2: Summary table of navigation taxonomy (Wang and Zlatanova, 2013).

	Navigation Case	Type	Environment Type		Application Domain	
			Road network	Free space	Human	Robots
Navigation cases with static obstacles	$<o,O,S,s>$	SPP	√	√	√	√
	$<o,M,S,s>$	TSP	x	√	x	•
	$<m,O,S,s>$	SPP	x	•	x	•
	$<m,M,S,s>$	TSP	x	√	√	•
	$<o,O,D,s>$	PEP	x	√	x	√
	$<m,O,D,s>$	PEP	x	√	x	√
	$<o,M,D,s>$	PEP	x	√	x	√
	$<m,M,D,s>$	PEP	x	√	x	√
Navigation cases with moving	$<o,O,S,m>$	SPP	√	√	√	√
	$<m,O,S,m>$	SPP	x	√	x	√
	$<o,M,S,m>$	TSP	x	•	x	•
	$<m,M,S,m>$	TSP	x	√	x	√

	$< o,O,D,m >$	**PEP**	**x**	√	**x**	√
	$< m,O,D,m >$	**PEP**	**x**	√	**x**	√
	$< o,M,D,m >$	**PEP**	**x**	√	**x**	√
	$< m,M,D,m >$	**PEP**	**x**	√	**x**	√

√- has been investigated, x - not investigated, ● – no information (uncertain)

The study has been performed with the view for outdoor navigation (which is usually on road network) and might need some refinements for indoors. It also does not pretend to be explicit. However, it is illustration that (indoor) navigation of one user to one target location (using a variants of SPP) is only a small part of the variety of navigation cases. It also shows that space partitioning is used to support the localisation. The sub-spaces do not have semantics, but only geometry and connectivity information.

Related to the navigation is also the type of path that has to be provided. Table 3 lists of the most common strategies for navigation and elaborates on merits and drawbacks. The most commonly-used strategies are the shortest distance and the shortest time but for many applications they might be not that crucial. Path adapted to the individual properties of the agent with non-standard size (e.g. a person pushing a trailer) would be more valuable than the standard shortest path. In such cases, non-navigable spaces (obstacles) can be aggregated in a larger spaces to speed up the computation.

Table 3: Possible indoor path.

Path Type	Merit	Drawback
Shortest-distance	With minimum distance	If obstacles are considered may result in following a difficult to explain path
Shortest time	With estimated minimum travel time	Speed should be considered
Simplest path	Minimum turns	Could be longer distance/travel time
Least-space-visited	Least-number of passed room	May lead more travelling time and distance
Least-obstruction	Least degree of blockage,	Need accurate information about (dynamic) obstacles
Safest path	Avoid specific areas	May result in log detours
Possible path	Considers profile of agent	Requires clearance
Floor strategy (go through specific areas)	Better performance of homing users regarding time, similar with Least-Effort path	May not with the minimum distance

4 2D approaches

Space subdivision for navigation has been largely performed using geometry of the indoor spaces and no elaborated semantic information has been maintained in most of the 2D approaches. The path is computed using either the original 2D plans, or a dedicated subdivision strategy (e.g. convex polygons) or regular subdivision into triangles or grids. In all approaches the geometry is leading. Semantics when applied indicates only construction elements important for navigation such as doors, rooms, stairs and lifts. Attribute information is also hardly taken into consideration. Afyouni et al, 2012 provide an extended review on al large variety of possible 2D and some 3D spatial subdivision for navigation. Therefore, this section only briefly presents some of the tendencies. We classify the approaches with respect to way of the applied partitioning of the space into: no or local subdivision, complete subdivision according to a certain criteria and complete regular subdivision. Some of the approaches use semantics (such as notations for doors, windows, walls) to refine the navigation path. These we mention explicitly when applicable.

4.1 No or partial subdivision: derivation of network

These approaches make use of the geometry of 2D floor plans (lines and/or polygons) as available. The navigable spaces are derived from the plans following closely the building structure. Space partitioning is not discussed. The aim is to derive a network to be used for path computation. Usually the network is based on Poincare Duality, Media Axis Transformation (MAT)/centre line algorithms/shape skeleton, Visibility Graph (VG) or combinations of them. Figure 15 is an illustration of the most common approach utilizing Poincare Duality, MAT and information about doors.

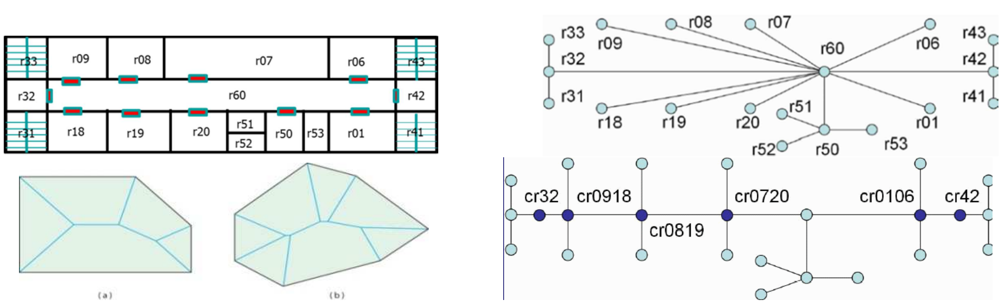

Figure 15: 2D network created on the basis of Poincare Quality, Media Axis Transform and information about doors.: floor plan (up left), metric network derived from Poincare duality (up, right), result of MAT for non-rectangular polygons (down, left) and corrected metric network considering the locations of the doors.

If MAT results in a sufficiently detailed path (as down, left Figure 15), no subdivision is needed. Otherwise, new nodes are introduced considering semantics, i.e. building elements such as doors and windows. From a conceptual point of view, this enhancement is a sub-spacing. In the example above, the corridor is subdivided into seven subspaces according to the Poincare duality. .

Another approach to create a network is VG. In contracts to MAT the VG does not follow the shape of the building spaces, but provides a direct path to the point of interest. Space subdivision is not needed, because the path connects the begin and end point directly. It is used to implement a 'door-to-door' manner of navigation, while MAT results normally in a 'room-to-room' path. MAT enhanced with information about doors results in longer paths than VG. VG provides by default the shortest path between two doors (Figure 16). More information on MAT and VG is given in section 4.

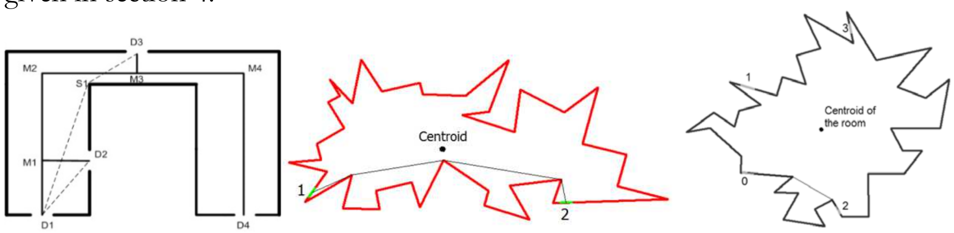

Figure 16: Visibility graph: comparison with MAT (left), shortest paths computed on a visibility graph (center, right). (Liu and Zlatanova, 2011).

Since both MAT and VG have weak points, Lorenz et al, 2006 proposes a modification of the above mentioned approaches. As shown in Figure 17(left), doors are abstracted as nodes (i.e. they are considered spaces). Similarly to the case in Figure 15 corridors are subdivided into smaller areas, but not necessarily making explicit use of the position of the door. In this case the doors (or windows) are used to identify 'door' spaces. We can conclude that an elementary semantics is used for partitioning of space. This approach allows for a 'room-door-room' type of navigation

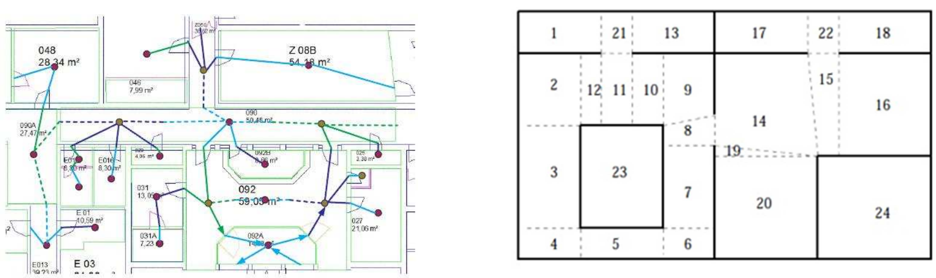

Figure 17: Partial subdivision (Lorenz et al, 2006) (left), Complete subdivision with Delaunay triangulation & Convex Cell optimisation (Lamarche & Donikian, 2004) (right).

4.2 Complete subdivision: derivation of a network

This type of methods concerns sub-division of 2D plans into cells according to certain criteria (e.g. convexity, distances between walls, visibility etc.). Several different criteria to sub-divide indoor space can be found in literature. With consideration of passing though bottlenecks and avoiding collision between moving objects, Lamarche & Donikian, 2004 apply a series of algorithms such as constrained Delaunay triangulation algorithm and Convex Cell optimisation to subdivide. Figure 17 (right) illustrates the result. The original spaces are subdivided into smaller convex areas, which are then used to derive network applying Poincare duality.

Stoffel et al, 2007 propose a method that partitions a floor plan into convex sub-regions according to the visibility criterion. This approach ensures that openings (doors, windows) on the shared surface of two room units are mutually visible if they are in a same sub-region (Figure 18). Openings are also visible if the straight line between the openings intersects the virtual lines used for the subdivision. If opening are not visible either directly or via the virtual lines, they are linked through the central point of the virtual lines. The generated network utilises VG and as such is a typical example of door-to-door navigation. Notion of openings (doors and windows) should be indeed known in advance.

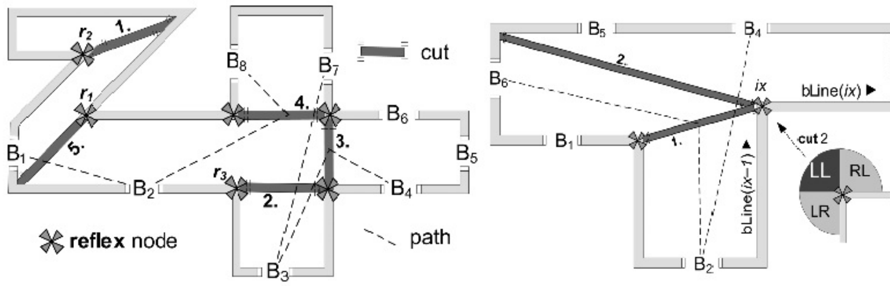

Figure 18: Visibility partitioning result (Stoffel et al, 2007)

Another example of subdivision considering a criteria is the Voronoi diagrams or variations of triangulation. Wallgruen 2005, develops a method for robot navigation based on the generalised Voronoi diagram (Figure 19). The approach is based on pure geometry (including obstacles) and essentially looks for spaces to pass through. In this respect notations of doors is of no importance. The author enhances further the network by removing the nodes in the corners, which are of no great importance for navigation.

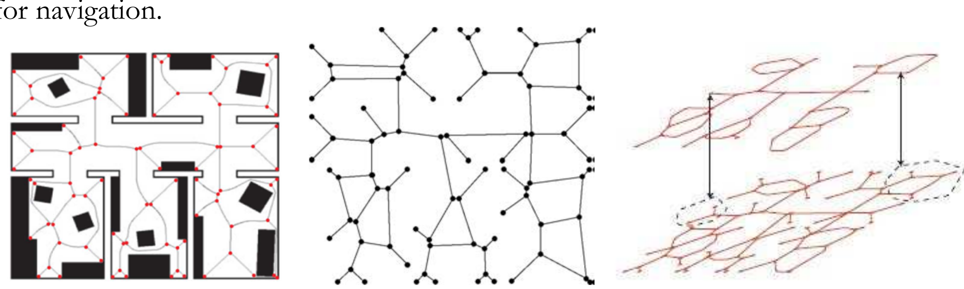

Figure 19: Voronoi diagram network: original plan, network and simplified network (Wallgruen, 2005).

Figure 20: Corridor map with closest points (1), closest points along a route and corresponding clearance(2), shrunk corridor (3), triangulation (4), Funnel shortest path algorithm (5) and smoothed path (Gerarerts, 2010).

Combinations of many criteria and algorithms (triangulation, Voronoi diagrams, Mikowski sum, Funnel shortest path, etc.) can result in a variety of approaches for subdivision. Gerarerts, 2010 presents an approach for path computation with a clearance based on Z-buffer subdivision (which provides a central line), explicit corridor (introducing additional points on the central line), followed by depicting the closest points and creating explicit (shrunk) corridors, triangulation, Funnel shortest path and smooth path (Figure 20). The algorithm is a good example of delineating the space to navigate through with a given tolerance and then running a series of algorithms to smooth the path. The result is equivalent to the visibility graph, but avoiding the complexity of building visibility graph for the entire environment. The approach relies exclusively on geometric algorithms, essentially avoiding obstacles. If applied for indoors, the doors should be considered open (as in the previous method).

4.3 Complete subdivision: regular grid

Another large group of approaches is based on regular grids such as rectangular, hexagon , octagon, etc. The discrete 2D grids overlap the 2D plan (Figure 21). Each grid cell obtains semantics according to the underlying 2D objects (room, door). This approach allows for a precise localisation in the entire open space and often is used for application which require tracking and correction of position (Girard et 2011) or integration with continue phenomena such as smoke, fire or flood. As mentioned previously, many of the grid-based approaches originate form robot navigation. Grids allow incremental movement (and speed control), which facilitates drive, collision detection and manoeuvring. The size of the grid is of critical importance. If the grid is too course, important indoor information might be lost. Alternatively too fine grid might be computational expensive.

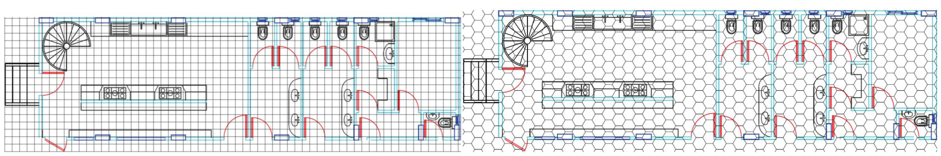

Figure 21: Square and hexagon subdivision (Afyouni et al 2012).

A graph can also be generated from the grid: the nodes represent the centres of the grid cells and edges of a certain node represent link relationships between the node and its neighbours (Li et al, 2010). Shortest path algorithms are easy to execute. (Figure 22). However, many shortest path algorithms are adapted to run on grid, e.g. A*, Funnel, etc.

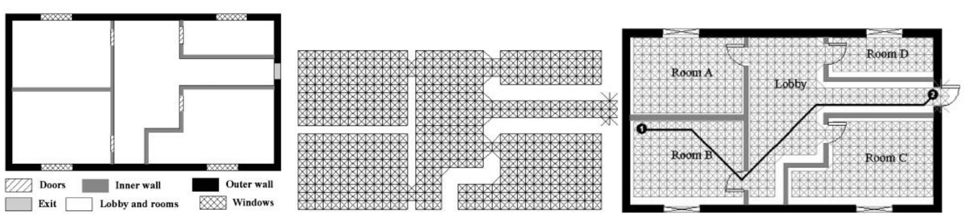

Figure 22: Semantic annotations, generated grid and the shortest path on the grid (Li et al, 2010).

Enhancement of sell movement is the cross country movement planning. Bemmelen et al, 1993 provide a numbers of possible directions on cell. With different number of nodes on the sides of a raster cell, the number of directions to be used also varies. There are two kinds of nodes: data nodes related to raster cells and search nodes located on the sides of the cells. Figure 23 illustrates the directions to be followed, which vary with respect to the different emitting lines. This raster approach gives benefits to path-finding in an open space and may provide improved shortest path-finding.

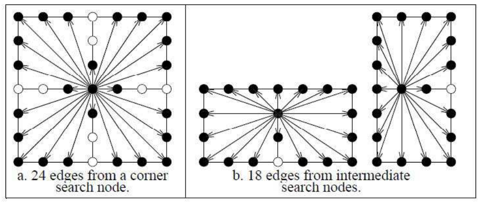

Figure 23: Edges from corner search node & intermediate search node (Bemmelen et al, 1993).

The overview of approaches given above does not pretend to be complete, but it reveals some tendencies. As mentioned above, most of the methods consider geometric subdivisions. The subdivision supports path finding algorithms and does not rely heavily on the logical, functional, thematic meaning of the sub-spaces. Table 4 provides an estimation of the fitness of the approaches to the indoor requirements as specified above. The requirements are subdivided into four groups. Indoor environments reflect requirements to the indoor subdivision as defined either by the construction of the building, or user, scenario and task. The group called Indoor spaces refers to the qualitative descriptions and characteristics that should be attached to the spaces to facilitate the navigation. The third group consists of one requirement, i.e. transfer between the spaces such as doors and windows. Finally, the last group is dedicated to the obstacles.

Table 4: Evaluation of the different approaches with respect to the indoor requirements.

Requirement No./Methods	Partial sub-spacing network	Compete sub-spacing network	Complete sub-spacing Regular grid
Indoor Environment			
1	0	0	+
2	+	0	+
3	-	+	+
4	0	+	++
5	-	-	++
6	-	-	-
Indoor Space			
7	-	-	-
8	-	-	-
9	0	+	-
10	-	-	-
Indoor Transfer Space			
11	+	+	+
Indoor Obstacle Space			
12	-	0	+
13	-	+	+
14	-	0	0
15	-	-	-

-not supported, 0 basic, +supported, ++ well supported

Regular grid methods are slightly superior to network methods, but this is mostly because they are developed for the more complex robot navigation. Network methods tend to be used for human navigation and as such, they provide less detailed routing assuming human intelligence will compensate for inaccuracies.

5 3D approaches

We group the 3D approaches, similarly to those in 2D, into partial subdivision (network), complete subdivision (network) and complete subdivision (grid). In contrast to 2D very limited research has been reported on complete subdivision (grid) or partial subdivision of 3D space. Instead, many approaches are developed, which mimic a 3D representation by layered models of 2D floor plans. We consider these as a partial subdivision. To simplify the complexity of 3D geometry, semantics is being largely incorporated in the models for navigation and the path finding algorithms.

5.1 Partial subdivision: network

A quite common approach to 3D space (especially with regular buildings) is the embedding of 2D floor plans into building 3D spaces. As mentioned previously many commercial systems adopted this approach. Thill et al, 2011 adopt this approach and show it can be successfully applied in combination with outside networks (Figure 24).

Figure 24: 2D floor plans embedded in 3D space and linked to the outside network (Thill, et al 2011).

Such approaches manage to accommodate many properties specific to indoor spaces, such as ingress and egress, vertical movements in stairs and elevators, movements on escalators, segments that are not traversable due to personal disability. Visual mapping and rendering can be done in both 2D and 3D view and can enhance the routing constructs associated with individual movements through indoor spaces. Navigation on the individual 2D floor plans can be performed according to any of the 2D approaches mentioned in the previous section. Depending on the purpose of the navigation even a combinations of several approaches can be used. For example if tracking and automatic correction when the path is lost can be performed following regular grid approach, while in other cases a network might be derived. The navigation can be organised in a layered manner by coding accordingly the floors and the parts of the buildings. These approaches also compensate for some of the deficiencies of the conventional pure node–arc network data models as much geometric information is available to attach semantics to. However any application that needs information about walls and ceilings or more detailed locations in connecting spaces such as stairs and elevators, would experience problems..

Another group of approaches consider walkable connected surfaces for navigation (Slingsby and Raper, 2008; Schaap, 2010). The concept of space subdivision is replaced with topologically-connected and navigable spaces (surfaces) embedded in 3D space. Slingby and Raper, 2008 construct a navigable space model from 2D plan with additional information about heights and surface constraints (Figure 25). This approach assumes existence of quite some specific semantics (e.g. stairs, types of surfaces) and connectivity relation between all spaces.

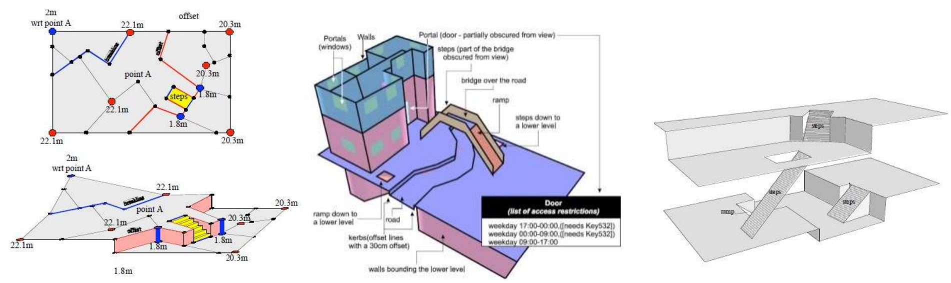

Figure 25: The space accessible to walk: constraints (left), over spanning objects (middle) and indoor (right) (Slingsby and Raper, 2008).

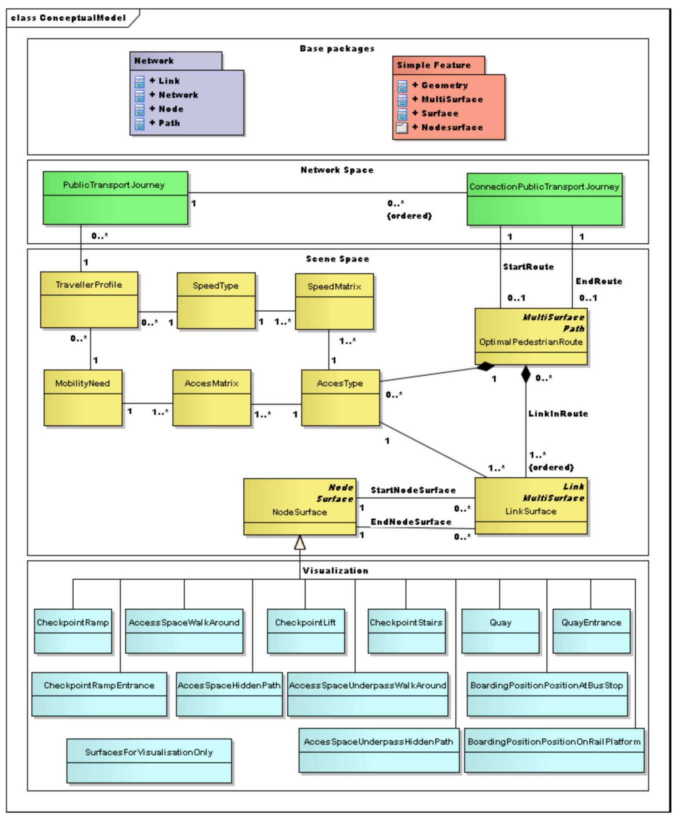

Figure 26: UML diagram of the model for navigation (Schaap et al, 2010).

A compatible approach is followed by Schaap et al, 2010, who propose, a model for multimodal transportation, which should provide navigation to pedestrians in railway or bus stations. The conceptual model incorporates Network Space and Scene Space with enhanced semantics for visualisation purposes. The Network Space indicates constraints created by planned public transport journeys such as public transport line names, delays, disturbances or vehicle properties, etc. Scene Space represent the spaces accessible for public (Figure 26). The Scene Space part of the model contains information about the pedestrians and the environment. The spaces where the pedestrians can move are explicitly modelled as surfaces.

The general idea was to define a network for navigation based on overlapping surfaces (Figure 27). Therefore some of the surfaces (e.g. WalkAround) are dedicated to navigation and they must overlap. The overlap relationship is not explicitly maintained, instead it is derived from the geometry of the surfaces. The intention was to use available operation of spatial DBMS to check for 'overlap'. The set of surfaces for navigation is selected on the basis of half-perimeter distance computation.

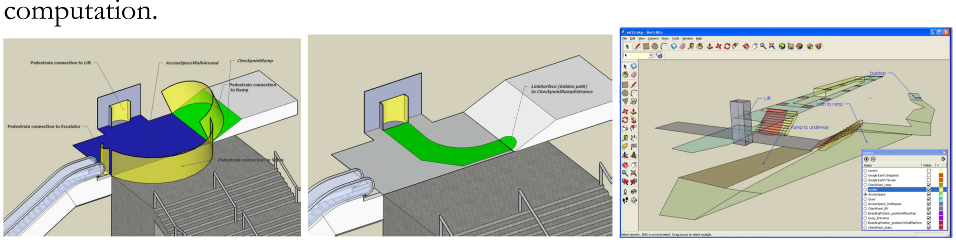

Figure 27: Navigation with overlapping spaces: node with possible directions for movement (left), WalkAround path (middle) and the network of overlapping surfaces.

However, the first pedestrian routing (without accessibility restrictions) has revealed some limitations. The used distance calculation algorithm in the prototype, was not precise enough to be useful for optimal pedestrian routing (but quite crucial in optimal route computation). Furthermore, wrong pedestrian connections were created at certain locations due to the limited 3D intersection capabilities of Oracle Spatial 11g. The Oracle Spatial 11g offers only ANYINTERACT between two surfaces in 3D. The operator SDO_RELATE with various masks to test for the different kind of spatial relations is available only for 2D geometries. In further evaluation of the prototype the problematic WalkAround Single spaces were replaced with Hidden path and NodeSurfaces to overcome these limitations.

5.2 Complete subdivision: network

The approaches than make use of network navigation are again based on Poincare duality and consider volumes and surfaces. This is to say that the dual a volume is a node and the dual of surface in an edge (Figure 28, left). Lee 2004 introduces the Node-Relation Data Structure, defining a strict mathematical foundation between different mathematical spaces (Euclidian, Topological). Boguslawski et al, 2012 follow similar approach (Figure 28, right). There is little elaboration on the semantics assuming that the approaches will work with any space subdivision and space definition.

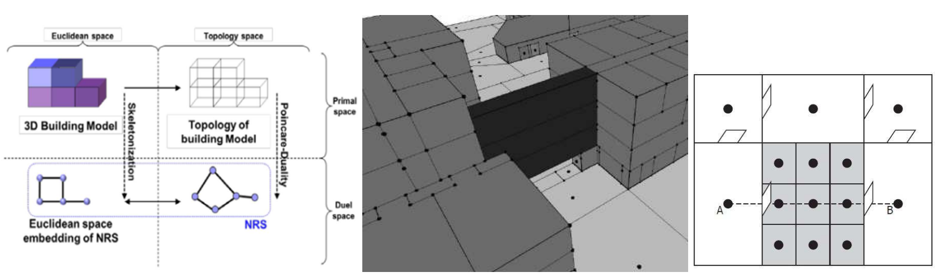

Figure 28: Lee, 2004: Node relation data structure (left), Boguslawski et al, 2011: topological model (middle) and derived path using outside space (right).

All models, in which the semantics is leading or very well developed, belong to this group. The difference with pure geometric subdivision is that if a space subdivision is needed it is defined by the semantics (function, type, purpose) of the space. Several approaches can be mentioned:

- Extraction of navigation path from a semantically-reach common purpose buildings models such as CityGML (LOD4) and IFC
- Semantic models created with the purpose of application (reconstruction, facility management, navigation)

The first group of approaches reuses the semantic& geometric subdivision and derives connectivity information via openings like doors and windows. Theoretically CityGML LOD4 (Gröger et al 2012) offers straightforward approach as the rooms are described by bounding surfaces which are linked to the openings (Figure 29). Information about obstacles can be derived from the objects defined as IntBuildingInstallation. Some complications exist with transition spaces such as stairs, ramps, which are recorded also as interior building installation.

Following directly duality graph, the straightforward steps would be: 1) create the duality graph (each space is approximated with a node and each connection with a link), 2) assign metrics to the nodes to create a metric graph, 3) include openings to enhance the graph. The challenges are the same as for the 2D case as in Figure 15 but then in 3D. First of all, long or irregular indoor spaces (such as corridors, concave shapes) require further partial subdivision, because one node does not represent well the structure or the way of movement in the space. Assigning 3D metrics to the nodes should be considered with care as some nodes may be outside of the spaces.

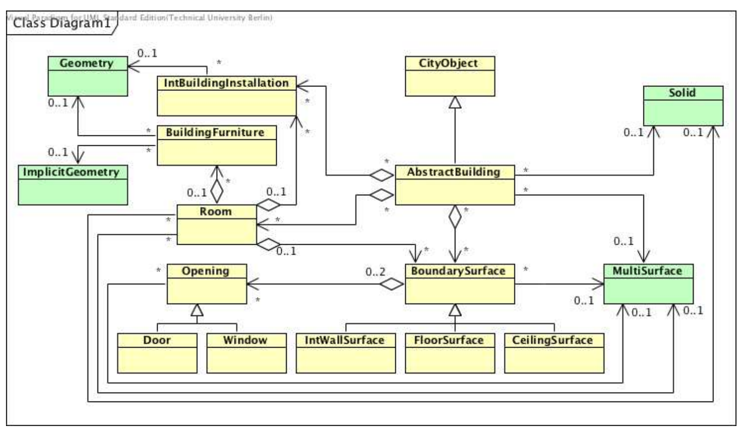

Figure 29: Generalized schema of CityGML LOD4 (Brown et al, 2013).

Alternatively, the problem can be reduced to 2D. The steps to derive the metric network will be: 1) derive the duality graph, 2) extract all floor surfaces and doors of the spaces, 3) perform MAT and replace each node of the duality graph with the corresponding MAT path and 4) enhance with information about doors. Theoretically, all 2D approaches can be considered when the floor surfaces are derived.

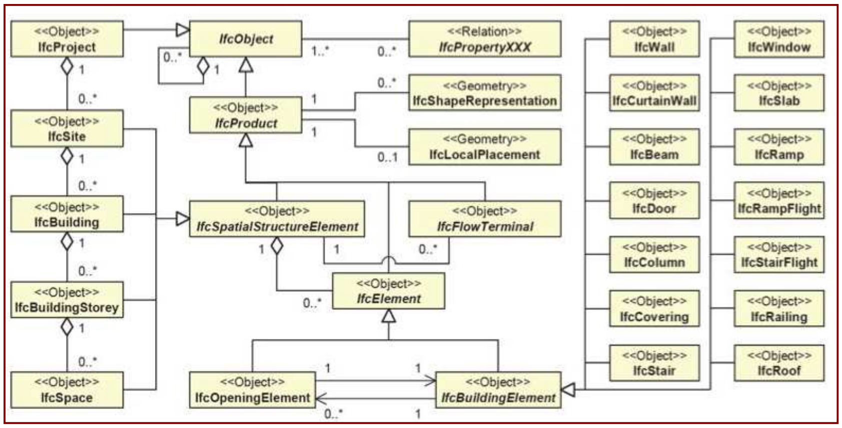

Figure 30: Generalized schema of IFC classes (Brown et al, 2013).

Industrial foundation classes (IFC) provide detailed semantic information indoors but from the perspective of the construction of the building. While the spaces for navigation are readily available in CityGML, IFC maintains information about the concrete elements of the building. Many of the classes may have the same name (as walls, doors, windows and roofs) but the geometric meaning is different. To derive a network from such a model will require quite some geometric computations. Similar to cases with CityGML, 3D and 2D approach can be followed. Figure 31 illustrates the 2D workflow: 1) walls and slabs will define the room surfaces, 2) MAT is performed on the room surfaces, 3) doors, windows and stairs will refine the network. The 3D approach may benefit of the special class Space, which is a closed volume and represent the empty space in each room. The ifcSpace has to be however available in the IFC file.

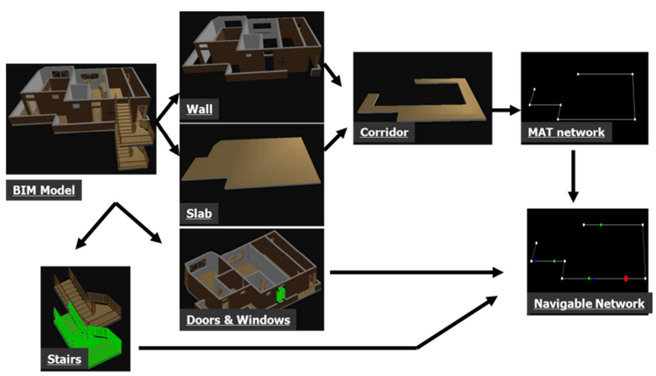

Figure 31: Schematic representation of network creation from BIM model.

Table 5 illustrates how CityGML and IFC fit the user requirements defined in Section 3.2.

Table 5: Comparison between CityGML and IFC.

Requirement No.	CityGML	IFC
Indoor Environment		
1	++	++
2	+	++
3	+	+
4	+	++
5	++	++
6	+	++
Indoor Space		
7	++	++
8	++	++
9	-	-
10	-	-
Transfer Space		
11	++	+
Indoor Obstacle Space		
12	+	+
13	+	++
14	+	+
15	-	+

-not supported, +supported, ++ well supported

Although very rich semantically, the two models are not readily available to derive a network for navigation. Therefore, several models have been developed with the explicit purpose to define a large spectrum of spaces, their properties and relationships between them for the navigation network. Some examples are listed below.

Brown et al, 2011 proposes a model, which distinguishes between obstacles and spaces for navigation (transition and indoor spaces). Corridors and rooms are explicitly maintained, which gives indications what is the connection between different types of spaces. Rooms are connected normally with one other space only (i.e. corridor). A differentiation is made between(Figure 32). vertical and horizontal passages.

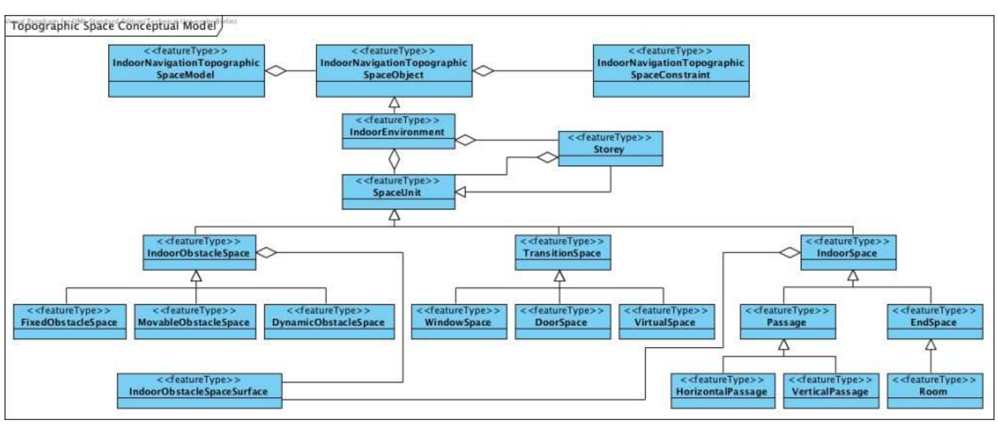

Figure 32: Indoor Navigation model (Brown et al, 2011).

Liu and Zlatanova, 2012 elaborate further on the distinction between vertical and horizontal spaces making the link between vertical and horizontal spaces more explicit. Using this explicit semantics, the connectivity graph can be readily derived out of it. The navigation can then be organised at two levels. The first level is a kind of duality graph but derived from the semantics and the explicit relationships stored in the model. The second level is a local navigation in each individual space (room or a corridor).

Figure 33 is an example of a building (for simplicity only the layered model is visualized) and the derived connectivity graph. The graph contains no metrics; therefore the path algorithms should be run utilizing other information that is available in the semantic description, either as definition or as attribute. For example the meaning of the spaces ('pursue a connector space') the number of the traversed room ('find least room traversal'), the percentage of obstacles in a room, which is kept as an attribute ('find least obstacles path'), etc. .

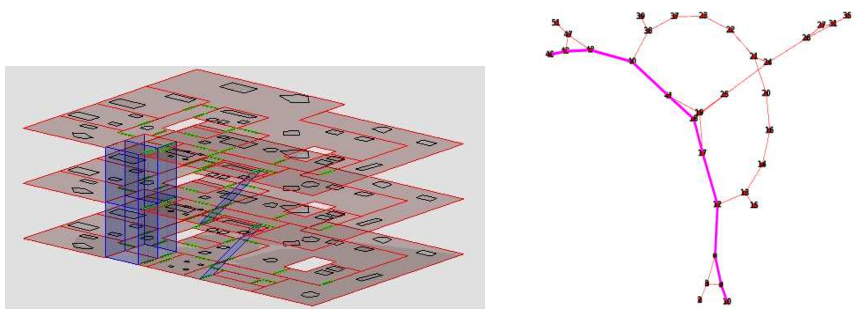

Figure 33: A layered model of a building and the connectivity graph.

After the space sequence is determined, a metric detailed path would be searched orderly in each space. At this level, specific details such as obstacles and multiple doors connecting two spaces are taken into consideration. Figure 34 illustrates a connectivity graph around obstacles built in one of the rooms in the test building.

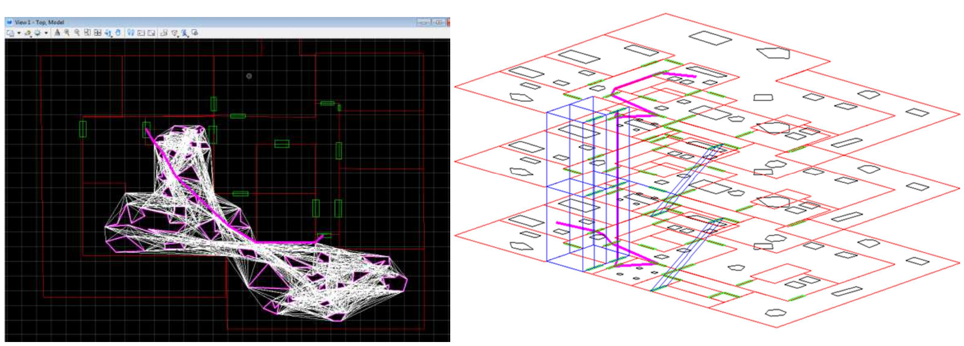

Figure 34: Visibility graph in a room considering obstacles and the final path.

According to different scenarios, several cases in a single space could be considered:

- No obstacles. A path algorithm can be run considering only the shape of the space
- Static obstacles. A (shortest) path algorithm is run to the next door. If there are multiple doors, a selection is made on the basis of the most prominent criterion. If no path to any door leading to the next space, then return the last space and re-compute space sequence;

- Dynamic obstacles. The path will be computed considering the last available status of the obstacles.

This approach can best be combined with passive or active tracking to request the detailed metric path only when the user is at front of the space to be passed. The data model can be updated by this time with any available dynamic information.

Meijers et al, 2006, suggest that data models for navigation can be derived during the reconstruction procedure and the space subdivision can be adapted to fit different purposes. Suppose spaces have to be reconstructed from a lasers scanning, the semantic model is built around planar polygons which bind the spaces.

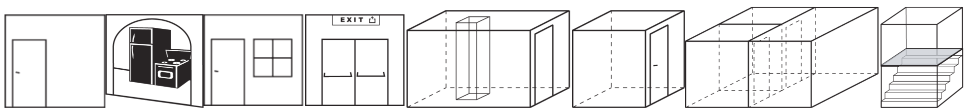

Figure 35: Persistent (door and wall), virtual polygon, full granting polygon (door), limited granting polygon (exit door), non-accessible section (column in a room), end section, complex of sections and vertical section subdivided with virtual polygon.

Each polygon identified from the point cloud is classified according to the function it performs. The polygon classifications are based on four properties: *persistence*, *existence*, *access-granting* and *types of passing*. The *persistency* of polygons reflects the possibility of a polygon to be temporarily removed (if needed) as a wall that can be folded and thus two spaces can be joined. *Existence* can be two types: *virtual* (e.g. virtual walls do not exist in reality but only in the model to close spaces). This classification is critical for visualization process; virtual polygons should not be rendered. *Access-granting* is also two types. *Non-granting* polygons prohibit entering a section (e.g. wall). *Granting* polygons could give *full access* (no conditions, these are the exits, e.g. polygons representing doors), *semi access* (usually exists but have some restrictions, e.g. one needs to have a key) and *limited* access (under normal circumstances not used as exist, e.g. emergency exist and windows). The *types of passing* can be *uni- and bi-directional* depending on the possible way of entering. For example many exits allow only one-way of entering. The consequence of such an entrance is that once inside a particular section the person may not get out using the same way.

The building is separated into well-defined spaces called *sections*. A section is defined as being the smallest amount of bounded space in a building that has a specific function (e.g. meeting room, stairs, etc.) with the following restrictions:

- Sections are composed of 'paper' walls (no thickness of walls is considered)
- Sections must be closed. If not they are sealed with virtual polygons.
- Section must be distinct and may not overlap with any other section.

Similar to the other semantic models the sections are classified with respect to their purpose for the navigation into: *end* (only one entrance/exit), *connector* (more than one entrance/exit) and *non- accessible* (no entrance/exit) sections. Connector sections can be corridors, elevators, stairs and sometimes rooms (if they connect two and more spaces. Several sections may compose a *complex-of-section*s.

Having the classification above, interesting interrelations can be observed. The type of polygons bounding a section has influence on (is related to) the type of section, i.e. only particular types of a polygon can be a part of some of the sections. For example *non-granting* polygons can be only *real* and close *non-assessable* sections only.

Type of access and type of passing are critical polygon parameters for computing evacuation routes.

Compare to the sematic models above, this data model distinguishes only between end and connector spaces, but provides many characteristics to the composing elements. These characteristics provide important properties for the connectivity between the spaces.

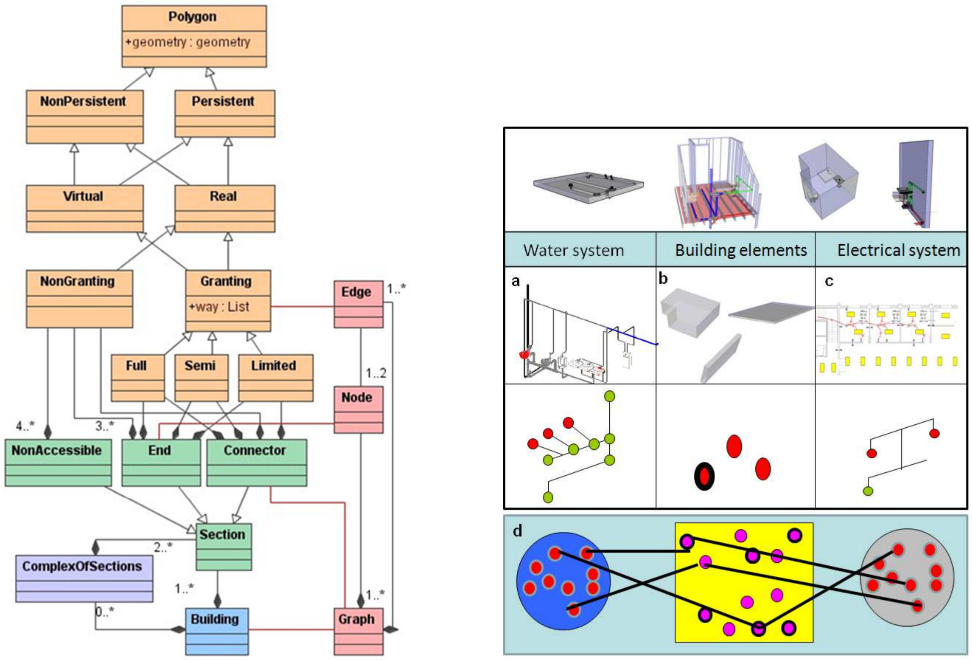

Figure 36: UML model for a reconstruction-oriented for space definition (left); NIBU: a model considering indoor utilities (right).

All above approaches concentrate on the free space available for navigation. Resources and non-navigable spaces (as shafts for cables and pipes) hidden in non-navigable spaces (walls) are left out of scope. Hidjazi et al, 2011, 2012 have suggested that such spaces have to be taken into consideration as well, to be able to navigate to them for utility management. The idea of this research is to establish relations between the walls and the corresponding components of the utility network. The interesting point here is that the notation of walls should be clearly defined. The concept of walls differs in the semantic models. Some models consider 'paper' wall, consisting of one polygon only, others assume wall is space (wall with thickness). The walls considering the thickness can still be defined differently. For example, CityGML takes into account the thickness of walls/ceilings/floors but as empty space between two 'paper' walls/ceilings/floors defining the neighbouring rooms. In contracts IFC has a notion of wall/slab, which represents the concrete physical wall/slab spanned through the whole building (Figure 37, left, Figure 31). IFC concept is suitable for representing shafts for utility networks. CityGML concept may create ambiguities.

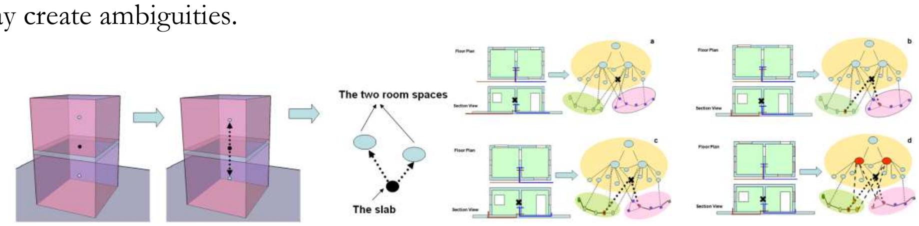

Figure 37: Topology between rooms and slabs (left) and Topology between utility networks and building elements (right).

The utilities network system is represented using the classes' *NetworkSystem* (Figure 38). The two classes *Fittings* and *Segments* are specialisations of the class *Dist_NetworkElement*. *Fittings* represent fixtures that connect two flow segments (e.g. pipes) and are intended to represent the nodes in the logical graph structure of the service system network. Therefore a point representation is associated with this class to allow having a physical point represent this class. This class has several sub-types listed in the enumeration list. On other hand, the *Segment* class represents the flow segment, which is an edge in the logical graph structure; the class can have a curve representation that offer a physical simple representation of this class. Both classes comprise the class *Network_GRAPH* which links the *Dist_NetworkElement* sub-classes.

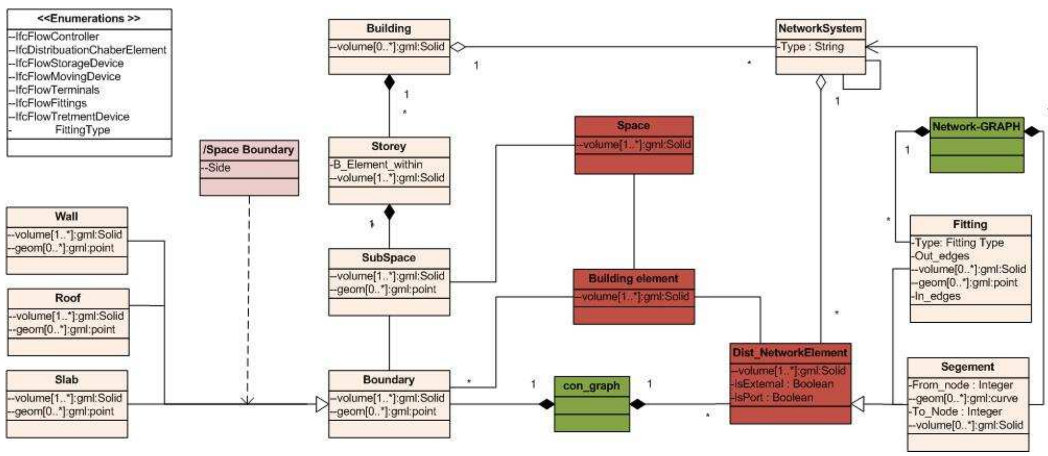

Figure 38: UML diagram of the integrated model (Hidjazi et al, 2012).

The building structure is represented using the classes on the left-hand side. The *SubSpace* class represents the minimum space part that could be decomposed from a space that is represented by the 3D building models. Therefore, the *SubSpace* class has a relation with the *Space* class, which provides interface to connect 3D building semantic models: e.g. IFC represents space as *IfcSpace* and CityGML represents space as *Room* surrounded by surfaces. Similarly, the *Boundary* class represents the smallest part of the building element that is enclosing the volume of the 3D space. The link between the networks and the rooms is given by the walls considering the concrete physical walls as in IFC. The dual graphs derived from the spaces are linked as schematically demonstrated on Figure 37(right).

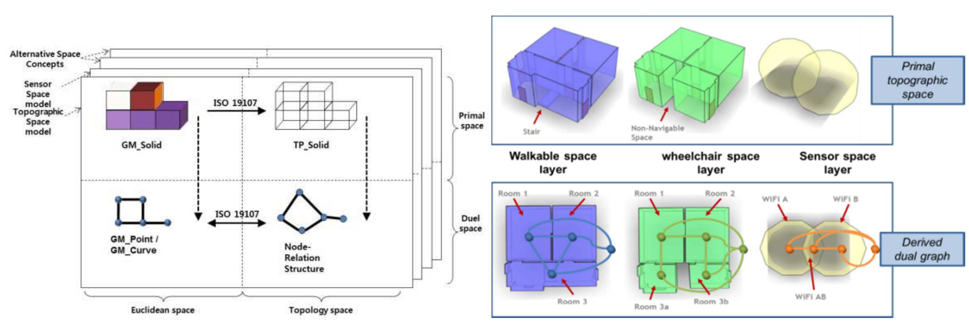

Figure 39: MSLM : layers representing space subdivision: models & layers(left) and example spaces (right).

Another step further in the spaces subdivision is considering the agent properties such as user characteristics, environment and tasks. In this respect, the Milti Layred Space Model (Becker at al, 2008) provides the most general concept for semantic space subdivision. Space can be subdivided not only with respect to topographic/geometric/construction properties of buildings but also with respect to the spaces as defined by security issues, wifi coverage, disability, emergency situations etc. Following the concept of Dual graph, the networks derived by the subdivisions can be linked and used for common analysis and navigation.

5.3 Complete subdivision: regular grid

Basically 3D regular grid is the extension of the 2D grid graph. The purpose of 3D grid-based (voxel) graph is to represent the complete 3D space of indoor space. In contrast to 2D not that much research has been performed on 3D grid subdivision. Yuan and Schneider, 2010 propose a model called LEGO graph based on 3D voxels. This method computes the accessible parts of indoor environments with consideration of constraints of widths and heights of pedestrians. LEGO-graph only provides all feasible or possible paths with different accessible widths and heights (Figure 40).

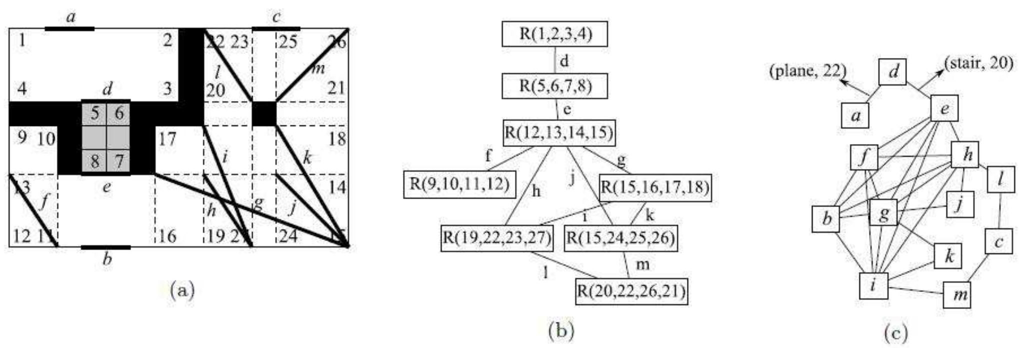

Figure 40: Floor plane (left), the graph representing the connectivity of blocks (middle) the corresponding LEGO graph (right) (Yuan & Schneider, 2010).

Bandi and Thalmann, 1998 discretize space into 3D voxels and compute an obstacle-free feasible route with consideration of surmountable and insurmountable obstacles and "hole area" (i.e. insurmountable obstacles may be encompassed in a closure of reachable grids) in space (Figure 41). The method provide navigation on surface

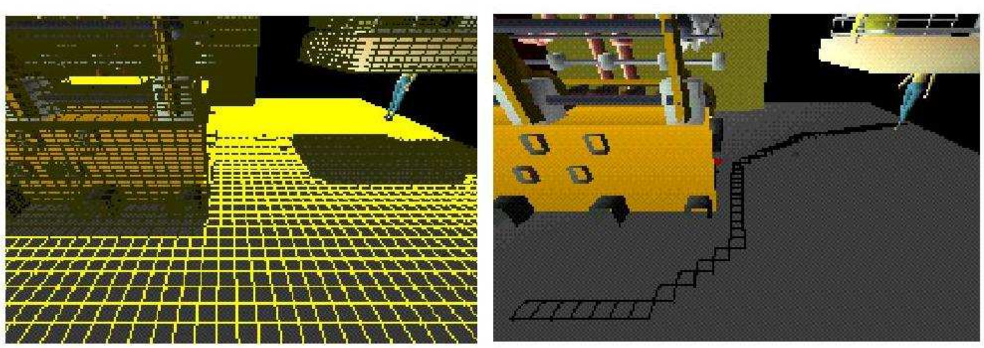

Figure 41: Reachable regions and the generated path (Bandi & Thalmann, 1998).

As mentioned previously, grids are used mostly in robot navigation. Some 3D grids approaches for navigation are applied also in game simulations. Game simulations have many similarities with the robot and human navigation. Many agents (game characters, avatars) could move like real humans. For example, they can climb up the low obstacles or even crawl through the wholes on walls if allowed. On the other hand, all these moving ability and the collision avoidance have to be explicitly defined during the program design process. The activities of simulated agent are preprogramed and controlled by corresponding codes. However the problems how to model the space to allow climbing over and crawling under remain the same. A typical research topic in this field is to project all the obstacles of the animated scene to a 2D bitmap to accelerate the process of forming path plan (Kuffner, 1998).

Andujar et al, 2004, present an algorithm for camera path computation, based on voxelisation. The algorithm determines the free-space structure of the scene (using so called a cell and portal graph) and various measure to determine the best path for visiting. The algorithm subdivides open (obstructed) spaces (Figure 42).

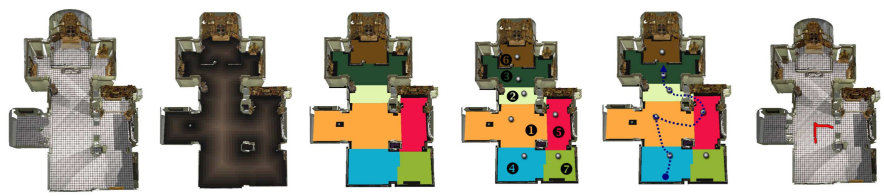

Figure 42: Top view of the original model, Computed distance field, Final cells detected, Ordered cells based on their entropy, High level path through the 5 most interesting cells and Computed low-level path for the most interesting cell (Andujar et al, 2004).

Generally, 3D regular-girds have a great potential. In addition to advantages of grid processing they can readily point out the membership (e.g. corridors, rooms and stairways) of a grid/voxel and incorporate various semantics per pixel. 3D grids can also take into consideration height constraints and permit computing paths either on the surface of flying above at certain height above, under or around objects applying 3D shortest path algorithms such as A*. Some disadvantages such as losing accuracy because of too course grid or long processing time with fine grid can be compensate with two-level approach described above.

The overview of 3D approaches is an exemplary selection of some common approaches intended for human navigation. It is not an extensive survey of robot or computer game approaches. As indicated above, the human based approaches consider much more semantics compared to 2D approaches. The subdivision considers functional, thematic meaning of the sub-spaces, abilities of users and importance of tasks they perform. Table 6 provides a rough evaluation of the mentioned 3D approaches to the indoor requirements. Regular grid are slightly superior to network methods, but this is mostly because they are developed for the more complex robot navigation. Network methods tend to be used for human navigation and as such they provide less detailed routing assuming human intelligence will compensate for inaccuracies.

Table 6: Evaluation of the different approaches with respect to the indoor requirements.

Requirement No./Methods	Partial sub-spacing network	Compete sub-spacing network	Complete sub-spacing Regular grid
Indoor Environment			
1	0	++	+
2	+	+	+
3	+	+	+
4	0	+	++
5	+	++	++
6	+	+	+
Indoor Space			

7	+	++	-
8	+	++	++
9	+	-	++
10	0	-	++
Indoor Transfer Space			
11	+	++	+
Indoor Obstacle Space			
12	+	+	++
13	+	+	++
14	0	+	0
15	-	-	+

-not supported, 0 basic, +supported, ++ well supported

6 Conclusion

We have introduced a framework for a formal description of all components that influence space subdivision. These are space (navigable and non-navigable), agent, resource, activity and modifier. Using these concepts, we have identified 11 navigation cases and information management requirements. The requirements specify which geometric, topological (connectivity, accessibility) and sematic properties have to be available for most of the identified indoor navigation cases.

The review of application and methods for indoor data model and approaches for navigation allows drawing few important conclusions:

- Space definition, subdivision and aggregations are important aspects of navigation. Space has been subdivided mostly to represent geometrically better the path for navigation. However, semantics descriptions and properties have been increasingly introduced.
- Semantic is becoming more important as complexity of spaces and tasks of users increases. The semantics is intended to enhance quantitatively the computed path (by adding information about function and type of spaces such as rooms, corridors, doors, windows, etc.). Using semantics annotations, parts of buildings and floors can be avoided, the routing can be better adapted to the locomotion mode and the task of the user, knowledge-engineering approaches can be applied (reasoning).
- 3D models are valuable contribution but it is also apparent that it is not needed for all types of applications. Successful routing can be performed on 2D floor plans, embedded in 2D or 3D space especially for regularly structured buildings. However, 3D is of importance for complex irregular structures and in cases when vertical information needs to be considered (height of obstacles, clearance of floors) or routing above and below objects, without touching a surface (e.g. fly).
- 3D models result in complex networks and grid models. Therefore new approaches should be investigated, which consider levels of detail for navigation and combination of different approaches. The derived graph or voxel subdivision should be performed on the fly to be able to reflect dynamic changes
- Partial and complete subdivision, which is used to derive a logical and metric graph, is predominantly used for human navigation, while regular grids are utilised for robot navigation and games.

The review of approaches does not reveal standardized method for sub-dividing indoor space. Indoor space is subdivided with respect to agent properties and activities, and thematic utilization of space (topographic, sensor, security). The purpose of subdivision is to ensure start and end location of agent and/or resource can be sufficiently precise identified. Most of the navigation approaches aim at computing network (or grid) rather than identifying spaces and space subdivision/aggregation. Space subdivision has be explicitly mentioned only in approaches based on Poincare duality. However, many of the methods to create automatically a network can be related to duality of space. Therefore, the Poincare duality is adopted as theoretical background of IndoorGML (OGC standard in preparation, http://www.opengeospatial.org/projects/groups/indoorgmlswg). Following duality of space, the problem of network/grid computation shifts to the problem of space subdivision/aggregation and establishing connectivity between navigable spaces.

Recommendations:

- Approaches for space subdivision and aggregation should be investigated, especially if semantics identification is intended. Most of the presented models assume the spaces exist. If they do not exist, dedicated data sets are manually created.
- Methods for sematic annotation of geometric models should be developed
- More attention should be given to navigation trough obstacles (static and dynamic)
- Regular grid models should be further investigated for human application as well as for indoor robots (e.g. flying)
- Approaches for navigation of multiple agents to multiple agents should be considered as well.

Bibliography

Afyouni, I., C. Ray, and C. Claramunt, 2012, Spatial models for context-aware indoor navigation systems: A survey, Journal of Spatial Information Science, Number 4 (2012), pp. 85–123

Becker, T., C. Nagel, T.H. Kolbe, 2008, A Multilayered Space-Event Model for Navigation in Indoor Spaces. In: Lee, Zlatanova (eds.). 3D Geo-Information Scienes, Lecture Notes in Geoinformation and Cartography, 2009, Part II, 61-77.

Bandi, S. and D. Thalmann , 1998, Space discretization for efficient human navigation, Wiley Online Library.

Bemmelen, J. van, W. Quak, M. Van Hekken, and P. Van Oosderom, 1993, Vector vs. raster-based algorithms for cross-country movement planning. Proceedings Auto-Carto 11: 304–17.

Brown, G., C. Nagel, S. Zlatanova and T.H. Kolbe, 2013, Modelling 3D Topographic Space Against Indoor Navigation Requirements, In J. Pouliot, S. Daniel, F. Hubert and A. Zamyadi (Eds.), Progress and New Trends in 3D Geoinformation Science, LNG&C, Springer, Heidelberg, New York, Dordrecht, London, pp. 1-22

EPA, 2009, Buildings and their Impact on the Environment: A Statistical Summary, 7p., available online http://www.epa.gov/greenbuilding/pubs/gbstats.pdf

Gerarerts, R. 2010, Planning short paths with clearance using explicit corridors, 2010 IEEE International Conference on Robotics and Automation, Anchorage Convention District, May 3-8, 2010, Anchorage, Alaska, USA, pp. 1997-2004

Girard, G., S. Côté, S. Zlatanova, Y. Barette, J. St-Pierre and P. van Oosterom, 2011, Indoor Pedestrian Navigation Using Foot-Mounted IMU and Portable Ultrasound Range Sensors, In: Sensors 2011, Volume 11, pp. 7606-7624

Gröger, G., Th. H. Kolbe, C. Nagel and K.-H. Häfele, 2012 OGC City Geography Markup Language (CityGML) Encoding standard, Version 2.0.0, 344p. available at http://www.opengis.net/spec/citygml/2.0

Hijazi, I., M. Ehlers and S. Zlatanova, 2012, NIBU: a new approach to representing and analyzing interior utility networks within 3D geo-information systems, In: International Journal of Digital Earth, Vol. 5. Issue 1, pp. 22-42

Hijazi, I.,M. Ehlers, S. Zlatanova, T. Becker and L. van Berlo, 2011, Initial investigations for modeling interior Utilities within 3D Geo Context: Transforming IFC- interior utility to CityGML UtilityNetworkADE, In: Kolbe, König&Nagel (Eds.), Advances in 3D Geo-Information Sciences, pp. 95-113

Hijazi, I., S. Zlatanova and M. Ehlers, 2011, NIBU: An integrated framework for representing the relation among building structure and interior utilities in micro-scale environment, In: Geo-Spatial Information Science, Volume 14, 2, pp. 98-108

Isikdag, U. and S. Zlatanova, 2011, Sensor services for buildings: a framework and opportunities, In: Altan, Backhause, Boccardo&Zlatanova (Eds.), International Archives ISPRS XXXVIII, 7th Gi4DM, 3-7 May, Anltalya, Turkey, 9 p.

Kemec, S., S. Zlatanova and H. S. Duzgun, 2010, A Framework for Defining a 3D Model in Support of Risk Management, In: Konecny, Zlatanova& Bandrova (Eds.), Geographic Information and Cartography for Risk and Crisis Management - Towards Better Solutions, Springer, 2010, pp. 69-82

Kuffner, J., 1998, Goal-directed navigation for animated characters using real-time path planning and control, Lecture Notes in Computer Science: 171-186

Lee, J. and S. Zlatanova, 2008, A 3D data model and topological analyses for emergency response in urban areas, In: Zlatanova&Li (Eds.), Geospatial information technology for emergency response (ISPRS book series), Taylor & Francis Group, London, UK, ppH50642. 143-168.

Lamarche F. and S. Donikian, 2004, Crowd of virtual humans: a new approach for real time navigation in complex and structured environments, Computer Graphics Forum, vol. 23, no. 3, pp. 509–518.

Lee, J. , 2004, A spatial access-oriented implementation of a 3-D GIS topological data model for urban entities. Geoinformatica, 8 (3), pp. 237–264

Li, X., C. Claramuntb and C. Rayb, 2010, A grid graph-based model for the analysis of 2D indoor spaces. Computers, Environment and Urban Systems, Vol. 34 (6), pp. 532-540.

Liu, L. and S. Zlatanova, 2013, A two-level path-finding for indoor navigation, In: S. Zlatanova, R. Peters, A. Dilo and H. Scholten (Eds.); Intelligent systems for crisis response, LNG&C, Springer, Heidelberg, New York, Dordrecht, London, pp. 31-42

Liu, L. and S. Zlatanova, 2012, A semantic data model for indoor navigation. In P Kröger, E Tanin & P Widmayer (Eds.), ISA '12 Workshop papers (pp. 1-8). s.l.: SIGSPATIAL

Liu, L. and S. Zlatanova, 2011, A 'door-to-door' path-finding approach for indoor navigation, In: Altan, Backhause, Boccardo&Zlatanova (Eds.), International Archives ISPRS XXXVIII, 7th Gi4DM, 3-7 May, Anltalya, Turkey, 6p.

Lorenz, B., H.J. Ohlbach and E.P. Stoffel, 2006, A Hybrid Spatial Model for Representing Indoor Environments. In Proceedings of W2GIS (LNCS 4295): 102-112. Hong Kong, China.

Meijers, M., S. Zlatanova and N. Pfeifer, 2005, 3D geoinformation indoors: structuring for evacuation, In: Proceedings of Next generation 3D city models, 21-22 June, Bonn, Germany, 6 p.

Nedkov, S. and S. Zlatanova, 2012, Google maps for crowdsourced emergency routing, In: M. Shortis, M. Madden (Eds.); International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXIX-B4, XXII ISPRS Congress, August-September 2012, pp. 477-482

Niu, L. and S. Zlatanova, 2012, Review of grid navigation research in the context of emergency routing. In S Zlatanova, R Peters & EM Fendel (Eds.), Proceedings of the 8th International Conference on Geo-information Disaster Management (pp. 135-148). Enschede: Universiteit Twente.

Ogawa, K.,E. Verbree, S. Zlatanova, N. Kohtake and Y. Ohkami, 2011, Toward Seamless Indoor-Outdoor Applications: Developing Stakeholder-Oriented Location-Based Services, In: Geo-Spatial Information Science, Volume 14, 2, pp. 109-118

Pu, S. and S. Zlatanova, 2005, Evacuation route calculation of inner buildings, In: van Oosterom, Zlatanova & Fendel (Eds.), Geo-information for disaster management, Springer Verlag, Heidelberg, pp. 1143-1161 (pdf)

Schaap, J.,S. Zlatanova and P.J.M. van Oosterom, 2012, Towards a 3D geo-data model to support pedestrian routing in multimodal public transport travel advices, In: Zlatanova, Ledoux, Fendel&Rumor (Eds.), Urban and Regional Data Management, UDMS Annual 2011, CRCpress/Taylor and Francis Group, Boca Raton, London, pp. 63-78

Stoffel, E., B. Lorenz and H. Ohlbach, 2007, Towards a Semantic Spatial Model for Pedestrian Indoor Navigation. In Hainaut, J., Rundensteiner, E., eds.: ER '07 Workshops / Advances in Conceptual Modeling, Springer, 328–337.

Thill, J.-C., T.H.D. Dao and Y. Zhou, 2011, Travelling in the three-dimecional city: applications in route planning, accessibility assessment. Location analysis and beyond, Journal of Transport Geography, 19 (12011), pp. 405-421

Wallgruen, J. 2005, Autonomous construction of hierarchical Voronoi-based route graph representations. In Proce. International Conference on Spatial Cognition IV (Berlin, 2005), Springer, pp. 413–433. .

Wang, Z. and S. Zlatanova, 2013a, Taxonomy of Navigation for First Responders, In J. Krisp (Eds.) Progress in Location-Based Services, LNG&C, Springer, Heidelberg, New York, Dordrecht, London, pp. 297-315

Wang, Z. and S. Zlatanova, 2013b, An A*-based search approach for navigation among moving obstacles, In: S. Zlatanova, R. Peters, A. Dilo and H. Scholten (Eds.); Intelligent systems for crisis response, LNG&C, Springer, Heidelberg, New York, Dordrecht, London, pp. 17-30

Yuan, W. and M. Schneider, 2010, iNav: An indoor navigation model supporting length-dependent optimal routing. In The 13th AGILE International Conference on Geographic Information Science. Heidelberg: Springer.

Zlatanova, S. and S. Baharin, 2008, Optimal Navigation for First Responders, In: Van der Walle, Song, Zlatanova&Li (Eds,), Information systems for crisis response and management, Joint ISCRAM-CHINA, Gi4DM Conference, 4-6 August, 2008, Harbin, China, pp. 529-542

Zlatanova, S. and F. van den Heuvel, 2001, 3D city modelling for augmented reality applications, In: Proceedings of the International Symposium on architectural photogrammetry, 8-21 September, Postdam, Germany, p. 152-159

Reports published before in this series

1. GISt Report No. 1, Oosterom, P.J. van, Research issues in integrated querying of geometric and thematic cadastral information (1), Delft University of Technology, Rapport aan Concernstaf Kadaster, Delft 2000, 29 p.p.
2. GISt Report No. 2, Stoter, J.E., Considerations for a 3D Cadastre, Delft University of Technology, Rapport aan Concernstaf Kadaster, Delft 2000, 30.p.
3. GISt Report No. 3, Fendel, E.M. en A.B. Smits (eds.), Java GIS Seminar, Opening GDMC, Delft 15 November 2000, Delft University of Technology, GISt. No. 3, 25 p.p.
4. GISt Report No. 4, Oosterom, P.J.M. van, Research issues in integrated querying of geometric and thematic cadastral information (2), Delft University of Technology, Rapport aan Concernstaf Kadaster, Delft 2000, 29 p.p.
5. GISt Report No. 5, Oosterom, P.J.M. van, C.W. Quak, J.E. Stoter, T.P.M. Tijssen en M.E. de Vries, Objectgerichtheid TOP10vector: Achtergrond en commentaar op de gebruikersspecificaties en het conceptuele gegevensmodel, Rapport aan Topografische Dienst Nederland, E.M. Fendel (eds.), Delft University of Technology, Delft 2000, 18 p.p.
6. GISt Report No. 6, Quak, C.W., An implementation of a classification algorithm for houses, Rapport aan Concernstaf Kadaster, Delft 2001, 13.p.
7. GISt Report No. 7, Tijssen, T.P.M., C.W. Quak and P.J.M. van Oosterom, Spatial DBMS testing with data from the Cadastre and TNO NITG, Delft 2001, 119 p.
8. GISt Report No. 8, Vries, M.E. de en E. Verbree, Internet GIS met ArcIMS, Delft 2001, 38 p.
9. GISt Report No. 9, Vries, M.E. de, T.P.M. Tijssen, J.E. Stoter, C.W. Quak and P.J.M. van Oosterom, The GML prototype of the new TOP10vector object model, Report for the Topographic Service, Delft 2001, 132 p.
10. GISt Report No. 10, Stoter, J.E., Nauwkeurig bepalen van grondverzet op basis van CAD ontgravingsprofielen en GIS, een haalbaarheidsstudie, Rapport aan de Bouwdienst van Rijkswaterstaat, Delft 2001, 23 p.
11. GISt Report No. 11, Geo DBMS, De basis van GIS-toepassingen, KvAG/AGGN Themamiddag, 14 november 2001, J. Flim (eds.), Delft 2001, 37 p.
12. GISt Report No. 12, Vries, M.E. de, T.P.M. Tijssen, J.E. Stoter, C.W. Quak and P.J.M. van Oosterom, The second GML prototype of the new TOP10vector object model, Report for the Topographic Service, Delft 2002, Part 1, Main text, 63 p. and Part 2, Appendices B and C, 85 p.
13. GISt Report No. 13, Vries, M.E. de, T.P.M. Tijssen en P.J.M. van Oosterom, Comparing the storage of Shell data in Oracle spatial and in Oracle/ArcSDE compressed binary format, Delft 2002, .72 p. (Confidential)
14. GISt Report No. 14, Stoter, J.E., 3D Cadastre, Progress Report, Report to Concernstaf Kadaster, Delft 2002, 16 p.
15. GISt Report No. 15, Zlatanova, S., Research Project on the Usability of Oracle Spatial within the RWS Organisation, Detailed Project Plan (MD-NR. 3215), Report to Meetkundige Dienst – Rijkswaterstaat, Delft 2002, 13 p.
16. GISt Report No. 16, Verbree, E., Driedimensionale Topografische Terreinmodellering op basis van Tetraëder Netwerken: Top10-3D, Report aan Topografische Dienst Nederland, Delft 2002, 15 p.
17. GISt Report No. 17, Zlatanova, S. Augmented Reality Technology, Report to SURFnet bv, Delft 2002, 72 p.

18. GISt Report No. 18, Vries, M.E. de, Ontsluiting van Geo-informatie via netwerken, Plan van aanpak, Delft 2002, 17p.
19. GISt Report No. 19, Tijssen, T.P.M., Testing Informix DBMS with spatial data from the cadastre, Delft 2002, 62 p.
20. GISt Report No. 20, Oosterom, P.J.M. van, Vision for the next decade of GIS technology, A research agenda for the TU Delft the Netherlands, Delft 2003, 55 p.
21. GISt Report No. 21, Zlatanova, S., T.P.M. Tijssen, P.J.M. van Oosterom and C.W. Quak, Research on usability of Oracle Spatial within the RWS organisation, (AGI-GAG-2003-21), Report to Meetkundige Dienst – Rijkswaterstaat, Delft 2003, 74 p.
22. GISt Report No. 22, Verbree, E., Kartografische hoogtevoorstelling TOP10vector, Report aan Topografische Dienst Nederland, Delft 2003, 28 p.
23. GISt Report No. 23, Tijssen, T.P.M., M.E. de Vries and P.J.M. van Oosterom, Comparing the storage of Shell data in Oracle SDO_Geometry version 9i and version 10g Beta 2 (in the context of ArcGIS 8.3), Delft 2003, 20 p. (Confidential)
24. GISt Report No. 24, Stoter, J.E., 3D aspects of property transactions: Comparison of registration of 3D properties in the Netherlands and Denmark, Report on the short-term scientific mission in the CIST – G9 framework at the Department of Development and Planning, Center of 3D geo-information, Aalborg, Denmark, Delft 2003, 22 p.
25. GISt Report No. 25, Verbree, E., Comparison Gridding with ArcGIS 8.2 versus CPS/3, Report to Shell International Exploration and Production B.V., Delft 2004, 14 p. (confidential).
26. GISt Report No. 26, Penninga, F., Oracle 10g Topology, Testing Oracle 10g Topology with cadastral data, Delft 2004, 48 p.
27. GISt Report No. 27, Penninga, F., 3D Topography, Realization of a three dimensional topographic terrain representation in a feature-based integrated TIN/TEN model, Delft 2004, 27 p.
28. GISt Report No. 28, Penninga, F., Kartografische hoogtevoorstelling binnen TOP10NL, Inventarisatie mogelijkheden op basis van TOP10NL uitgebreid met een Digitaal Hoogtemodel, Delft 2004, 29 p.
29. GISt Report No. 29, Verbree, E. en S.Zlatanova, 3D-Modeling with respect to boundary representations within geo-DBMS, Delft 2004, 30 p.
30. GISt Report No. 30, Penninga, F., Introductie van de 3e dimensie in de TOP10NL; Voorstel voor een onderzoekstraject naar het stapsgewijs introduceren van 3D data in de TOP10NL, Delft 2005, 25 p.
31. GISt Report No. 31, P. van Asperen, M. Grothe, S. Zlatanova, M. de Vries, T. Tijssen, P. van Oosterom and A. Kabamba, Specificatie datamodel Beheerkaart Nat, RWS-AGI report/GIST Report, Delft, 2005, 130 p.
32. GISt Report No. 32, E.M. Fendel, Looking back at Gi4DM, Delft 2005, 22 p.
33. GISt Report No. 33, P. van Oosterom, T. Tijssen and F. Penninga, Topology Storage and the Use in the context of consistent data management, Delft 2005, 35 p.
34. GISt Report No. 34, E. Verbree en F. Penninga, RGI 3D Topo - DP 1-1, Inventarisatie huidige toegankelijkheid, gebruik en mogelijke toepassingen 3D topografische informatie en systemen, 3D Topo Report No. RGI-011-01/GISt Report No. 34, Delft 2005, 29 p.
35. GISt Report No. 35, E. Verbree, F. Penninga en S. Zlatanova, Datamodellering en datastructurering voor 3D topografie, 3D Topo Report No. RGI-011-02/GISt Report No. 35, Delft 2005, 44 p.

36. GISt Report No. 36, W. Looijen, M. Uitentuis en P. Bange, RGI-026: LBS-24-7, Tussenrapportage DP-1: Gebruikerswensen LBS onder redactie van E. Verbree en E. Fendel, RGI LBS-026-01/GISt Rapport No. 36, Delft 2005, 21 p.
37. GISt Report No. 37, C. van Strien, W. Looijen, P. Bange, A. Wilcsinszky, J. Steenbruggen en E. Verbree, RGI-026: LBS-24-7, Tussenrapportage DP-2: Inventarisatie geo-informatie en -services onder redactie van E. Verbree en E. Fendel, RGI LBS-026-02/GISt Rapport No. 37, Delft 2005, 21 p.
38. GISt Report No. 38, E. Verbree, S. Zlatanova en E. Wisse, RGI-026: LBS-24-7, Tussenrapportage DP-3: Specifieke wensen en eisen op het gebied van plaatsbepaling, privacy en beeldvorming, onder redactie van E. Verbree en E. Fendel, RGI LBS-026-03/GISt Rapport No. 38, Delft 2005, 15 p.
39. GISt Report No. 39, E. Verbree, E. Fendel, M. Uitentuis, P. Bange, W. Looijen, C. van Strien, E. Wisse en A. Wilcsinszky en E. Verbree, RGI-026: LBS-24-7, Eindrapportage DP-4: Workshop 28-07-2005 Geo-informatie voor politie, brandweer en hulpverlening ter plaatse, RGI LBS-026-04/GISt Rapport No. 39, Delft 2005, 18 p.
40. GISt Report No. 40, P.J.M. van Oosterom, F. Penninga and M.E. de Vries, Trendrapport GIS, GISt Report No. 40 / RWS Report AGI-2005-GAB-01, Delft, 2005, 48 p.
41. GISt Report No. 41, R. Thompson, Proof of Assertions in the Investigation of the Regular Polytope, GISt Report No. 41 / NRM-ISS090, Delft, 2005, 44 p.
42. GISt Report No. 42, F. Penninga and P. van Oosterom, Kabel- en leidingnetwerken in de kadastrale registratie (in Dutch) GISt Report No. 42, Delft, 2006, 38 p.
43. GISt Report No. 43, F. Penninga and P.J.M. van Oosterom, Editing Features in a TEN-based DBMS approach for 3D Topographic Data Modelling, Technical Report, Delft, 2006, 21 p.
44. GISt Report No. 44, M.E. de Vries, Open source clients voor UMN MapServer: PHP/Mapscript, JavaScript, Flash of Google (in Dutch), Delft, 2007, 13 p.
45. GISt Report No. 45, W. Tegtmeier, Harmonization of geo-information related to the lifecycle of civil engineering objects – with focus on uncertainty and quality of surveyed data and derived real world representations, Delft, 2007, 40 p.
46. GISt Report No. 46, W. Xu, Geo-information and formal semantics for disaster management, Delft, 2007, 31 p.
47. GISt Report No. 47, E. Verbree and E.M. Fendel, GIS technology – Trend Report, Delft, 2007, 30 p.
48. GISt Report No. 48, B.M. Meijers, Variable-Scale Geo-Information, Delft, 2008, 30 p.
49. GISt Report No. 48, Maja Bitenc, Kajsa Dahlberg, Fatih Doner, Bas van Goort, Kai Lin,Yi Yin, Xiaoyu Yuan and Sisi Zlatanova, Utilty Registration, Delft, 2008, 35 p.
50. GISt Report No 50, T.P.M. Tijssen en S. Zlatanova, Oracle Spatial 11g en ArcGIS 9.2 voor het beheer van puntenwolken (Confidential), Delft, 2008, 16 p.
51. GISt Report No. 51, S. Zlatanova, Geo-information for Crisis Management, Delft, 2008, 24 p.
52. GISt Report No. 52, P.J.M. van Oosterom, INSPIRE activiteiten in het jaar 2008 (partly in Dutch), Delft, 2009, 142 p.

53. GISt Report No. 53, P.J.M. van Oosterom with input of and feedback by Rod Thompson and Steve Huch (Department of Environment and Resource Management, Queensland Government), Delft, 2010, 60 p.
54. GISt Report No. 54, A. Dilo and S. Zlatanova, Data modeling for emergency response, Delft, 2010, 74 p.
55. GISt Report No. 55, Liu Liu, 3D indoor " door-to-door" navigation approach to support first responders in emergency response – PhD Research Proposal, Delft, 2011, 47 p.
56. GISt Report No. 56, Md. Nazmul Alam, Shadow effect on 3D City Modelling for Photovoltaic Cells – PhD Proposal, Delft, 2011, 39 p.
57. GIST Report No. 57, G.A.K. Arroyo Ohori, Realsing the Foundations of a Higher Dimensional GIS: A Study of Higher Dimensional Data Models, Data Structures and Operations – PhD Research Proposal, Delft, 2011, 68 p.
58. GISt Report No. 58, Zhiyong Wang, Integrating Spatio-Temporal Data into Agent-Based Simulation for Emergency Navigation Support – PhD Research Proposal, Delft, 2012, 49 p.
59. GISt Report No. 59, Theo Tijssen, Wilko Quak and Peter van Oosterom, Geo-DBMS als standard bouwsteen voor Rijkswaterstaat (in Dutch), Delft, 2012, 167 p.
60. GISt Report No. 60, Amin Mobasheri, Designing formal semantics of geo-information for disaster response – PhD Research Proposal, Delft, 2012, 61 p.
61. GISt Report No. 61, Simeon Nedkov, Crowdsourced WebGIS for routing applications in disaster management situations, Delft, 2012, 31 p.
62. GISt Report No. 62, Filip Biljecki, The concept of level of detail in 3D city models – PhD Research Proposal, Delft, 2013, 58 p.
63. GISt Report No. 63, Theo Tijssen & Wilko Quak, GISt activiteiten voor het GeoValley project – Projectnummer: GBP / 21F.005, Delft, 2013, 39 p.
64. GISt Report No. 64, Radan Šuba, Content of Variable-scale Maps – PhD Proposal, Delft, 2013, 36 p.
65. GISt Report No. 65, Ravi Peters, Feature aware Digital Surface Model analysis and generalization based on the 3D Medial Axis Transform, - PhD Research Proposal, Delft 2014, 55 p.


ZUIDPOLDER
VAN DELFGAUW
MOLENSLOOT
AKKERDIJKSCHE
POLDER
PARALLELWEG