Space Subdivision for Indoor Navigation

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ABSTRACT

The aim of the research was to develop conceptual model for determination of functional areas with abstract borders within indoor space and to illustrate how determined functional areas can be applied to facilitate wayfinding process in indoor environments. The objectives of the research were to define criteria for determination of functional areas of objects by adopting principles of human behaviour and human perception of the environment, to develop rules how to subdivide indoor space into navigable and non-navigable areas and to incorporate functional areas in a navigation model.

Based on literature review conceptual model for functional area determination was developed. The designed model suggests that functional areas of indoor objects depend on their characteristics such as attractiveness, necessity, limited capacity, closeness to central areas, possession of transition area. Additionally, the developed model introduces private space concept to delineate functional areas taking into account human behavioural rules. Mathematical expressions and rules to deal with special cases in order to delineate functional areas were established. The proposed model was implemented for two case studies: Rotterdam Central Station (for peak and off-peak hours) and Faculty of Architecture and the Built Environment, TU Delft. The partition of indoor environment for wayfinding purposes was performed in two steps. Firstly, semantic indoor space partition was performed: separate functional areas were determined and the indoor space was partitioned into navigable and non-navigable areas using GIS tools (buffer, union, difference, aggregation). Secondly, geometric space subdivision was executed where navigable area was subdivided applying constrained Delaunay triangulation to generate navigation network in which functional areas were represented as *dead-end nodes*.

The results derived applying the proposed model were verified using photographs and video records. Functional areas of objects were determined by measuring areas occupied by people around specific objects and distances that people keep between each other and objects. Measurements obtained from photographs were compared with the results obtained using the proposed model. Video records were inspected to examine people movement trajectories.

The results of the image and video analysis indicate that the research successfully integrated findings of previous studies and new concepts introduced in this research in order to provide more realistic abstraction of the indoor environment and more accurate navigation path. Eight

cases of determined functional areas were examined and the outcome of the validation showed that only one case was not supported. On the basis of the results of the validation, it was concluded that the selected criteria are appropriate measures to determine separate functional areas within indoor space and provide reliable results. In this research the determined functional areas were represented as dead-end nodes in the generated navigation networks. The results of the performed path computation tests showed that indication of these functional areas in computations of navigation paths allows generation of more realistic routes that adopt principles of human natural movement and avoidance of areas that are usually occupied.

However, the findings of research showed that additional attention has to be paid while determining ranges of the criteria, analysis of object's closeness to surrounding location has to be improved. Furthermore, the findings revealed that time impact on properties of objects has to be carefully evaluated taking into consideration different factors such as occurring events in the environment, total number of people within the environment, habits of people and other. Moreover, the research suggests that in the future studies different navigation models could be built such as navigation network based on a visibility graph or grid based navigation model, in order to investigate how functional areas can be indicated in these models and analyse which approach provides better path calculation results.

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1. INTRODUCTION

Wayfinding is a process of orientation and navigation in order to reach specific distant destination from the origin especially in complex and spacious environments indoors or outdoors (Kikiras, Tsetsos and Hadjiefthymiades, 2006). The process of wayfinding is a fundamental human activity and part of everyday life: it is knowing where the person and desired location are and how to get there (Timpf, Volta, Pollock and Egenhofer, 1992). Many people have problems finding their way in public buildings such as airports, stations, hospitals, universities and other. Current outdoor navigation systems using GPS technology are reliable, widely available and can assist people to find their way. However, the mature navigation systems for outdoor environment cannot be applied to indoor spaces due to substantial differences in required positioning systems and frameworks for digital models. Indoor environment is far more complex as the orientation inside the building is complicated by the existence of multiple floors, relatively smaller spaces and more difficult overview of the entire indoor space. Moreover, people have an option to move freely within rooms and corridors in contrast to road network defined by strict regulations. Additionally, in indoor environment furniture, columns, podiums and groups of people might act as obstacles thus they need to be considered while orienting and navigating (Nagel et al., 2010). The increase of indoor activities and complexity of indoor spaces demands context aware indoor navigation systems in order to determine the most optimal path from one location to the other (Afyouni, Ray and Claramunt, 2012; Becker, Nagel and Kolbe, 2009a).

1.1 Motivation

There are great attempts to develop indoor navigation approaches that provide the most optimal path and guidance as finding a way in a large building can be a challenging task. People follow certain behavioural rules during the wayfinding process based on a spatial arrangement of the environment (spatial relationships between objects including proximity, separation, order and enclosure), thus human navigation systems require storing and retrieving different types of information: physical, temporal and thematic information, for localization, path planning and guidance purposes (Becker et al., 2009a; Raubal and Worboys, 1999). Among the others the dimension of indoor environment is human-scaled, therefore indoor spaces require greater accuracy with higher level of details taking into consideration presence of people, in order to deliver accurate indoor localization and navigation services

(Lertlakkhanakul, Li, Choi and Bu, 2009). As a result the outcome of indoor navigation system strongly depends on a building model. In order to deliver navigation services indoor environment is usually approximated using network, regular or irregular tessellations (Afyouni et al., 2012; Tsetsos, Anagnostopoulos, Kikiras and Hadjiefthymiades, 2006). Network based abstractions of the environment are the most common for human navigation systems where semantic, topological and geometric information is stored. Network is a graph-based model where environment is described by means of nodes and edges, roughly corresponding to places and their spatial relations (Lorenz, Ohlbach and Stoffel, 2006). Moving from one node to the other is allowed only when there is a link between them which. Thus the link indicates connectivity between nodes. Moreover the node can contain additional information about the location that might be useful to the user i.e. descriptions and other location-related information. For instance, in the geometric network model presented by Lee (2004) rooms within the building are represented as single nodes and links represent distances between nodes (Figure 1.1).

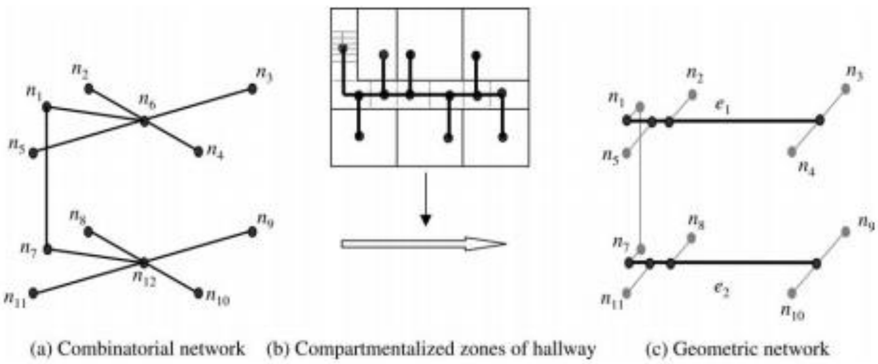


Figure 1.1: Geometric network model for representing topological relationship within 3D objects (Lee, 2004).

However, majority of existing models for navigation lack for details and can only provide coarse routes without considering complex indoor structures and presence of people within indoor space. Most of the navigation systems do not consider high level of detail subdivision – rooms are modelled as single indivisible elements and detailed partition of a room into special areas (smoking area, check-in counters and coffee corner) is not permitted (Liu and Zlatanova, 2011). In order to represent the real situation to maximum extent, representation of the whole room as one single indivisible unit is not enough since such representation is very abstract and this could make the navigation difficult and result into inefficient route planning. Determination of separate functional areas is especially important inside the buildings that do not have regular shape and contain large open spaces such as railway stations, airports or museums. These buildings are usually crowded with people who are unfamiliar with the environment; people gather in groups around shops, cafeterias and waiting areas and obstruct the areas for walking. For this reason, some studies focused on more detail representation of the environment for indoor navigation were conducted. For instance, Goetz and Zipf (2011) consider distinct areas in huge rooms and solid obstacles inside rooms in order to improve navigation accuracy. The generated graph contains semantic information such as room labels, door accessibility and other constraints (Figure 1.2).

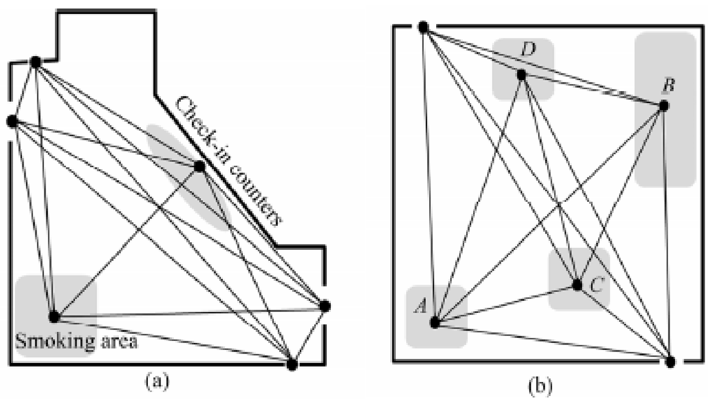


Figure 1.2: Routing graph a) for an airport entrance hall; b) for an exhibition hall (Goetz and Zipf, 2011).

Additionally, Lorenz et al. (2006) proposed graph structure where cell decomposition is performed depending on several criteria: size and concavity of a room and according to basic functional properties of spatial units. Large corridors are represented with several nodes and separate functional areas within large rooms such as meeting point, information desk, coffee corner and other objects are represented as separate nodes that are connected through links (Figure 1.3).

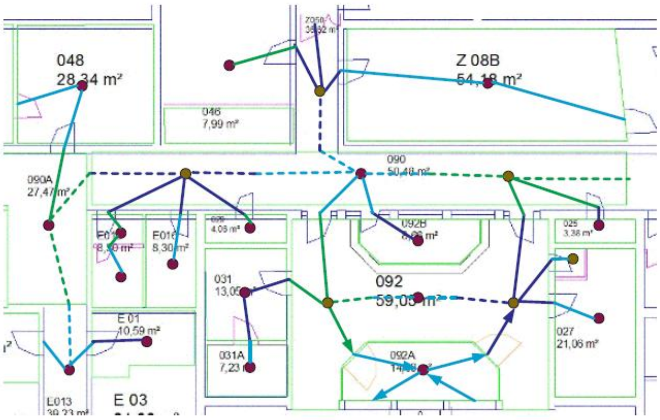


Figure 1.3*:* Cell decomposition according to size of rooms and separate functional units (Lorenz et al., 2006).

Richter, Winter and Ruetschi (2009) suggested hierarchical representation of indoor space with respect to structural, functional and organisational aspects of the environment. In their research different functional areas such as gates in airports, different departments in building were linked to each other according to their connectivity.

The above mentioned studies indicate that semantic determination of particular spaces within a room or a hall would allow more accurate localization within indoor space which enhance an understanding of the environment and raise users' spatial awareness. Furthermore, detailed space subdivision enables navigation of individuals to these separate areas and provides users with more precise guidelines (Figure 1.4).

However, there is no accepted method to determine the functional spaces within large rooms/halls based on the human perception of the environment. As a result the existing indoor models for navigation lack the indication of special areas with respect to human perception of the environment which results in coarse descriptive location information and inefficient navigation path.

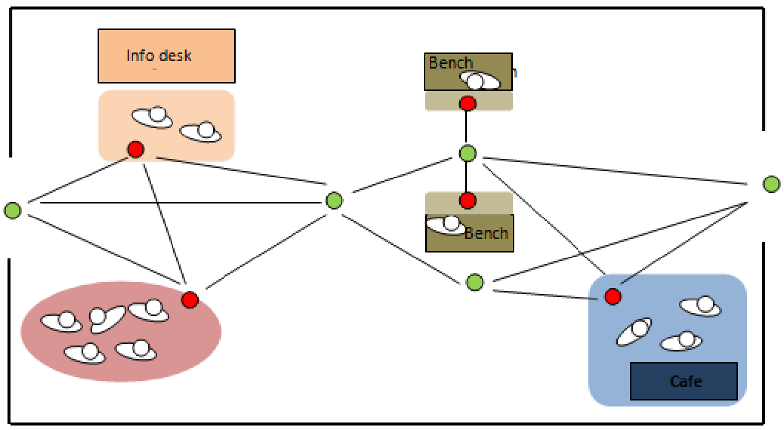


Figure 1.4: Routing graph for bypassing obstacles inside rooms.

1.2 Research Objective and Research Questions

This research seeks to explore how the elements of indoor environment have to be identified and conceptualised for wayfinding purposes. The aim of the work is to develop a conceptual model for determination of functional areas within indoor space and to illustrate how the determined functional areas can be incorporated in a navigation model to facilitate wayfinding process. The objectives of the research are to define criteria for the determination of functional areas of objects by adopting principles of human behaviour and human perception of the environment, to develop rules how to subdivide indoor space into navigable and non-navigable areas and to incorporate functional areas in a navigation model. In this study abstract borders of spatial elements are of importance and the term *functional area* defines space where certain set of activities takes place. *Functional area* of a certain spatial element is described as an area around the object at a certain distance where people are served by this spatial element or are waiting for services provided by this spatial unit. For example, a queue of people is waiting at the airline information desk in airport, thus these people are waiting to be served by the information desk and area occupied by the queue of people can be considered as the functional area of the airline information desk. As a result, this functional area becomes non-navigable for other individuals and should be identified and considered while deriving navigation path.

The proposed partition and description of interior of an indoor environment will cover different aspects of wayfinding process:

- will provide location information while identifying separate functional areas,
- will enable navigation of individuals to these subspaces,
- will allow generation of more realistic navigation path.

The main research question to be answered in further analysis is defined as:

"In which manner should the indoor space be subdivided to support more realistic abstraction of indoor environment and generation of a navigation path while taking account of human perception of the environment and social aspects of human interaction?"

As the proposed topic and the problem defined above is complex, the specific research sub-questions were formulated:

1. *How properties of indoor environment influencing human distribution inside buildings can be applied for derivation of functional areas?*
2. *How rules that people tend to follow during navigation inside buildings and their social interaction can be applied to generate navigable and non-navigable areas within indoor space?*
3. *How to incorporate functional areas in a navigation model and provide more accurate navigation path?*

1.3 Methodology

In order to answer the formulated main research question, research methodology which includes literature/desk research, design of conceptual model, implementation and verification of the model is proposed.

In more detail the following steps are applied (Figure 1.5):

1. **Literature review:** Literature review serves as a basis for the development of theoretical framework for an indoor space subdivision. In this phase indoor space properties, human navigation behaviour and social interaction rules are investigated. Additionally, current methods used to model indoor space for navigation services are explored and their advantages and disadvantages are presented.
2. **Design of conceptual model:**
    - Based on findings of the literature review criteria that can be used to indicate distribution of people within indoor environment and delineate separate functional areas within indoor space are described.
    - Codification method for criteria is presented. Criteria are evaluated and different ranges are set.
    - Additionally, mathematical expressions to obtain metric values for estimation of size of object's functional area are derived.
    - Representation of functional areas as line buffers is implemented using GIS tools.
    - Solutions for occurrence of special cases (overlaps, marginal distances) are determined applying GIS analysis tools.
3. **Implementation:** The developed model for indoor space subdivision is implemented for two buildings: Rotterdam Central Station and Faculty of Architecture and the Built Environment. Two case studies are selected due to their different structure and functionality in order to analyse model's applicability to different type of buildings. Ground floor plans of the buildings are used to implement the proposed model. Rotterdam Central station indoor environment is subdivided for peak and off-peak hours while single subdivision is designed for the Faculty of Architecture and the Built Environment. In the implementation process the following steps are taken:
    - Functional areas of indoor objects are delineated according the proposed expressions using GIS functions in Python programming language.

- Indoor space is partitioned into navigable and non-navigable areas applying GIS tools.
- Navigable space is further subdivided to generate navigation network applying constrained Delaunay triangulation. To achieve the results Python and PostGIS database are used.
- Navigation path is derived adopting A* and path smoothing algorithms in order to illustrate how separate functional areas can be incorporated in the navigation process (PostGIS and Python script).

4. **Verification of the model.** The designed conceptual model is tested analysing people distribution and movement trajectories from photographs and video records. Conclusions are drawn based on the findings of image and video analysis and implementation results.
    - Distribution of distances is analysed after processing images with specific software.
    - Video records are inspected with human eye in order to determine general movement patterns.

1.4 Outline

The rest of the paper is organised as follows. Section two provides an in-depth literature review on human wayfinding process and current indoor navigation models. Section three provides the description of the theoretical model for the determination of functional areas. Section four presents the implementation of the proposed model for two different buildings. Section five explains the validity of the theoretical model. Section six discusses the research findings. Section seven provides conclusions by outlining the main contributions of the research along with the venues for the future research.

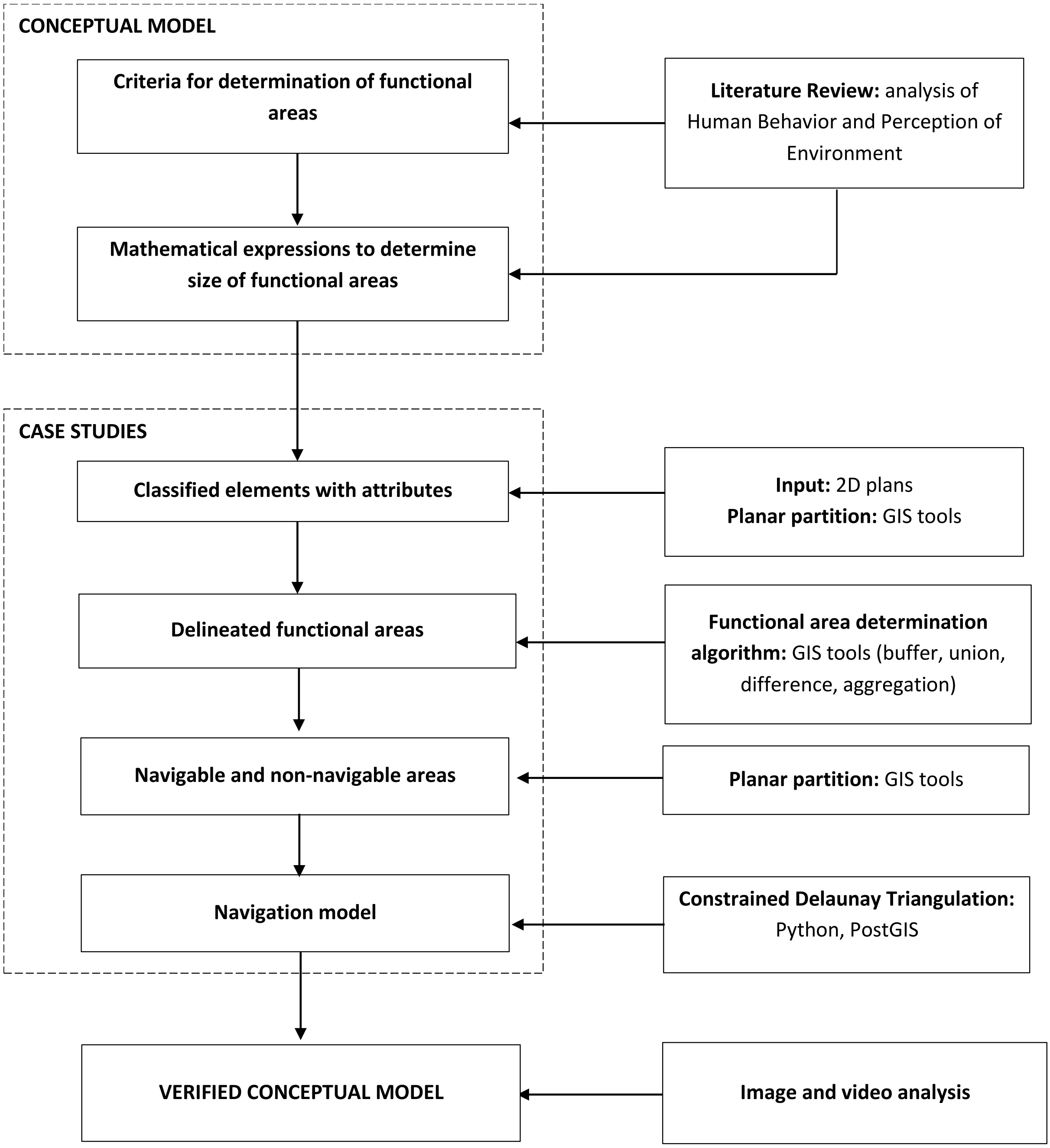


Figure 1.5: Methodology followed in this research.

2. LITERATURE REVIEW

2.1 Human wayfinding

The term *wayfinding* was firstly formally defined by Lynch (1960, p. 3) as *"a consistent use and organization of definite sensory cues from the external environment"*. Later researchers describe wayfinding as a process of determining and following a path between origin and destination that cannot be directly perceived by the traveller. In other studies wayfinding is described as directed and motivated movement which involves interaction between the wayfinder and the environment (Allen, 1999; Golledge, 1999; Raubal and Worboys, 1999). In more specific terms, wayfinding is a process of identifying a current location and knowing how to get to a desired destination quickly and effortlessly (Brunye, Mahoney and Gardony, 2010). Human wayfinding usually takes place in large spaces which cannot be perceived from a single viewpoint and people have to navigate through these spaces to familiarize with them (Kuipers, 2000). The examples of large space can be countryside, cities and buildings. As the wayfinding process is a fundamental human activity it is analysed by researchers from different disciplines: cognitive science, psychology, architecture, urban planning and computer science (Kikiras et al., 2006; Timpf et al., 1992). Wayfinding studies analyse people movement in space and try to explain what is needed to find the way and how people's verbal, visual and other individual and environmental characteristics influence orientation and navigation processes.

2.1.1 Human factors in wayfinding

People use various spatial and cognitive abilities to understand the environment. Allen (1999) investigated that these abilities depend on four interactive resources: spatial perceptual capabilities, information processing capabilities, prior knowledge of the environment and motor capabilities. Spatial perceptual capabilities describe ability of individual to perceive the environment with sensing and cognitive mechanisms while fundamental information processing capabilities define degree to which the individual understands the environment using perceptual capabilities. Timpf et al. (1992) investigated that cognitive abilities strongly depend where the task is performed. Different cognitive abilities will be used in finding a way in a street network and navigating in a building. Therefore, in order to successfully find the way, people have to monitor external and internal cues, and representations of space have to be formed and manipulated (Wiener, Büchner and Hölscher, 2009). It is widely assumed that people navigating in the environment design a *cognitive map* (Downs and Stea, 1973; Golledge, 1999; Kaplan, 1983; Passini, 1992). Spatial orientation is defined as a person's ability to form a *cognitive map*. The term *cognitive map* was firstly introduced by Tolman (1948) defining a mental representation that corresponds to peoples' perceptions of the real world. Cognitive maps provide generalized view of the environment with identification of spatial relationships between places (Kaplan, 1983). Cognitive maps store and recall information about the locations, however cognitive maps and real physical representation of the environment differ. Researchers (Golledge, 1999; Timpf et al., 1992) argue that these differences show what people consider to be the most important features of the environment. People construct their cognitive maps based on a recording of information through perception, natural language and inferences. For instance, cognitive maps of blind people have more indications concerning sound and touch cues compared to sighted people. Moreover, people in wheelchairs emphasize physical barriers in contrast to people without physical disabilities. Therefore cognitive maps might show where people go and what routes they tend to select (Raubal and Worboys, 1999).

2.1.2 Human navigation behaviour and perception of the environment

There is a strong relationship between the configuration of space and the pattern of human aggregated movement in buildings and urban areas. City design principles introduced by Lynch (1960) act as a foundation for human wayfinding research. The research describes wayfinding as a continuous perception of environment through sensory cues; establishes link between an individual's spatial orientation and physical environment. The studies performed by Weisman (1981) and Gärling, Böök and Lindberg (1986) show that the level of complexity of the environment and visual access, degree to which one can see other parts of the building from a given location, influence the navigation of individuals.

A number of different wayfinding strategies were observed and discussed in research community, the results of performed studies show that in general people prefer to minimise mental and physical efforts needed to find their way. Therefore people typically try to find the shortest distance or the shortest time paths. Hölscher et al. (2006) analysed human navigation process and determined three main strategies that people use to find the way. People that use *central point strategy* stick as much as possible to well-known parts of a building such as main corridors or main entrance. People that try to follow routes which first head towards horizontal position of the destination employ *direction strategy*. *Floor strategy* relies on routes that firstly direct towards the floor of the destination despite the horizontal position of the final goal. Much of the existing research suggests that when people are unfamiliar with the environment, they tend to rely on certain navigation strategies to develop their complete understanding of the new environment. However, natural movement in space differs from directed wayfinding process. Henderson (1974) investigated crowd dynamics and suggested that the behaviour of pedestrian crowds is similar to the dynamics of gases or fluids. The observations indicate that footsteps of pedestrians in snow look similar to streamlines of fluids, moreover river-like streams are formed when stationary pedestrian crowds need to be crossed or propagation of waves can be noticed when dense pedestrian crowd move forward. Pedestrians spontaneously organize themselves in lanes if the pedestrian density is high enough. Helbing, Molnar, Farkas and Bolay (2001) indicate that pedestrians avoid changing direction of movement even if the route in walking direction is crowded. Additionally, their research showed that people tend to select the fastest routes to their destination. Natural movement theory implies that people movement in space is mainly governed by spatial configuration. According to Hillier et al. (1993) people move along line of sight. Gibson (1979) in his research proposes that people perceive the environment directly and use *affordances* within it to guide themselves. Walkable surface provides affordance for further walkable surface. Or in other words, people move in a direction where further movement is possible. Peponis, Zimring and Choi (1990) observed that people continue following the same direction if there are no significant changes in the environment. The route decisions are influenced by available view of the environment: when a new view allows seeing more open space or more activity, people change their direction of movement. Additionally, people avoid backtracking. Conroy Dalton (2003) and Hochmair and Frank (2002) described least-angle strategy. The findings suggest that people appear to be attempting to maintain the track of the target direction and try to reduce the total angle turned (keep straight heading). Christenfeld (1995) supports findings of Conroy Dalton (2003) and Hochmair and Frank (2002) and also emphasizes that in order to minimise mental effort and the chance of getting lost, people tend to choose routes with the least number of turns. Furthermore, Bailenson, Shum, and Uttal (2000) noted that people not only prefer routes with longer straight initial segments regardless of the length of the left portions but also select different routes depending on direction of movement. Furthermore, the presence of other people in the same space influences movement of individuals (Hall, 1969; Helbing and Molnar, 1995). A pedestrian normally feels increasingly uncomfortable the closer he/she gets to a strange person who may react in an aggressive way. This results in repulsive effects of other pedestrians. A pedestrian also keeps a certain distance from borders of buildings, walls, streets or other obstacles as a feeling of comfort decreases the closer to the border individual walks since more attention has to be paid to avoid of getting hurt. Hall (1969) proposed a basic classification of distances between individuals (Figure 2.1):

- Intimate distance (0-45 cm): unmistakable involvement with another body (lover or close friend).
- Personal distance (45-120 cm): comfortable separation, interaction with friends.
- Social distance (120-360 cm): reduced involvement, interaction with non-friends.
- Public distance (>360 cm): outside circle of meaningful involvement, public speaking.

Hall (1969) underlines that these distances were deduced from observations of American and European subjects. Specific distance between individuals varies depending on a cultural background, gender, age, familiarity, relationship, pose and other individual factors. Personal spaces might overlap or almost disappear in certain environments such as a crowded subway car or elevator (Sommer, 1969). Furthermore, personal distance is smaller as the pedestrian hurries. Resting individuals (waiting on a railway platform for a train, sitting in a dining hall or lying at a beach) are uniformly distributed over the available area if there are no acquaintances among the individuals but personal distance decreases with growing density of individuals (Helbing and Molnar, 1995). However, generally individuals choose to navigate around rather than violate other's personal space weather they are acting in groups or as individuals.

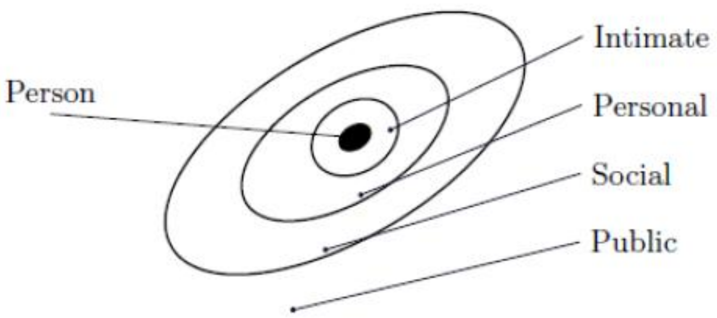


Figure 2.1: Classification of Hall's distances (Hall, 1969).

Research performed by Nakauchi and Simmons (2002) analysed how people stand in line. They estimated personal space of people standing in line and outcome of the study indicates that personal space ranges between 40-80 cm. Furthermore, it was observed that personal space is roughly oval and larger towards the front of individual (Figure 2.2).

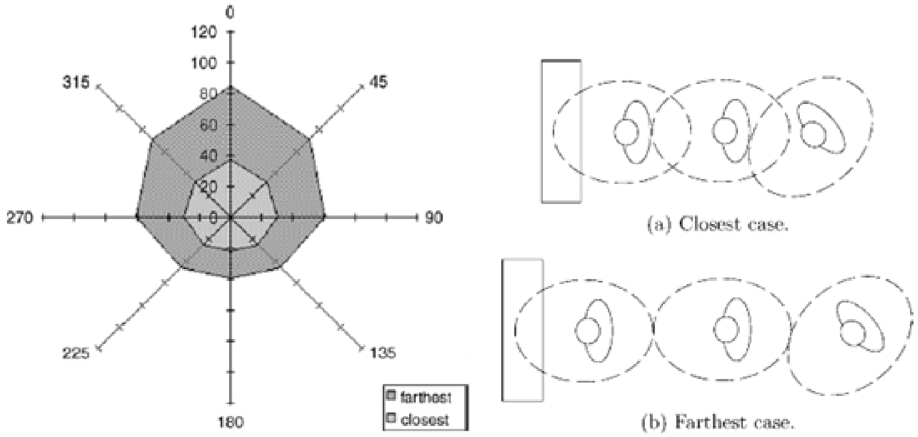


Figure 2.2: Actual size of personal space when people stand in line (Nakauchi and Simmons, 2002).

In addition people navigation is influenced by characteristics of the environment. People tend form groups at locations that provide people reason to go and stay there and at places that look welcoming and are accessible (Carmona, Tiesdell, Heath and Oc, 2003). People might be attracted not only by other individuals (friends, street artist, etc.) but also by objects (e.g. window displays) and this property can influence navigation decisions of individuals within the environment (Emo, Hölscher, Wiener and Dalton, 2012; Furtado, Fileto and Renso, 2013, Peponis et al., 1990). Attractiveness of an object explains how much something is able to attract the attention and influence the decisions of individuals, however the interest is declining over time and the attractiveness is decreasing (Helbing and Molnar, 1995; Uchino, Furihata, Tanaka and Takahashi, 2005). In a field of spatial urban dynamics the attractiveness of a place is measured using various criteria such as popularity, size of the place, distances to other places or dynamic factors, e.g., restaurants are more attractive at dinner time (Giannotti, Nanni, Pinelli and Pedreschi, 2007; Huang, Li and Yue, 2010). Frankenstein, Büchner, Tenbrink and Hölscher (2010) analyse how attractiveness of objects affects path choices inside of buildings. Their observations support findings of Furtado et al. (2013) and suggest that people tend to choose routes that have welcoming structure (rooms with artworks, glass doors) and are close to the central locations of the building.

Space syntax theory introduced by Hillier and Hanson (1984) is widely used to analyse the interaction between space and individuals. Researchers (Jiang, Claramunt and Batty, 1999; Kim, Jun, Cho and Kim, 2008; Worboys, 2011) suggest that space syntax can be used as an alternative criterion for indoor space modelling in order to analyse general patterns of movement and flow inside a building. Space syntax theory uses topological structure of the environment to examine its social use (Haq and Zimring, 2003; Peponis et al., 1990). For instance, outcomes Haq and Zimring (2003) study indicate that people tend to stay at locations that provide wide overview of a rest of the environment. The results of other studies show that space syntax analysis may be a powerful way not only to represent the spatial structure of a building but also and its likely impact on navigation. Research of Hillier and Iida (2005) suggests that locations that are closer to all other locations are visited more often than those that are more remote. Thus due to space configuration, centrally located points are attractive and act as destinations more often that the less accessible ones. Therefore researchers introduced centrality measures such as betweenness and closeness in order to simulate human movement patterns (Hillier and Iida, 2005; Kazerani and Winter, 2009).

2.2 Current indoor navigation approaches

Representation of indoor environment of buildings must provide reliable data structure for indoor analysis and indoor queries related to determination of navigable and non-navigable areas. Khan and Kolbe (2013) determined the main requirement for indoor space structuring which indicates that model of the building for the indoor navigation must provide semantic, geometric and topological information. Brown, Nagel, Zlatanova and Kolbe (2012) present a detailed list of topographic space requirements for indoor navigation where importance of semantic information is also emphasized. In addition, partition of indoor space into smaller spaces (functional areas) is identified as one of the main requirements.

2.2.2 Indoor models for navigation

Successful accomplishment of navigation task involves: indoor localization of the start point and destination, route computation and guidance of the user (Worboys, 2011). Although substantial research has been carried out concerning positioning methods for indoor navigation, the research focused on identifying and organizing indoor spatial information to derive navigation paths is still fragmented (Zlatanova, Liu and Sithole, 2013). From the perspective of the semantic identification of space part of the navigation approaches use semantics only to identify the connectivity and accessibility between indoor elements while other approaches heavily concentrate on the use of semantics in order to provide flexible navigation and knowledge about indoor space (support of context-aware services) (Zlatanova, Liu and Sithole, 2013).

An abstraction method presented by Becker et al. (2009a) supports different context of indoor environment. Becker et al. (2009a) propose a framework for semantic space subdivision which allows integration of conceptually separated indoor space models within a multilayered representation. These layers represent separate decompositions of indoor space such as topography or even sensor coverage area which is independent from a building structure (for example, Wi-Fi signal, RFID tag system), and subdivision of space with respect to thematic criteria (accessibility, security zones, evacuation area). Using Dual graph these layers are linked and the spatial analysis for different navigation cases can be performed (Figure 2.3).

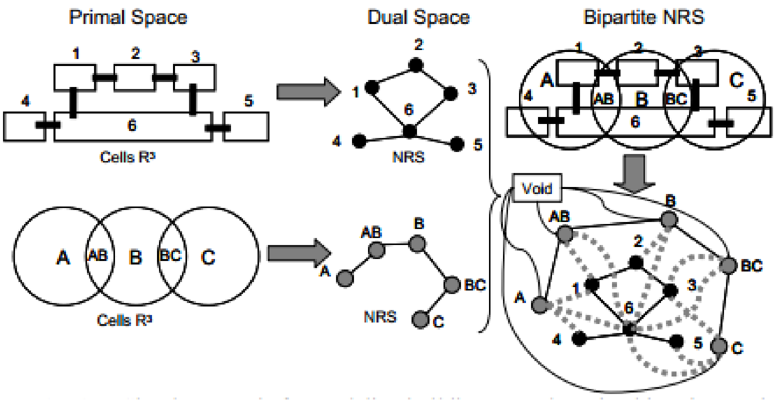


Figure 2.3: Multilayered representation of space (Becker et al., 2009a).

Each layer represents specific properties of space but in general all layers cover the same indoor space. Therefore, more detail decomposition of indoor space is required for more precise indoor route planning. Becker et al. (2009b) continued their work and suggested further topographic space subdivision into subspaces to support multiple contexts of navigation. Layers of subspaces reflect only a context specific partition of the main topographic layer, for instance, derivation of navigable space for a wheel chair. Depending on navigation use case specific layers of subspaces are selected (Figure 2.4). Such smaller partitions of topographic space may provide means for more precise route planning.

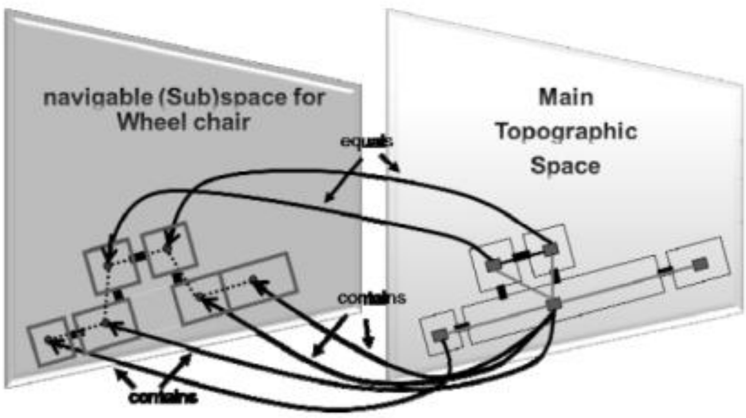


Figure 2.4: Topographic subspacing (Becker et al., 2009).

As it was mentioned before Lorenz et al. (2006) proposed hierarchical graph structure. Different levels of abstraction are introduced meaning that a floor of the building might be represented as a graph at a certain level and at the same time this floor graph is just a node in a graph of a higher level – the whole building. Cell decomposition is performed depending on several criteria: size and concavity of a room and according to basic functional properties. Furthermore, different functional areas within a single room are represented in the graph. Hu and Lee (2004) presented semantic location model which represents environment two types of hierarchies: location hierarchy and exit hierarchy. Additionally, the model also provides geometric information of the building. Richter, Winter and Ruetschi (2009) have also presented hierarchical representation of indoor space. In their research structural, functional and organisational aspects of indoor environment were taken into account. Structural aspects represent how space is organised and define accessibility between different areas such as different floors in a building or gate areas in an airport. Functional dimension defines different functions of the structural elements such as offices, ticket counters, check-in counters or duty free shops at airports while organisational aspects indicate different organisational units such as research groups, departments or different airlines. Functional and organisational hierarchization depends on user groups. Room might have different functional and organisational roles for different users. The elements of space are linked to each other according to their connectivity. Additionally weights are assigned to these links and impedance parameter is introduced. Passable doors and openings have impedance value of zero while locked doors have infinite impedance. The weight of the link depends on a user role and perspective (spatial, functional or organisational). For example, stairs have infinite impedance for people sitting in wheelchairs. Moreover going upstairs might have different impedance than going downstairs considering older age users. Such indoor space modelling exploits structural, functional and organisational dimensions and enables personalisation of indoor environment. Since the navigation highly depends on a user physical abilities and how the space is experienced by individual, Kikiras et al. (2006) developed user centred indoor navigation system OntoNav which uses ontologies. This ontology contains user classes and elements of the context. OntoNav provides navigation paths and guidelines which are generated according to users' physical and perceptual capabilities as well as their particular routing preferences. Navigation oriented user profile is based on general user demographic information such as age and gender and physical capabilities which refer to capabilities to walk, to see and to hear. Additionally perceptual capabilities which describe how easily individual can be guided within an unknown environment are also considered in the development of user profile. Moreover user navigational preferences such as the fastest or the simplest path are also taken into account. Navigation model developed by Khan and Kolbe (2012) represents navigable and non-navigable areas in 3D environment. In this research user's requirements, semantic, topologic and geometric constraints for different locomotion modes are identified (Figure 2.5 and Figure 2.6). In their research three locomotion types are considered: walking person, driving mode – movement of a person in a wheelchair and flying mode which refers to Unmanned Aerial Vehicle (UAV). Furthermore navigable areas (subspaces) are determined for normal and emergency cases. Physical constraints such as height, width, length, volume or maximum speed are classified for different locomotion types. These constraints are essential for determining navigable and non-navigable environment for certain locomotion mode. However, the main limitation of the framework is that it does not support high level of subdivision – the smallest unit is a room or a corridor. Therefore, more accurate localization within the room is not enabled.

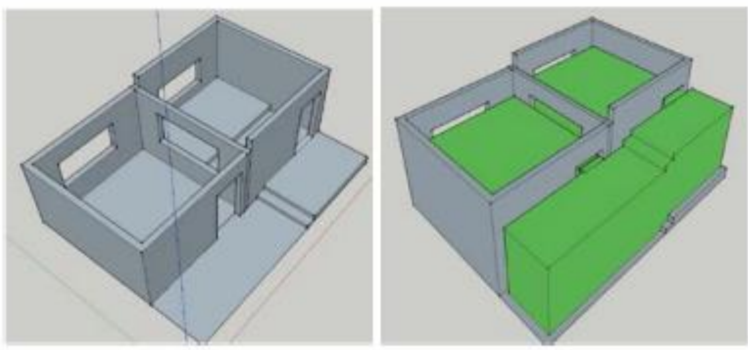


Figure 2.5: Left: Two rooms connected through an open window and a corridor. Corridor and right room consists of a step in each. Right: Navigable 3D space (in green) for a walking person (Khan and Kolbe, 2013).

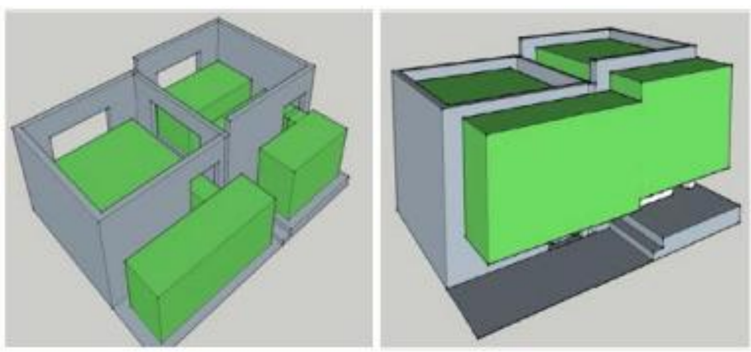


Figure 2.6: Left: Navigable 3D space (in green) for a wheelchair. Right: Navigable 3D space (in green) for UAV (Khan and Kolbe, 2013).

2.2.3 Navigation models

In order to support routing algorithms, building models are simplified and usually approximated with regular or irregular tessellations or networks (Liu and Zlatanova, 2011).

Well known regular subdivision of space is a grid model (Figure 2.7). The environment is partitioned into a finite number of non-overlapping areas and various types of information are assigned to the cells (Afyouni et al., 2012). The main advantage of grid approaches is that they support different geometry-based queries as well as cell-level interactions. However, the performance depends on the size of the model and size of the grid cell. If the grid is too course important information might be lost while overly fine grid might disproportionally increase processing time and consume excessive amounts of memory although it provides precise movement in space (Franz, Mallot and Wiener, 2005).

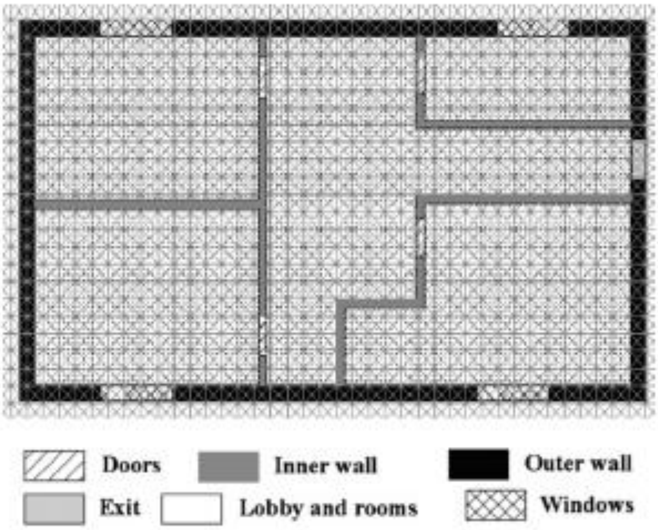


Figure 2.7: Grid model (Li, Claramunt and Ray, 2010)

Generation of Voronoi diagrams or triangulation of space are common methods to subdivide indoor environment into irregular tessellations (Afyouni et al., 2012) (Figure 2.8). In such cases the navigation is performed by finding the intermediate cells that form a route to destination. This partition is often referred to as a navigation mesh and in this tessellation usually only navigable space is partitioned and obstacles are omitted. Compared to regular tessellation irregular partitions provide smoother representation of the environment as small narrow navigable areas can be mapped. Navigation meshes are an ideal solution to simulate movement of agents with different size constraints (Curtis, Snape and Manocha, 2012). However, such space representation is not suitable for guidance and navigation of a user of the navigation system since highly accurate localization is not supported. Irregular tessellations are commonly used in game industry to navigate agents as the agent does not have to follow strict guidelines and can freely move in space.

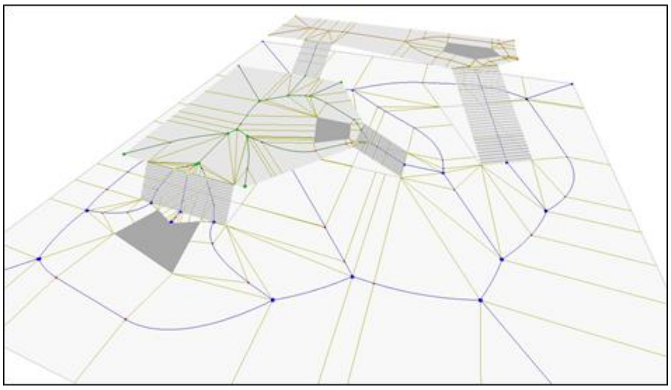


Figure 2.8: Navigation meshes (van Toll, Cook and Geraerts, 2011).

Network navigation models are the most common navigation model used for human navigation. Nodes in the network indicate landmarks or decision points and edges between them stand for the connections. Moving from one node to the other is allowed only when there is an edge between them. Usually cost of edges indicates distance or travel time between nodes. Moreover nodes can contain semantic information about the location (name, type, description, etc.). The following methods are usually used to derive navigation networks: triangulation, visibility graphs, medial axis transformation (Liu and Zlatanova, 2011).

Constrained Delaunay triangulation (CDT) is one of the most common approaches used to design navigation network (Figure 2.9). Triangles are one of the simplest features for computers to processes, therefore fast computations and easy maintenance are ensured. Additionally, CDT enforces obstacle constraints as specific segments are included in the triangulation process. Another advantage of CDT is that it allows determination of several constraints in order to derive the most suitable triangulation for generation of navigation network (Borovikov, 2011). Such constraints might be maximum area of triangle, minimum angle within triangle or maximum number of Steiner points that can be inserted. CDT is suitable for large open spaces as it can provide different movement options. Vertices of triangles, centroids of triangles or centres of triangle edges can be used as nodes in the navigation network. However, navigation network generated using triangulation typically lack for accuracy of location information and might provide navigation path with unrealistic turns (Afyouni et al., 2012).

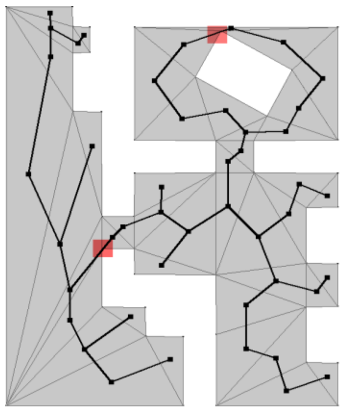


Figure 2.9: CDT and navigation network (Borovikov, 2011).

Another common approach for derivation of navigation network is visibility graph. Stoffel, Lorenz and Ohlbach (2007) developed navigation model where the indoor space is partitioned into convex polygons according to the visibility criterion (Figure 2.10).

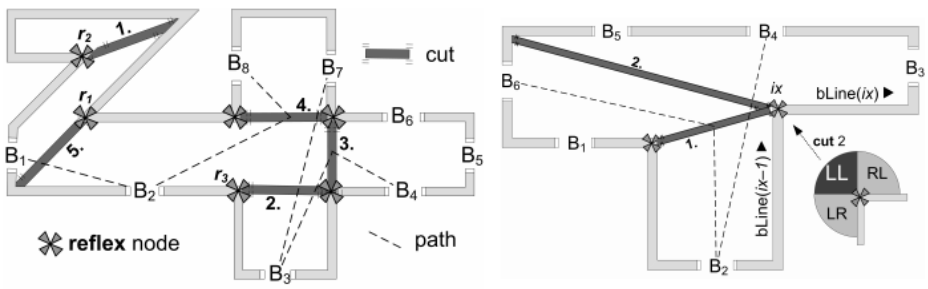
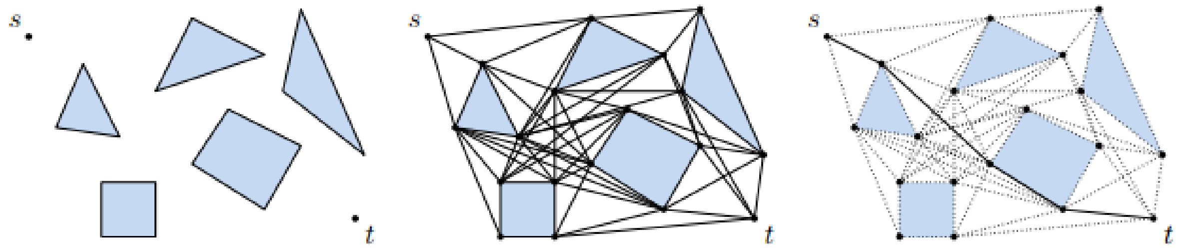


Figure 2.10: Space partition according to visibility (Stoffel et al., 2007).

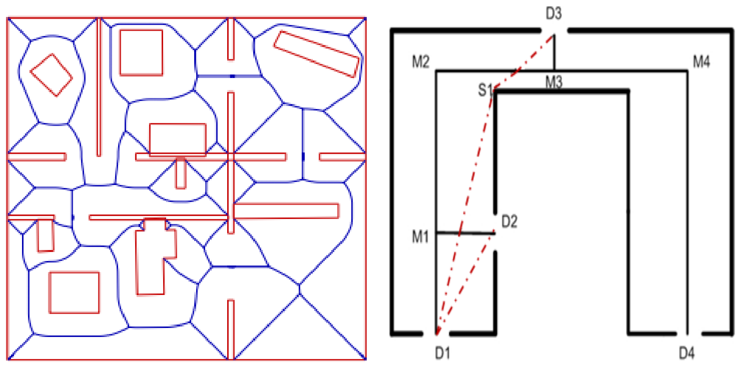
The visibility graph is composed of the start, target points and the vertices of polygonal obstacles. Its edges are the edges of obstacles and edges joining all pairs of vertices that are visible from each other. Thus, the visibility graph provides the shortest paths in most of the cases (Figure 2.11). The visibility graph is intended to represent more realistic navigation paths as it does not only follow the structure of the building but also provides paths towards the point of interest (Liu and Zlatanova, 2011; Stoffel et al., 2007). However, the path provided by the visibility graph is optimal in terms of length but because it also connects corners of objects within indoor environment, the derived navigation path may suggest for the user of the navigation system to move too close to the walls or corners of objects within indoor space. What is more, in environments that contain many obstacles complex visibility graphs are constructed with a large number of nodes and edges. Therefore the storage of visibility may require great amounts of space and calculations of navigation path might become time consuming.



a) b) c)

Figure 2.11: a) A set of polygonal objects; b) the associated visibility graph; c) the navigation path (Mount, 2013).

Another common approach to derive navigation networks is usage of Medial Axis Transformation (MAT) algorithm. Essentially MAT is a thinning algorithm which provides the skeleton of the polygon (Figure 2.12). MAT provides sufficient navigation path for regular buildings with long polygons but is not very appropriate for buildings with large open spaces as the generated network might suggest navigation paths that are unrealistic and usually are not taken by people (Kallmann and Kapadia, 2014).



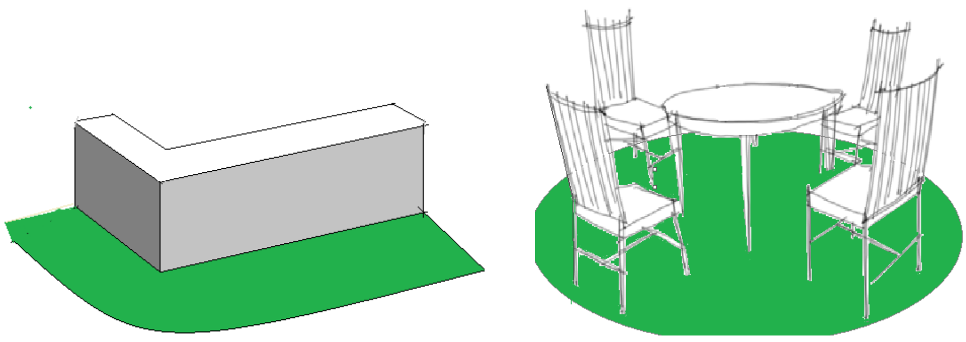
a) b)

Figure 2.12: a) Navigation network derived using MAT (Kallmann and Kapadia, 2014); b) comparison of networks built applying MAT (black line) and visibility graph (dashed red line) (Liu and Zlatanova, 2011).

The findings of the literature review suggest that the wayfinding process and human movement in space are investigated in depth while structuring of indoor environment that incorporates human behaviour in order to support a more realistic abstraction of the environment and provide more realistic navigation paths are not prevalent topic in the literature. Literature review suggests that human behavioural factors, including personal space preferences and interactions with others, can help to improve indoor navigation systems.

3. CONCEPTUAL MODEL

With the underlying theoretical concepts investigated in the previous section, this section will introduce and describe a conceptual framework to identify functional areas around spatial elements based on human perception of the environment and human behaviour inside buildings. As it was mentioned before, in this research functional areas are spaces where people are served by a spatial element or are waiting for services provided by the spatial unit. Therefore functional areas of objects appear in directions where services are provided. For instance, information desks are usually accessible from one or two sides while some tables such as coffee tables might be accessed from all their sides (Figure 3.1). Moreover, certain objects might attract a larger number of people compared to others. For instance, queue of people may appear near the before mentioned information desk while coffee table is usually seated by a certain number of people. In this research functional areas are used to determine navigable space within indoor environment as these generated functional areas act as non-navigable areas and should be avoided while planning navigation paths. However, the obtained functional can become navigable when they are start or target point of a user of the navigation system.



a) **b)**

Figure 3.1: a) Information desk with functional area (green); b) Coffee table with functional area (green).

3.1 Criteria for subdivision

In this study the main requirement for the indoor structure is that representation of indoor environment has to provide users with realistic organisation of the environment, introduce location descriptions and enable generation of more realistic navigation path. As noted by literature review for the realistic spatial abstraction of indoor environment not only the physical structure of the interior but also presence of people inside building should be taken into account (Peponis et al, 1990; Emo et al., 2012; Michalowski, Sabanovic and Simmons, 2006). Typically the arrangement of indoor environment differs with respect to the type of a building (airport, university, museum, station, exhibition pavilion, etc.) and number of people entering the building. However, all indoor elements have some common attributes regardless of their direct functions, for instance, spatial element can be found as attractive or not, moreover it might be highly important or not for people inside the building. For this reason, properties that spatial elements have in common are selected as criteria for determination of functional areas of objects within indoor space. Additionally, private space criterion which describes human behaviour is also chosen to structure indoor environment for localization, navigation and orientation purposes. Thus, the conceptual model for indoor space subdivision is provided in Figure 3.2. The model suggests that the functional area of a spatial element depends on characteristics of the spatial element and external factor. Furthermore, it should be noted that the smallest identifiable spatial element differs with respect to the use case of the navigation system and should be selected by the navigation system developer based on user requirements.

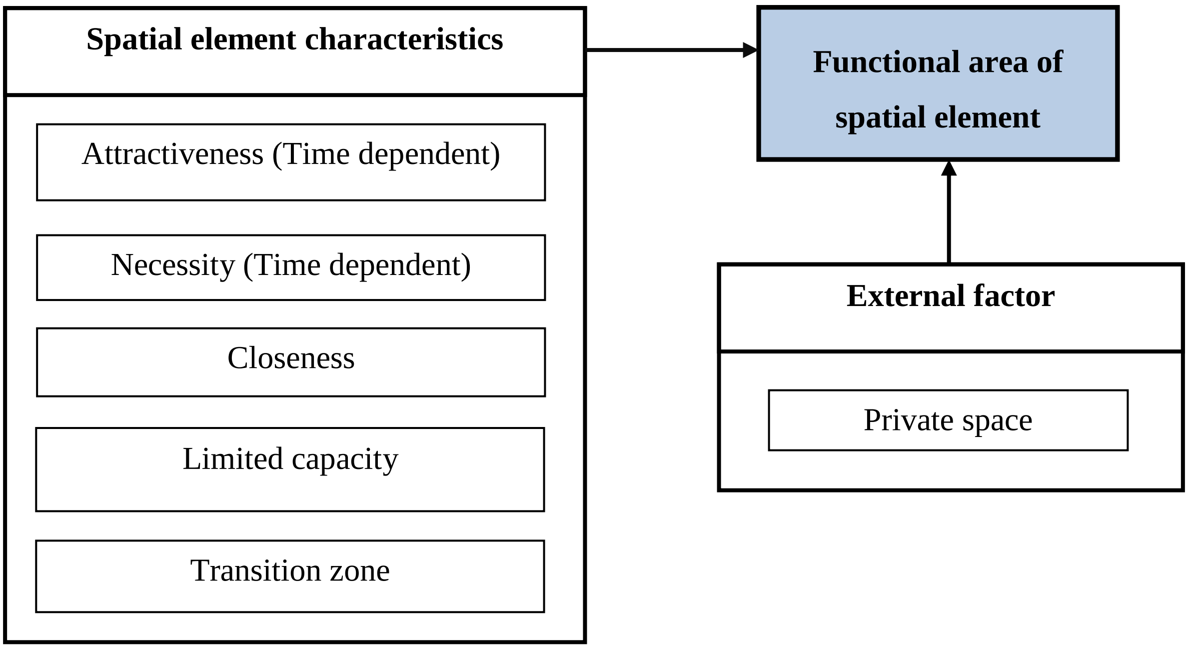


Figure 3.2: Conceptual model for the determination of functional areas.

3.1.1 Attractiveness

As it was discussed in the literature review attractiveness of an object is highly important property that influences distribution of people inside buildings (Carmona et al., 2003; Helbing et al., 2001). Attractiveness can be defined as a power of services to attract people (Uchino et al., 2005). Attractiveness is responsible for the formation of groups of people since density of individuals increases around particularly attractive places (Helbing and Molnar, 1995). Additionally, as noted by Frankenstein et al. (2010) objects are either attractive or not, and people are inclined to stay at places that offer inviting structure or act as an attractive landmark. For instance, coffee corners are found to be attractive features of the office environment while workplaces or printing corners are not that attractive and usually people are not gathering around these places. In this research description of the attractiveness of an object is adopted from research of Frankenstein et al. (2010) where attractiveness of the object is measured based on how inviting is the structure of the object and based on its ability to act as a landmark in a certain environment. The attractiveness criterion is codified as a trichotomous variable, meaning it can take three values: 1 indicates elements with low attractiveness, 2 describes moderately attractive objects and 3 indicates highly attractive elements within the environment indicating that they are visited by a larger number of people. The codification with three possible values (1 = low, 2 = medium, 3 = high) is used in order to introduce balance scaled (symmetric and equidistant) which prevents from possible bias in the results. In addition, three values are selected in order to provide a general overview of the attractiveness of elements in the environment and avoid introduction of high level personalization which might occur applying more detailed scale (e.g. scale of five values: highly unattractive, unattractive, neither attractive nor unattractive, attractive, highly attractive.

3.1.2 Necessity

Necessity of a spatial element is one of the criteria which are introduced in this research to determine functional areas of objects. The necessity of a spatial element describes how essential is the object in the specific environment; it determines if it is important that certain object would be placed in the environment. In case the essential object of indoor environment is missing, the functionality of the environment is partly disturbed. For instance, information screens in stations are considered to be essential and highly attractive objects of the environment which provide the latest information and in case they are missing, the indoor environment might become chaotic. However, part of spatial objects can be considered to be necessary but not attractive. For instance, in contrast to abovementioned information screens, information stands in train stations which also represent travel information are recognised as essential features of the environment but they are not that attractive, therefore they are visited by a smaller number of people. In this research introduced the necessity criterion is codified as a binary parameter in order to avoid ambiguity and provide clear description of objects. As a result taking into consideration type of the environment spatial element is described either as essential or as unessential object. Thus 0 specifies objects that are unessential and 1 indicates essential objects within the environment.

3.1.3 Closeness to central locations

Findings of the literature review suggest that people incline to gather in central or near central locations in space in order to minimise physical efforts while navigating: individuals pause at spots from where the least efforts are required to continue their trip (Helbing et al., 2001; Hillier and Iida, 2005; Peponis et al., 1990). For instance, in large train or metro stations with long platforms it can be observed that more people are waiting for the train or metro in areas around entrances that are closer to the central halls of stations. In addition, exhibits in museum that are located further away from entrances or are not clearly visible (e.g. they are placed in niches) attract less people. Furthermore, restaurants, cafeterias or shops in airports which are far away from gates and main waiting areas attract fewer customers. Thus, if the object is positioned far away from the entrance, central point or highly important point in space it is considered to be filled with lower number of people. As a result object's closeness to central locations of the environment is selected as another important property of objects that influences people distribution within space and can be used to identify occupancy of spatial element and its functional area. In this research closeness centrality is adopted from Sevtsuk and Mekonnen (2012) where using network analysis method closeness of an input features is defined as the inverse of cumulative distance required to reach from specific node to all other nodes that fall within the search radius along the shortest paths. In other words it can be said that closeness of an object describes how far the object is from its surrounding neighbours. Therefore, closeness is estimated as:

$$Closenesss^{r}\,[i] = \frac{1}{\sum_{j\in G-\{i\},d[i,j]\leq r}(\mathrm{d[i,j]})}$$

where $Closenesss^{r}\,[i]$ is the closeness of node within the search radius r, $d[i, j]$ is the shortest path distance between nodes i and j.

The proposed network analysis method takes into consideration both topology and geometry of the network. In order to calculate object closeness to all other features, at first adjacency matrix is computed between all input objects in the graph. The calculated adjacency matrix represents neighbour relationships and distances between object and its closest neighbours. Afterwards the centrality computation is performed and eventually, according to the results of centrality, the closeness values are estimated. Closeness values range from 0 to 1, where 0 corresponds to further away located objects and closeness value equal to 1 describes objects that are located close to the central spot in space and can be reached more easily than others (Sevtsuk and Mekonnen, 2012).

3.1.4 Limited capacity

Part of spatial elements can contain a limited number of people. For instance, workstation designed for one person is typically not occupied by other individuals (Figure 3.3). Also, such objects as benches can be seated on by a limited number of people and when all seats are taken, people try to find other places to stay. Therefore limited capacity of spatial object is another characteristic that influences functional areas of objects. It is considered that spatial elements which may be occupied by a limited number of people cannot expand or shrink, and other individuals bypass these objects at a certain distance. Consequently in this study introduced limited capacity criterion describes if spatial element has limited capacity or does not and is codified using Boolean expression: “yes” indicates that object has limited capacity and “no” identifies that object’s capacity is not limited.

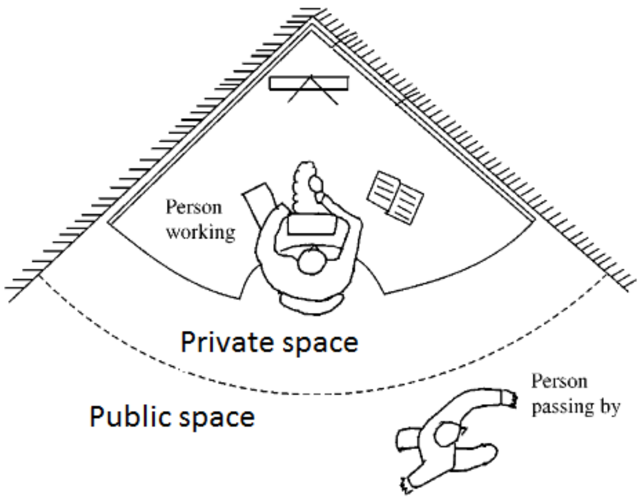


Figure 3.3: Functional area of object with limited capacity (adapted from Junestrand, Keijer and Tollmar, 2001).

3.1.5 Transition zone

Transition zone is another characteristic of spatial element which is introduced in this research and is considered to have effect on object’s functional area. Part of the spatial elements provides their services remotely. For example, in order to see painting or information screen people stand at a certain distance from these objects (Figure 3.4). Thus an area between such type of object and people observing it is called the transition zone. The transition zone is recognised as part of the functional area of object since it is usually not entered by other people. The transition zone is codified using numerical values which are assigned depending on a size of the object containing transition zone and space available in the environment.

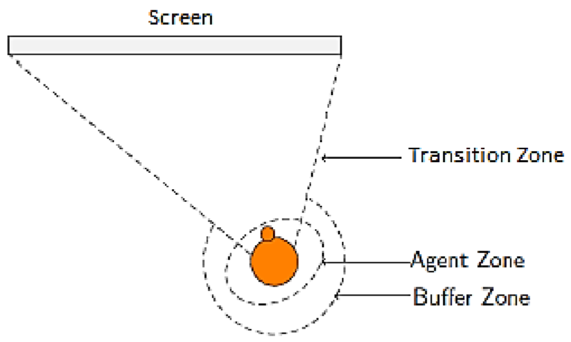


Figure 3.4: Spatial element and its transition zone (Lindner and Eschenbach, 2011).

3.1.6 Private space

As discussed in the literature review human navigation is influenced by other individuals (Helbing and Molnar, 1995). The private sphere of every individual, which can be interpreted as territorial effect, plays an essential role. When this private sphere is entered by a stranger, individual feels uncomfortable. As well the stranger avoids entering somebody’s private sphere for the same reason. Hence based on the previous research (Hall, 1969; Nakauchi and Simmons, 2002; Sommer, 1969) it can be concluded that private space concept influences functional areas of objects as groups of people or individual persons are bypassed in order not to enter their personal spaces. The perception of personal space differs with respect to the type of a building and amount of space available in the room. For instance, in crowded railway stations people keep smaller distances between each other compared to the formal office environment. Distances between people can be interpreted as buffers that determine safety and are identified as non-navigable areas. The definition of private space is adopted from the previous research of Hall (1969) and Sommer (1969), thus the private space criterion is measured with regards to the type of the building and is codified using numerical values.

3.1.7 Changes of functional areas over time

Distribution of people within indoor environment is not constant and changes over time. The structure of indoor environment might differ with respect to a day time or occurring events.

Therefore sizes of functional areas also change. For instance, shops, cafeterias or restaurants at airport are usually closed at night thus people are not going to stay at these places. Moreover, during lunch or dinner time attractiveness of restaurants and cafeterias increases, as a result the functional areas of the restaurants and cafeterias might expand. Additionally, information screens or information desks at public transportation stations become more important and attractive during rush hours compared to off-peak hour, therefore a larger amount of people might be observed close to these objects. Thus the attractiveness and necessity of objects changes over time. As a result, in this research it is suggested to derive average functional areas of objects within indoor environment and later adjust the attractiveness and necessity parameters of objects in order to derive finite number of partitions of space with respect to different periods of time such as peak and off-peak hour, lunch or dinner time and other occurring events.

3.2 Delineation of Functional Areas

3.2.1 Representation of functional areas

In order to delineate functional areas, indoor environment has to be organised in such way that planar partition would be constructed. Applying principles of planar partition space is represented with non-overlapping polygons, also there are no gaps between the polygons. Planar partition is necessary to represent correct topology and geometry of indoor space and to ensure that no ambiguity is introduced. In addition to space representation with polygons, line feature is introduced in order to represent service directions of indoor objects. Lines indicate in which directions objects functional area appears. The functional areas are calculated as one side line buffers with flat cap using GIS tools (Figure 3.5). Flat cap of the buffer indicates that the buffer ends at the endpoint of the input line feature. Such representation of functional area allows avoiding overlap with other indoor features and determines the area where services are provided more accurately.

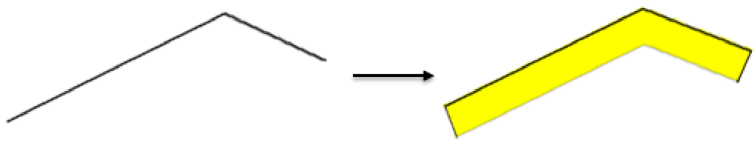


Figure 3.5: One side line buffer with flat cap.

As it was mention in the beginning of this chapter the functional areas depend on the type of object. Part of the objects such as ATMs or paintings provide their services in one direction, others such as reception desks can be accessed from two sides while other such as desks might be occupied from all sides (Figure 3.6). Size of the buffer is calculated using the expression described in the following subsection.

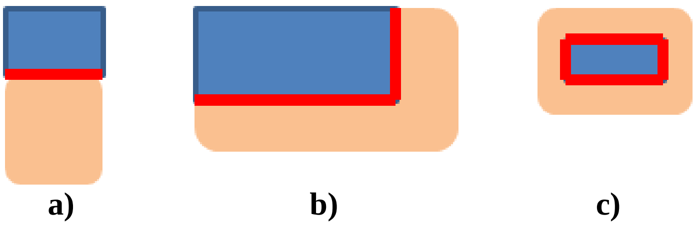


Figure 3.6: Functional areas (sand colour) of different type of objects (blue): a) functional area of ATM at service direction; b) functional area of reception desk at service directions; c) functional area of table at service directions.

3.2.2 Determining size of functional areas

Size of the buffer indicating functional areas depends on the values of criteria introduced in 3.1 subsection. Table 3.1 provides a summary of the proposed criteria and their value ranges. The buffer of the line representing service direction is calculated as weighted human body projection on a horizontal plane and indication of private space. The human body projection on a horizontal plane determines the average space required for a person to avoid physical contact and disturbance of others in a certain indoor environment. In this study, the required diameter of space for the individual is adopted from the observations of Neufert, E., and Neufert, P. (2012) which is equal to 0.6 meters (Figure 3.7). Neufert, E., and Neufert, P. (2012) has performed very detailed analysis on identification of minimal space requirements for individuals and groups in order to support human static positions and movement in space.

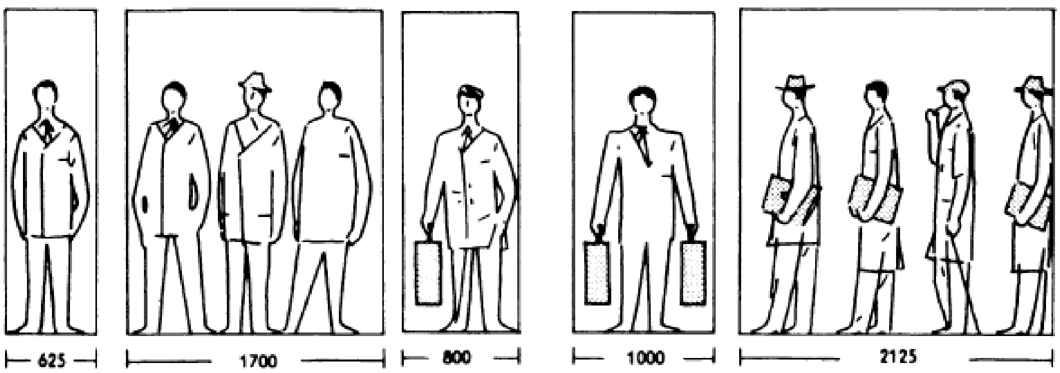


Figure 3.7: Space requirements (in millimetres) for a person, group of people, person with one and two suitcases and a queue of people (Neufert, E., and Neufert, P. , 2012).

Weight indicates sum of characteristics of spatial elements: *attractiveness*, *necessity* and *closeness*. The higher the values of attractiveness the large number of people gathered around the object is expected, hence the larger buffer is estimated (Figure 3.8). Additionally, the attractiveness and necessity values are time dependent, thus they can be adjusted with respect to occurring events or other temporal aspects.

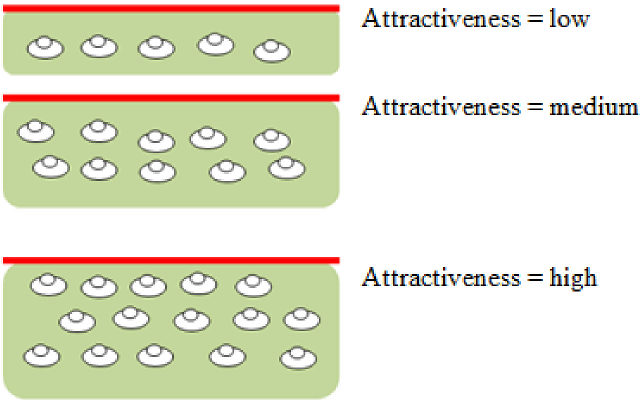


Figure 3.8: Size of functional area with different values of attractiveness.

The proposed personal space concept is used to indicate territoriality of a group of people gathered around specific object. The model suggest that the personal space concept is applied to a group of people and not to every individual separately since personal spaces disappear in groups and crowds (Sommer, 1969).

The proposed conceptual model for indoor space subdivision points out three different computational methods for determination of functional areas of indoor objects. In the following paragraphs the proposed computational methods are explained by giving examples of certain objects with likely values for the criteria. The determined subspaces become non-navigable except in cases they are start or target location of the individual.

Case 1. If only *attractiveness*, *necessity* and *closeness* parameters are applicable to an object, the distance from the physical border of the object to the border of the functional area is determined by weighted human body projection on a horizontal plane and private space:

CASE WHEN limited capacity = 'no' AND transition zone = 'no'

THEN functional area = human projection × ((attractiveness × time) + (necessity × time) + closeness) + private space

END

For instance, ATMs in stations are objects that do not possess transition zone and do not have limited capacity, therefore their functional areas are determined by their level of attractiveness (medium = 2), necessity (non-essential = 0) and their closeness to central locations (0.5). In order to indicate the private space concept the social distance of 1.2 meters suggested by Hall (1969) might be applied. Thus the functional area of ATM is estimated as:

Functional area = $0.6 \times (2 + 0 + 0.5) + 1.2 = 2.7$ meters.

Case 2. If the *transition zone* parameter is applicable to an object, the functional area of the spatial element is calculated by the transition distance, weighted human body projection on a horizontal plane and private space concept:

CASE WHEN
limited capacity = 'no' AND transition zone = 'yes'
THEN
functional area = transition distance + human projection × ((attractiveness × time) + (necessity × time) + closeness) + private space
END

Information screens placed in stations are examples of objects that possess transition zones, as a result their functional areas are determined by transition distance (1.5 meter), attractiveness (high = 3), necessity (essential = 1), closeness to central locations (0.5) and private space (1,2 meters). Thus, the functional area of information screen is estimated as:

Functional area = $1.5 + 0.6 \times (3 + 1 + 0.5) + 1.2 = 5.4$ meters.

Case 3. If the *limited capacity* parameter is valid for a spatial unit, the functional area of the object is constant and does not expand or shrink. It is considered that people bypass objects with limited capacity at approximately constant distance or more specifically, at such distance that personal space of individuals who occupy the object would not be violated. Thus, the functional area is calculated applying the following expression:

CASE WHEN
limited capacity = 'yes'
THEN
functional area = 'private space'
END

As it was mentioned in previous sections coffee tables are considered as objects with limited capacity, therefore their functional areas are determined by private space concept (1.2 meters). Thus, the functional area of information screen is estimated as:

Functional area = 1.2 meters.

Table 3.1: Criteria and value ranges.

Criterion	Measurement	Value range
Attractiveness	How inviting is the structure of the object?	1 – non-attractive 2 – moderately attractive 3 – highly attractive
Necessity	Is it necessary to have this object in this environment? Is it an important/essential feature of the environment?	0 – non-essential object 1 – essential object
Closeness to central locations	How close object is to all other surrounding objects?	[0-1] 0 – object is far away from other locations 1 – object is close to other locations
Limited capacity	Does the object have limited number of seats?	Yes – object has limited capacity No – object does not have limited capacity
Transition zone	Does the object provide services in a distance?	Numerical variable based on structure of the environment
Private space	What is the minimum distance that people keep in order not to violate others personal space in this environment?	Numerical variable based on type of the building (Hall's personal, social distances)

3.2.3 Special cases

In order to enable navigation system to provide accurate localization, navigation and guidance services, planar partition in order to represent the indoor environment is required. Structuring indoor environment into non-overlapping areas allows avoiding ambiguity and providing accurate localization descriptions. Therefore, in cases where estimated functional areas overlap a set of rules is applied in order to remove the overlap and ensure the planar partition of the environment.

Case 1. If the overlapping functional areas have the same name, they are merged together. For example, if two functional areas representing Starbucks cafe overlap, these functional areas are united since the location description does not change (Figure 3.9):

CASE WHEN

functional area(*i*) overlaps (functional area(*i+1*)) AND

functional area(*i*).name = functional area(*i+1*).name

THEN

functional area(*i*) union (functional area(*i+1*))

END

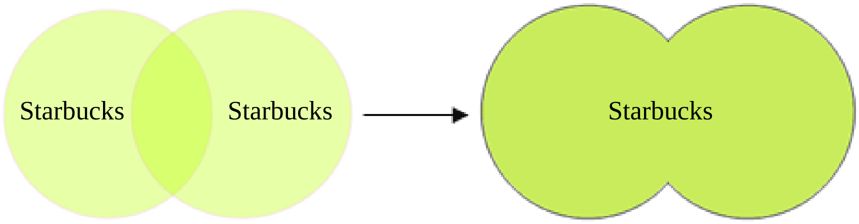


Figure 3.9: Overlap removal between spaces with the same name.

Case 2. If the overlapping functional areas contain different names and have different weight values, the priority is given to the object with the larger weight (W) and the intersecting area is subtracted from the object with the lower weight (Figure 3.10). As it was mention before weight is the sum of values of the following criteria: *attractiveness, necessity* and *closeness to central locations.* For instance, if functional areas of the above mentioned ATM and information screen overlap, the overlap is subtracted from the functional area of ATM since the weight of information screen is equal to 4.5 and is larger than weight of ATM (2.5).

CASE WHEN

functional area(*i*) overlaps (functional area(*i+1*)) AND

functional area(*i*).weight > functional area(*i+1*).weight

THEN

functional area(*i+1*) difference (functional area(*i*))

ELSE functional area(*i*) difference (functional area(*i+1*))

END

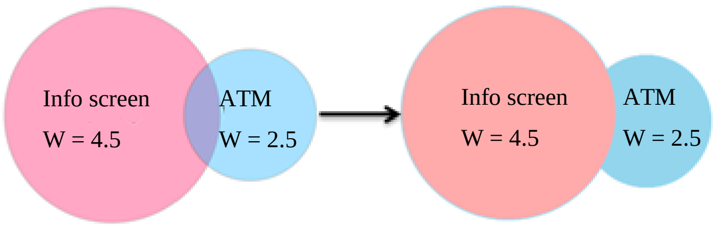


Figure 3.10: Overlap removal between spaces with different names and weight values.

Case 3. If the overlapping functional areas contain different names and have equal weights (W), the intersecting area is subtracted from the subspace with the larger area (A) (Figure 3.11). However, it should be noted that this case is highly unlikely as even adjacent objects are not at equal distance from all the other surrounding locations within the environment. Since the *closeness* values usually differ, the weights most probably are not equal as well. However, in case functional areas of ATM and vending machine overlap and their weight values are equal to 2.5, but their sizes are different, the overlapping area is removed from the larger functional area.

CASE WHEN

functional area(i) overlaps (functional area($i+1$)) AND

functional area(i).weight = functional area($i+1$).weight AND

functional area(i).area > functional area($i+1$).area

THEN

functional area(i) difference (functional area($i+1$))

ELSE functional area($i+1$) difference (functional area(i))

END

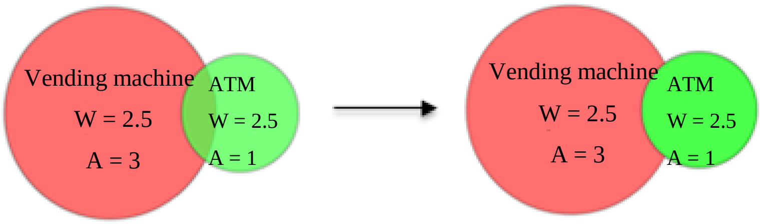


Figure 3.11: Overlap removal between functional areas with the same weight values.

Case 4. If there is a marginal distance (e.g. 0.5 meter, 1 meter, 1.5 meters) between generated functional, they are aggregated. Aggregation command means that adjacent functional areas and functional areas in close proximity are combined in order not to form too narrow passages which are not suitable for navigation. The smallest available distance between functional areas is selected according to a structure of the environment and user requiremets (Figure 3.12). The aggregated functional areas act as non-navigable space and are subtracted from the initial walkable area.

CASE WHEN

functional area DistWithin marginal distance

THEN

Generalised functional area = Aggregate (functional area)

END

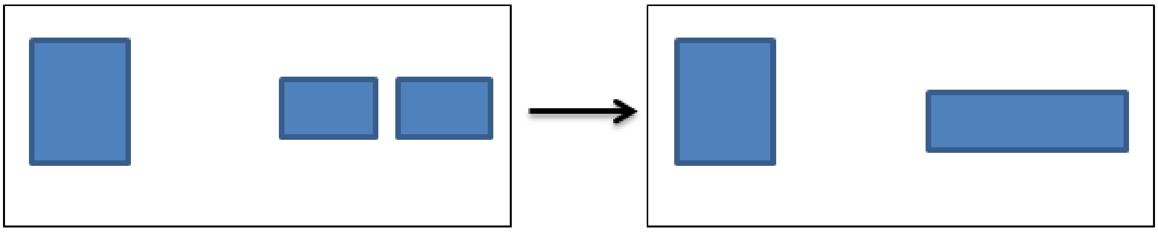


Figure 3.12: Aggregation of functional areas.

4. IMPLEMENTATION

The designed framework for determination of functional areas within indoor space with respect to human perception of the environment and people navigation behaviour was implemented in two buildings: Rotterdam Central Station (RC) and Faculty of Architecture and the Built Environment (BK) at TU Delft. The designed subdivision framework was applied in two buildings with different structure and environment in order to analyse model's applicability for different cases. RC station was selected due to its large open space which contains different types of objects. Additionally, indoor environment of the station is very dynamic and the total number of visitors substantially differs during peak and off-peak hours. For this reason two indoor space subdivisions were performed for RC station: space partition according to peak and off-peak hour. According to the report published by Ministry of Transport, Public Works and Water Managements in the Netherlands (2010) the total amount of passengers increases approximately twice during rush hour and it is considered that increase in total amount of passengers affects the functional areas of indoor objects. The BK faculty was selected as the case study since it also has open spaces but they are smaller than in the RC station and the indoor environment is more static compared to the station. Furthermore, visitors of the RC station are unfamiliar with other people acting in space and for part of visitors this station is unknown environment while visitors of the faculty are usually familiar with the environment and people within it. Due to more static environment single indoor space partition was performed in the BK faculty.

Implementation of the framework was taken in three parts: data preparation, semantic indoor space partition into navigable and non-navigable areas (delineation of functional areas) and geometric navigable space subdivision to build the navigation model. In order to apply the proposed model objects with different properties such as information screens, stands, information desks, shop displays, ticket machines, desks and benches were selected. The following subsections present the delineation of functional areas of certain objects in more detail.

4.1 Software

In the implementation process of the developed model for indoor space subdivision different software packages were used. In order to prepare data for further analysis ArcGIS software was used due to its high capabilities for data manipulation, editing, and analysis. Data preparation was performed manually. Additionally, open source Urban Network Analysis toolbox for ArcGIS was used to perform the closeness analysis in both case studies. Furthermore, representation of functional areas of objects as buffers, removal of overlaps between functional areas, aggregation of functional areas and generation of navigation networks were performed running scripts in Python programming language. The generated networks were stored in open source PostgreSQL database with PostGIS extension for spatial data. Furthermore, pgRouting extension of PostgreSQL database was used to perform navigation path calculations (connecting to database using Python script). Finally, navigation path smoothing algorithm was implemented running script in Python.

4.2 Data and preparation

Freely available 2D floor plans provided by administration offices of the RC station and the BK faculty were used in this research (Figure 4.1 and Figure 4.2). The obtained data was georeferenced using Google Maps and GIS tools. Only ground floor plans of both buildings were used in this research as other floors do not contain large open spaces and do not have objects that widely differ in their functionality whereas open spaces with different types of objects are of importance in this research.

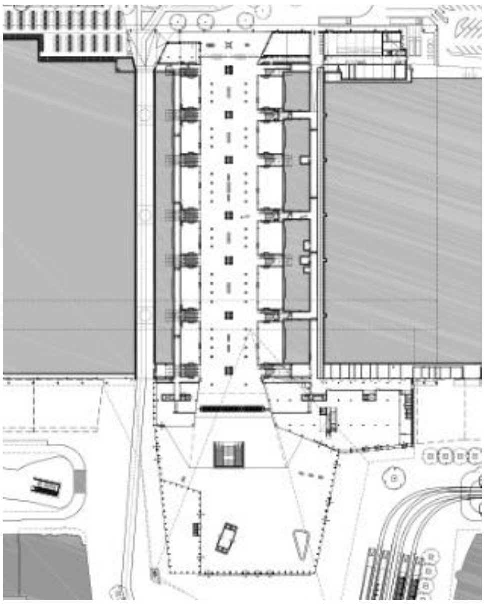


Figure 4.1: 2D floor plan provided by administration of the Rotterdam Central Station.

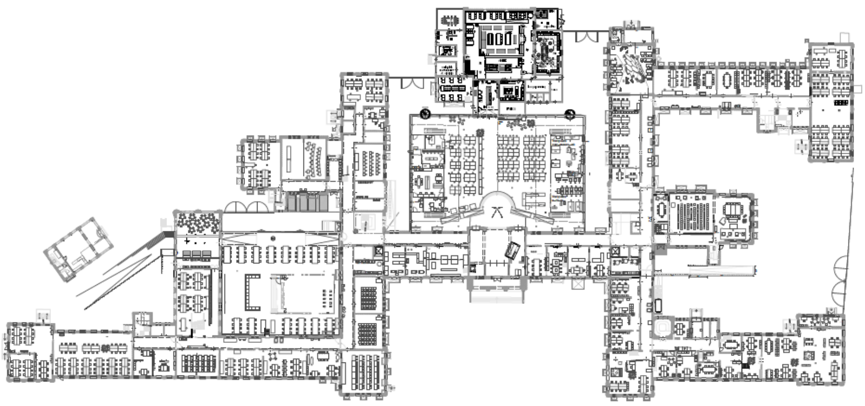


Figure 4.2: 2D floor plan provided by administration of the Faculty of Architecture and the Built Environment.

The georeferenced floor plans were prepared for the further processing. Indoor environment was classified into four polygon feature classes: objects, connectors, obstacles and floor (Figure 4.3). Objects indicate shops, cafeterias, rooms, information desks and screens, tables, benches and other important objects for the navigation that are located within the RC station and the BK faculty. Connectors represent stairs, escalators and elevators while obstacles indicate walls and columns. Floor represents ground area that is empty and is not physically occupied by any indoor object. These classes construct planar partition of the environment which means that there are no overlaps, gaps and disconnected polygons. As it was mentioned before planar partition is necessary to represent correct topology and geometry of indoor space.

As it was previously indicated, in addition to space representation with polygons, line feature is introduced to represent service directions of indoor objects. These lines indicate in which directions object's functional area appears and line buffers are used to represent functional areas. However, firstly in order to delineate functional areas, the following attributes are assigned to the line features: *Type, Name, Attractiveness, Necessity, Closeness, Limited capacity, Transition zone* and *Private space* (Figure 4.6, Figure 4.7 and Figure 4.8). Attribute *Type* provides general information about the object; it indicates if object is a room, shop, cafeteria, screen, information desk, etc. while attribute *Name* provides detailed information about the objects. *Name* indicates room numbers, names of the shops, restaurants or defines what kind of information is provided by the information screen or desk (e.g. West010, Desigual, Starbucks, departure information, train information).

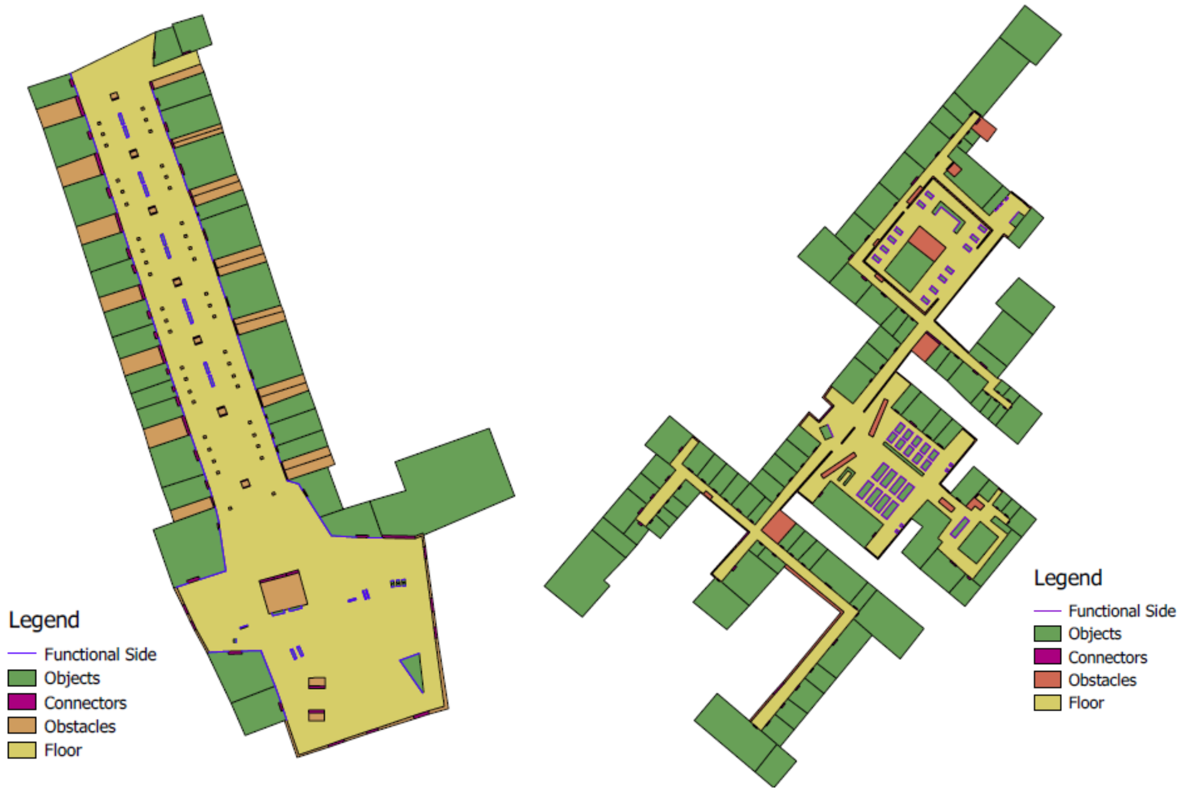


Figure 4.3: Planar partition of Rotterdam Central Station and Faculty of Architecture for the Built Environment.

Attractiveness, necessity, limited capacity and *transition zone* values were assigned to every object taking into consideration their function and type of the environment. As it was aforementioned two different subdivisions are derived for RC station: peak and off-peak hour, thus time impact on *attractiveness* and *necessity* values were evaluated and the values were adjusted. It is considered that functional areas that are formed during off-peak hour provide average sizes of functional areas and in order to derive space subdivision for peak hour, the time dependent parameters (*attractiveness* and *necessity*) have to be adjusted. In this research these values were adjusted by 50 per cent on the grounds that the total amount of visitors significantly increase during rush hour as it is stated in report of Ministry of Transport, Public Works and Water Managements in the Netherlands (2010).

Moreover, in this research *private space* value of 0.9 meters was selected to indicate the distance that people keep to bypass areas occupied by other individuals in RC station. Distance of 0.9 meters was applied because visitors of the station are usually in a rush and closer physical contact is expected while social distance of 1.2 meters was assigned to objects located in the BK faculty. Majority of open spaces within the faculty are work places and people avoid disturbing the others, therefore physical contact is less expected.

Closeness of objects to central locations of the indoor environment is determined applying network analysis method (Urban Network Analysis toolbox in ArcGIS). In order to calculate objects' closeness to all other surrounding features, objects of interest were selected as input features for the closeness analysis. Objects of interest are objects whose functional areas have to be computed: entrances of rooms, shops and cafes, information desks, tables, ticket machines. The selected features were represented as centroids of polygons and used as nodes of the graph on which the network analysis was run. The adjacency matrix, centrality and closeness analysis were computed (see section 3.1.3). The closeness of input features is defined as the inverse of cumulative distance required to reach from specific node to all other nodes that fall within the search radius along the shortest paths (Sevtsuk and Mekonnen, 2012). In this research search radius was not indicated therefore the default infinite radius was used in order to reach all parts of the graph. Figure 4.4 and Figure 4.5 represent closeness results of both case studies. The higher the value the closer location is to the other locations.

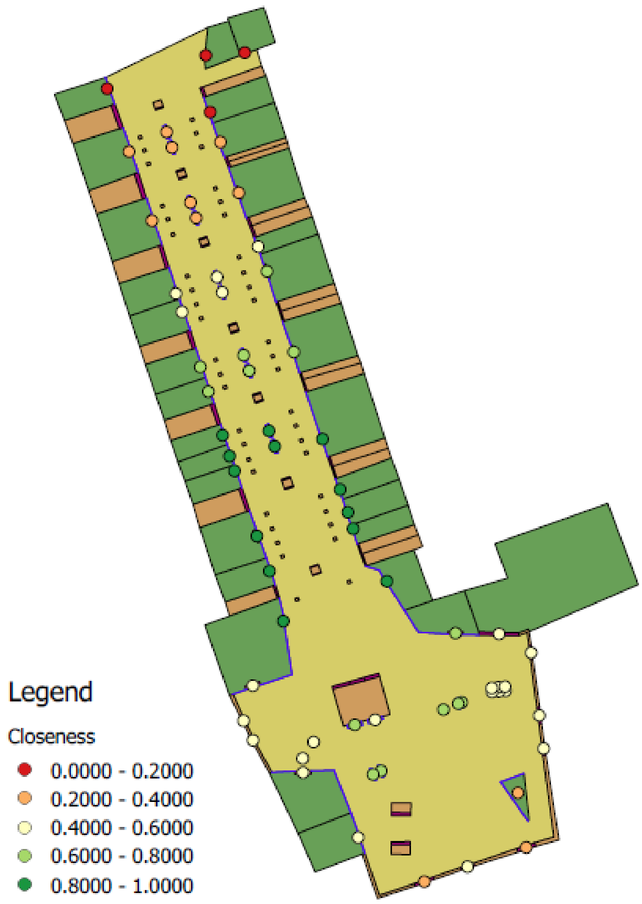


Figure 4.4: Closeness centrality to surrounding objects with no limiting radius in RC station.

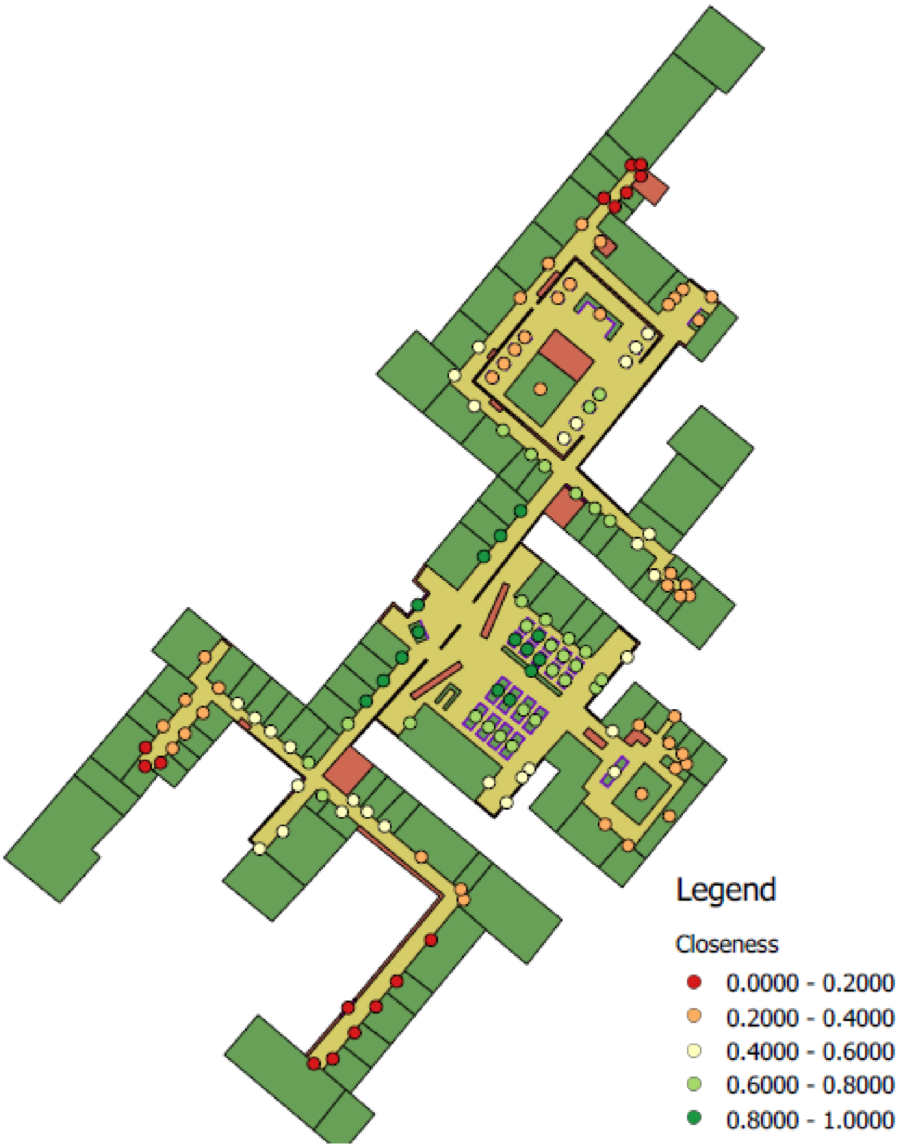


Figure 4.5: Closeness centrality to surrounding objects with no limiting radius in BK faculty.

Type	Name	Attractive	Necessity	Closeness	LimitedCap	Trans_area	Trans_dist	Private_Sp	Projection
information	tourist information	2.00000000000	1.00000000000	0.400	no	no	0.00000000000	0.90000000000	0.60000000000
bench	bench	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	0.90000000000	0.60000000000
bench	bench	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	0.90000000000	0.60000000000
bench	bench	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	0.90000000000	0.60000000000
shop window	Hema	1.00000000000	0.00000000000	0.930	no	no	0.00000000000	0.90000000000	0.60000000000
information	train informantion	2.00000000000	1.00000000000	0.400	no	no	0.00000000000	0.90000000000	0.60000000000
shop window	AH to go	3.00000000000	0.00000000000	0.930	no	no	0.00000000000	0.90000000000	0.60000000000
stand	information stand	1.00000000000	1.00000000000	0.580	no	no	0.00000000000	0.90000000000	0.60000000000
shop	ticket machine	2.00000000000	1.00000000000	0.550	no	no	0.00000000000	0.90000000000	0.60000000000
shop	ticket machine	2.00000000000	1.00000000000	0.550	no	no	0.00000000000	0.90000000000	0.60000000000
screen	information screen	3.00000000000	1.00000000000	0.730	no	yes	1.50000000000	0.90000000000	0.60000000000

Figure 4.6: Attribute table of line features representing parameters of objects in RC station during off-peak hour.

Type	Name	Attractive	Necessity	Closeness	LimitedCap	Trans_area	Trans_dist	Private_Sp	Projection
information	tourist information	3.00000	1.50000	0.400	no	no	0.00000000000	0.90000000000	0.60000000000
bench	bench	0.00000	0.00000	NULL	yes	no	0.00000000000	0.90000000000	0.60000000000
bench	bench	0.00000	0.00000	NULL	yes	no	0.00000000000	0.90000000000	0.60000000000
bench	bench	0.00000	0.00000	NULL	yes	no	0.00000000000	0.90000000000	0.60000000000
shop window	Hema	0.50000	0.00000	0.930	no	no	0.00000000000	0.90000000000	0.60000000000
information	train informantion	3.00000	1.50000	0.400	no	no	0.00000000000	0.90000000000	0.60000000000
shop window	AH to go	1.50000	0.00000	0.930	no	no	0.00000000000	0.90000000000	0.60000000000
stand	information stand	1.50000	1.50000	0.580	no	no	0.00000000000	0.90000000000	0.60000000000
shop	ticket machine	3.00000	1.50000	0.550	no	no	0.00000000000	0.90000000000	0.60000000000
shop	ticket machine	3.00000	1.50000	0.550	no	no	0.00000000000	0.90000000000	0.60000000000
screen	information screen	4.50000	1.50000	0.730	no	yes	1.50000000000	0.90000000000	0.60000000000

Figure 4.7: Attribute table of line features representing parameters of objects in RC station during peak hour.

Type	Name	Attractive	Necessity	Closeness	LimitedCap	Trans_area	Trans_dist	Private_Sp	Projection
information	information desk	1.00000000000	1.00000000000	0.930	no	no	0.00000000000	1.20000000000	0.60000000000
table	table	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	1.20000000000	0.60000000000
table	table	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	1.20000000000	0.60000000000
table	table	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	1.20000000000	0.60000000000
table	table	0.00000000000	0.00000000000	NULL	yes	no	0.00000000000	1.20000000000	0.60000000000
cafe	Espresso Bar	3.00000000000	0.00000000000	0.340	no	no	0.00000000000	1.20000000000	0.60000000000
cafe	canteen	2.00000000000	0.00000000000	0.530	no	no	0.00000000000	1.20000000000	0.60000000000
cafe	canteen	2.00000000000	0.00000000000	0.530	no	no	0.00000000000	1.20000000000	0.60000000000

Figure 4.8: Attribute table of line features representing parameters of objects in BK.

4.3 Determination of navigable and non-navigable areas

Applying the proposed model separate functional areas within the environment are determined which are considered to be non-navigable areas. These delineated functional areas are subtracted from the initial floor polygon and the outcome is the navigable space within indoor environment. However, the derived functional areas can become navigable in two cases: first, functional area is a start point of the individual and second, functional area is a destination of the individual. In this subsection generated functional areas of objects that possess different attribute values are presented in detail. Functional areas were calculated according to expressions determined in section 3.2. In the beginning first buffer was calculated, its value was determined by all the parameters expect the *private space* criterion. Thus the *private space* parameter was omitted in the first step, later the second buffer was created based on the expressions derived in section 3.2 and taking into consideration all the parameters. Finally, the overlap between two buffers was removed. Two buffers were created in order to use area determined by the private space as a node in the navigation network. The central point of the area determined by the private space was extracted in order to navigate people to the border area and not to the centre of the functional area which can be occupied by other people. Both buffers together define non-navigable area and were excluded from the initial floor plan.

4.3.1 Functional area of ticket machines

Functional areas of ticket machines placed in RC station were calculated for peak and off-peak hours. In RC station ticket machines are considered to be important but not highly attractive features of the environment. Additionally, the closeness analysis indicates that they are rather close to all other locations within the environment. What is more, it is expected that their attractiveness and necessity (importance) increase during rush hours as the total number of people in the station increases. Figure 4.9 provides general view of the functional areas while Figure 4.10 represents the exact calculations of the functional area based on the proposed model. In Figure 4.10 blue and pink colours represent functional area of the object while pink colour alone indicates private space. Applying the expressions derived in the section 3.2 it was estimated that the functional areas of ticket machines during off-peak hour are equal to 2.10 meters while during peak hour they are equal to 3.00 meters.

Figure 4.9: Functional area of the ticket machines.

Off-peak hour

Attractiveness: 2

Necessity: 1

Closeness: 0.550

Limited capacity: no

Transition zone: no

Private space: 0.9

Functional area:

0.6 × (2+1+0.55) + 0.9 = 2.10 m

Peak hour

Attractiveness: 3

Necessity: 1.5

Closeness: 0.550

Limited capacity: no

Transition zone: no

Private space: 0.9

Functional area:

0.6 × (3+1.5+0.55) + 0.9 = 3.00 m

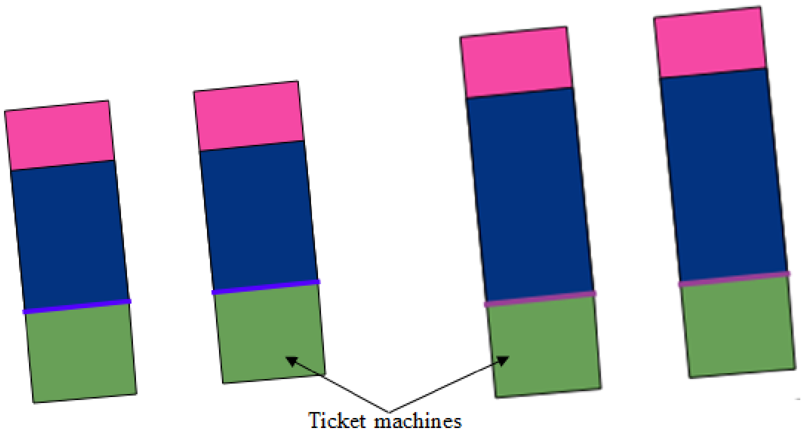


Figure 4.10: Functional areas of ticket machines in RC station.

4.3.2 Functional area of a shop

In RC station shop cloth shop Vila is considered to be unessential object with low attractiveness in this particular environment, additionally its attractiveness and necessity decrease during peak hour since people are in a rush and little attention is paid to the shop displays. Moreover, the network analysis indicates that closeness of this particular shop to other locations of the environment is high. Figure 4.11 provides general view of functional area of a shop while in Figure 4.12 calculations of the functional areas based on the proposed model are illustrated where blue and pink colours represent functional area of the object while pink colour alone stands for the provate space.

Figure 4.11: Functional area of the shop.

Off-peak hour

Attractiveness: 1

Necessity: 0

Closeness: 0.940

Limited capacity: no

Transition zone: no

Private space: 0.9

Functional area:

0.6 × (1+0+0.94) + 0.9 = 2.10 m

Peak hour

Attractiveness: 0.5

Necessity: 0

Closeness: 0.940

Limited capacity: no

Transition zone: no

Private space: 0.9

Functional area:

0.6 × (0.5+0+0.94) + 0.9 = 1.70 m

Figure 4.12: Functional areas of the shop in RC station.

4.3.3 Functional area of Espresso Bar

Furthermore, functional area of Espresso Bar in the BK faculty was estimated (Figure 4.13). Espresso Bar is perceived as one of the most distinctive features of the environment, therefore it is considered that Espresso Bar is highly attractive feature of the environment although it is not an essential object. However, it should be noted that the way people wait for services provided by Espresso Bar might differ every time due to a limited space in the room, thus strangely shaped queues might appear. In Figure 4.14 dark and light blue represent functional area and light blue alone stands for private space.

Figure 4.13: Functional area of the Espresso Bar.

Attractiveness: 3

Necessity: 0

Closeness: 0.340

Limited capacity: no

Transition zone: no

Private space: 1.2

Functional area:

0.6 × (3+0+0.34) + 1.2 = 3.20m

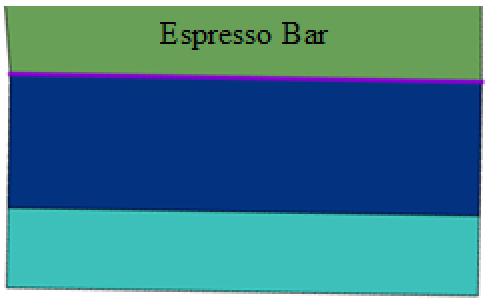


Figure 4.14: Functional areas of the Espresso Bar in BK faculty.

4.3.4 Functional area of information screen

Information screen is RC station is an object that has the transition zone, thus it is taken into account when the functional area is delineated (Figure 4.15). As it was mentioned before, the information screens are considered to be important and attractive features of the environment. What is more, the necessity and attractiveness of these objects increase with the growing number of visitors in the train station. In Figure 4.16 the attribute values are presented and blue and pink colours represent functional area of the information screen and pink colour alone stands for the private space.

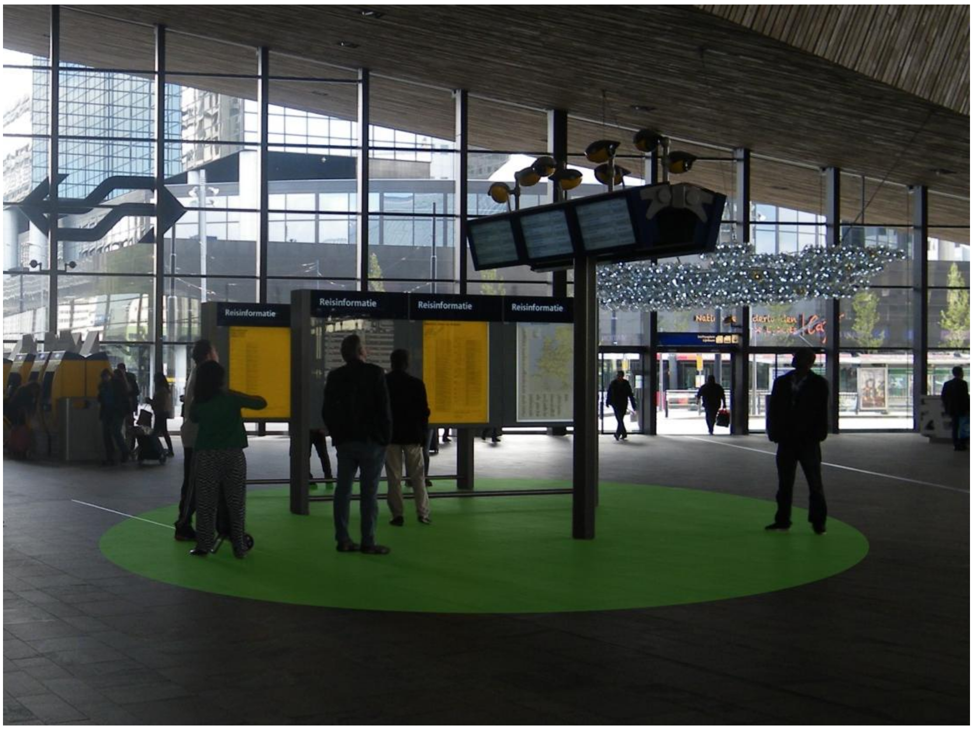


Figure 4.15: Functional area of the information screen.

Off-peak hour

Attractiveness: 3

Necessity: 1

Closeness: 0.730

Limited capacity: no

Transition zone: 1.5

Private space: 0.9

Functional area:

1.5 + 0.6 × (3+1+0.73) + 0.9 = 5.20 m

Peak hour

Attractiveness: 4.5

Necessity: 1.5

Closeness: 0.730

Limited capacity: no

Transition zone: 1.5

Private space: 0.9

Functional area:

1.5 + 0.6 × (4.5+1.5+0.73) + 0.9 = 6.50 m

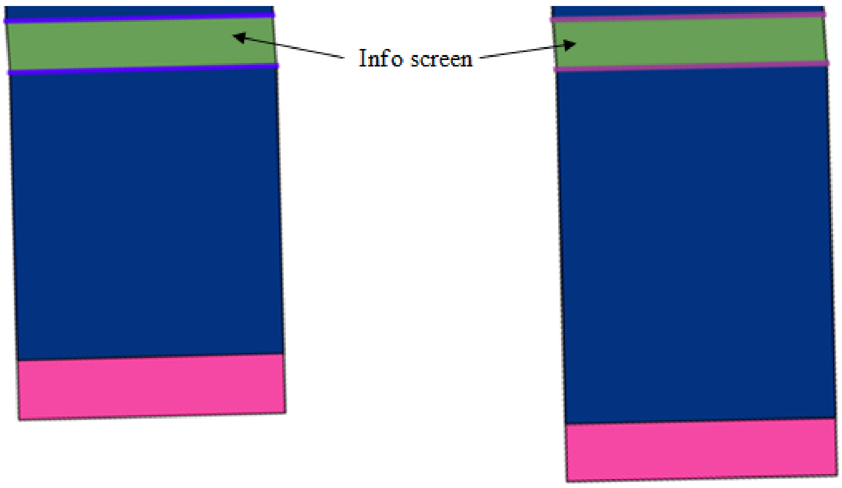


Figure 4.16: Functional areas of the information screen in RC station.

4.3.5 Functional areas of benches and desks

In the selected case studies benches in RC station and desks in BK faculty are the objects that have limited capacity. Therefore their functional areas are delineated applying private space concept. Figure 4.17 and Figure 4.18 provide general views of the functional areas of the benches and desks while in Figure 4.19 functional areas of benches and desks are illustrated based on the model calculations where pink and light blue colours represent functional areas, in these cases private space.

Figure 4.17: Functional area of the bench.

Figure 4.18: Functional area of the desk.

Limited capacity: yes

Private space: 0.9

Functional area: 0.9 m

Limited capacity: yes

Private space: 1.2

Functional area: 1.2 m

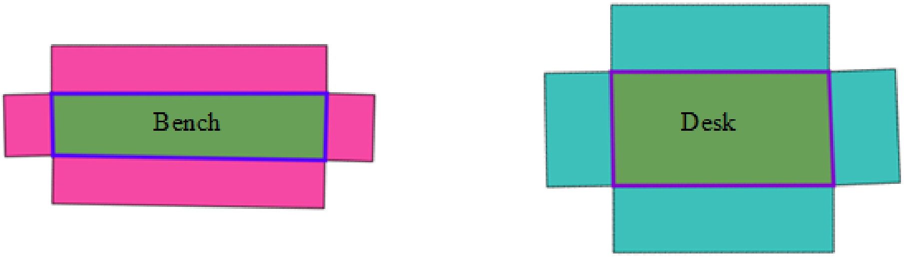


Figure 4.19: Functional areas of benches in RC station and desks in BK faculty.

4.3.6 Overlap removal and aggregation

The delineated functional areas of spatial objects are further processed in order to remove overlaps and small gaps so that no ambiguity would be introduced. In order to remove the overlaps the rules determined in section 3.2.3 were followed. In this research functional areas that are closer than one meter were aggregated in order not to produce unrealistic navigation paths since people avoid narrow passages. The *Aggregate* command in ArcGIS was used to generalize the produced functional areas while script in Python programming language was developed to remove overlapping areas. Figure 4.20, Figure 4.21 and Figure 4.22 illustrate the generalization process in parts of the environments. Initial functional areas within indoor spaces that might have overlaps and small gaps are presented in Appendix A and Appendix B presents the whole environment with aggregated functional areas which also do not overlap.

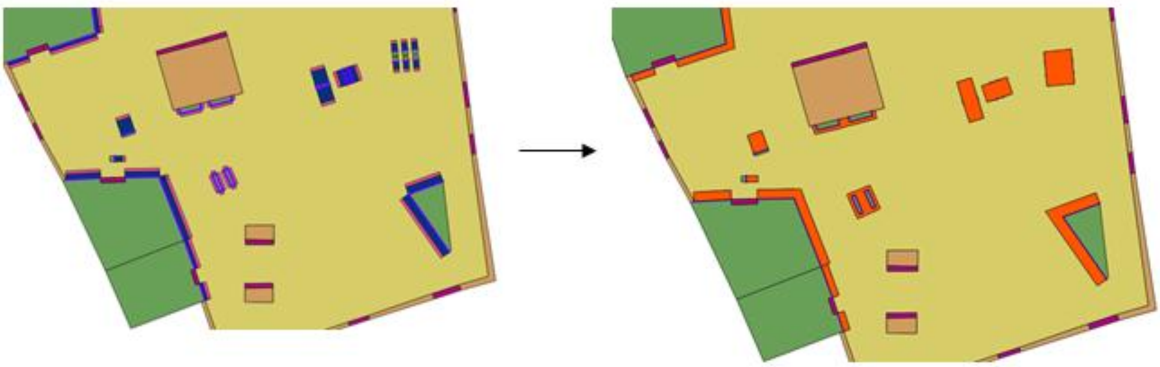


Figure 4.20: Functional areas in RC station before overlap removal and aggregation and after (during off-peak hours).

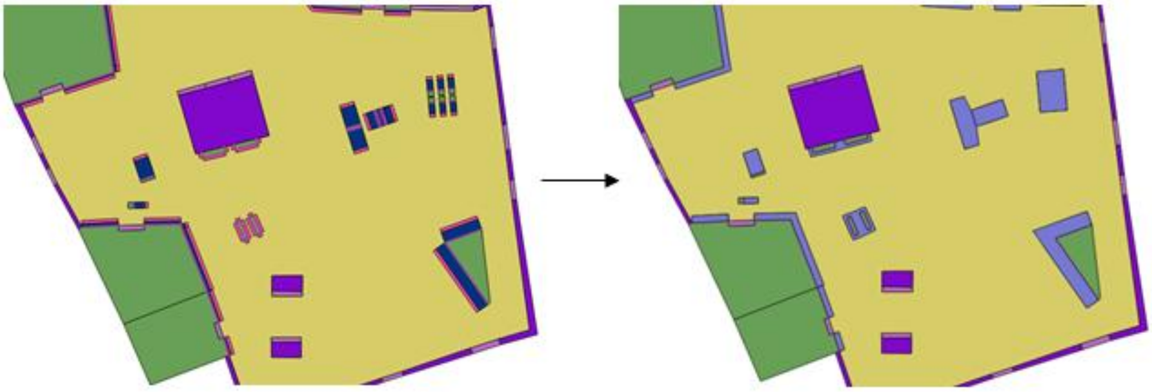


Figure 4.21: Functional areas in RC station before overlap removal and aggregation and after (during peak hours).

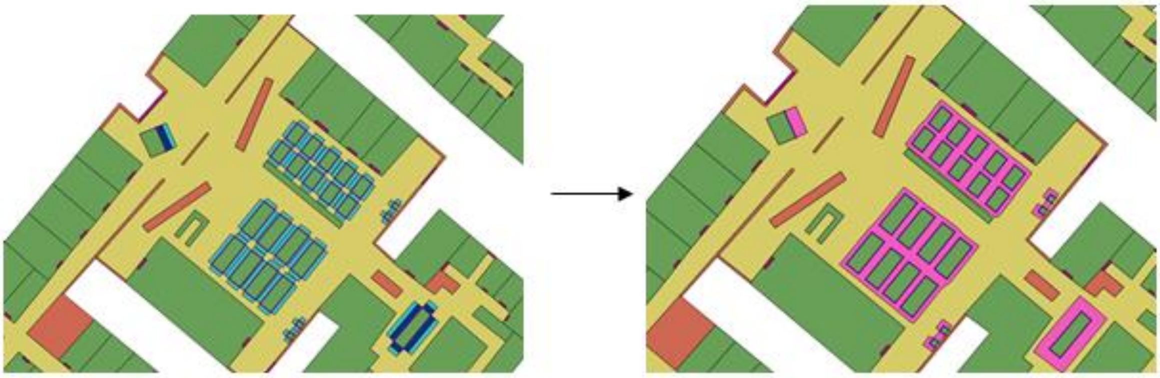


Figure 4.22: Functional areas in BK faculty before overlap removal and aggregation and after.

4.4 Navigable space subdivision

The objectives of this research are to identify navigable and non-navigable areas within indoor environments and to set up navigable space for indoor navigation purposes. Therefore, in this research indoor area that is occupied by static objects and functional areas of certain objects are considered to be non-navigable areas. Thus the navigable spaces are determined by subtracting aggregated functional areas from the initial floor plans (Figure 4.23 and Figure 4.24). The procedure is performed using GIS spatial analysis tools. The generated navigable space is further subdivided in order to derive navigation network. Network was selected as navigation model due to its support for geometric, topologic and semantic information. Moreover, network model enables lower data processing time compared to grid navigation model which is essential in such large buildings. In addition, in order to represent different floors of a building network allows easier implementation of connections between different floors while applying grid method the indoor space should be represented using 3D grid which might result into excessive amounts of memory and long processing time.

Navigation meshes were rejected since they are not suitable to provide guideline services. Navigable space representation with navigation meshes might lead to coarse navigation paths.

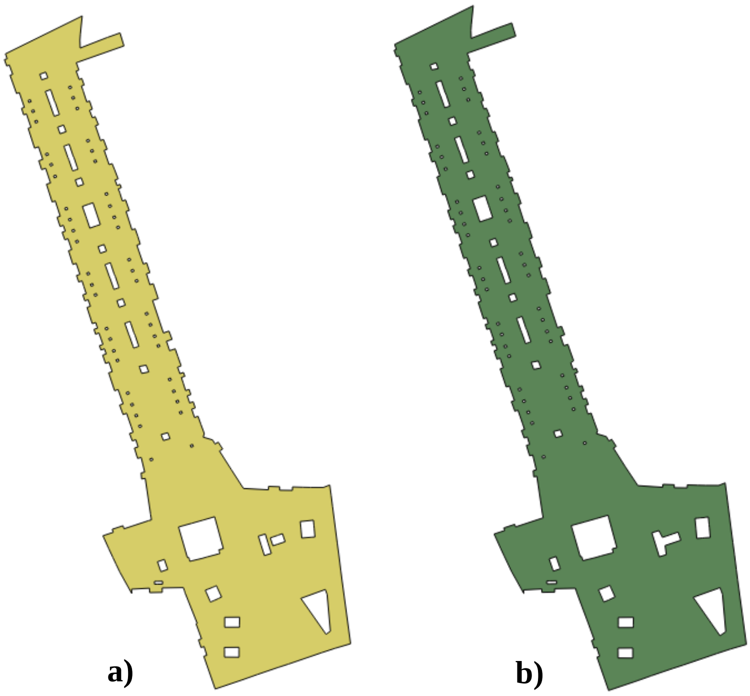


Figure 4.23: Navigable space in RC station during a) off-peak hour and b) peak hour.

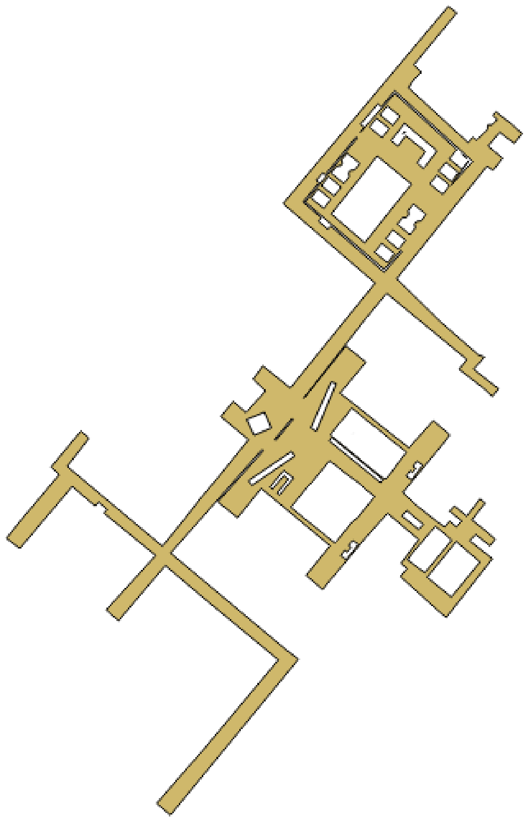


Figure 4.24: Navigable space of the BK faculty.

4.4.1 Constrained Delaunay triangulation

In order to build the navigation network constrained Delaunay triangulation (CDT) was performed. CDT employs vertices of input polygon (in these cases polygons representing navigable space) to construct triangles. CDT was selected because of its suitability for open spaces as the whole navigable space is triangulated while Medial Axis Transformation provides only central lines of the polygon which are not suitable for navigation in large open spaces. CDT coverage of the whole area enables different options for path computations and might provide navigation path that is more realistic and might employ principles of human natural movement. Although visibility graphs provide navigation routes with line of sight principle, however visibility graphs touch obstacles at their vertices or even edges which results into unsafe and strange route. Therefore, the CDT was chosen to design the navigation network. Moreover, another advantage of the CDT is that it does not require large amounts of storage space and allows fast path calculation.

The CDT has ability to preserve a shape of the input polygon, edges of the polygons are taken into consideration therefore holes within the polygons are not triangulated and not incorporated into the navigation network. Furthermore, CDT allows setting different constraints such as minimum angle within triangles or maximum area of triangle constraints by adding Steiner points to the set of input vertices which enables generation of triangles that are more equal to each other and are more evenly distributed in order not to derive coarse navigation paths. In this research the CDT with default parameters was applied in both case studies but the triangulation did not return proper results which could be used for accurate navigation purposes. The outcome of the triangulation contained large and narrow triangles which are not suitable for the generation of the navigation network as the derived navigation network would be very coarse (Figure 4.25). Therefore, it was decided to introduce Steiner points by setting different angle and area constraints while performing the triangulation. The minimum angle constraint returned similar size triangles however the generated network of triangles was very dense which would be computationally expensive in further processing steps. Tests with different maximum area constraint values showed that majority of triangulation results provided uneven distribution of triangles which might produce coarse navigation network (Appendix C). However, the performed tests showed that the outcome of the CDT with the maximum area constraint for triangles of 200 system units returned triangle mesh which is not too dense and triangles are evenly distributed. Thus, the CDT with the area constraint of 200 system units was applied to derive the navigation network in RC station and

CDT with maximum area of 50 system units for triangles was selected to derive navigation network in the BK faculty (Figure 4.26).

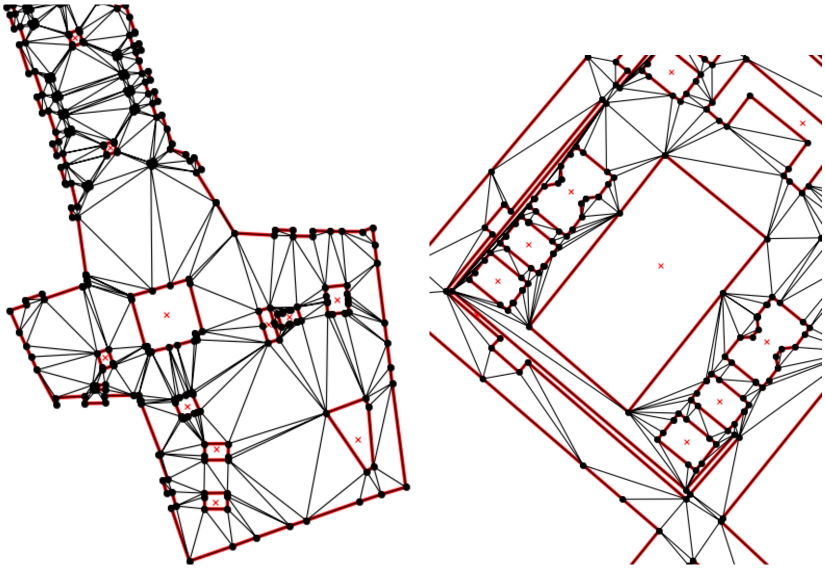


Figure 4.25: CDT without any additional constraints in RC station (left) and BK faculty (right).

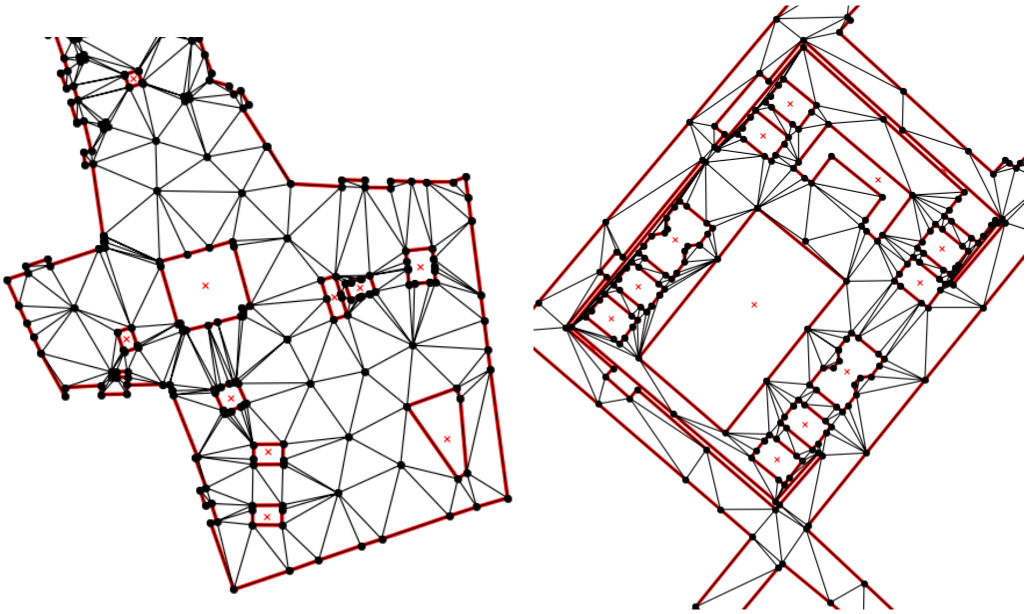


Figure 4.26: CDT with area constraint in RC station (left) and BK faculty (right).

4.4.2 Construction of navigation network

The navigation networks for both case studies were constructed by calculating centroids of triangles and establishing links between centroids of neighbouring triangles. Additionally, central points of polygons of connectors were calculated and linked to the centroid of adjacent triangle. Furthermore, delineated functional areas were incorporated into the navigation networks. The central points of the areas determined by the private space concept were extracted and represented as nodes in the navigation networks so that people would be navigated to the border area and not to the centre of the functional area which might be occupied by others (Figure 4.27). The centroids of functional areas are linked to the closest node in the network and might have maximum one link (*dead-end nodes*). Nodes of the functional areas have only one link so that they would be only start or end point in navigation path and would be avoided in other cases.

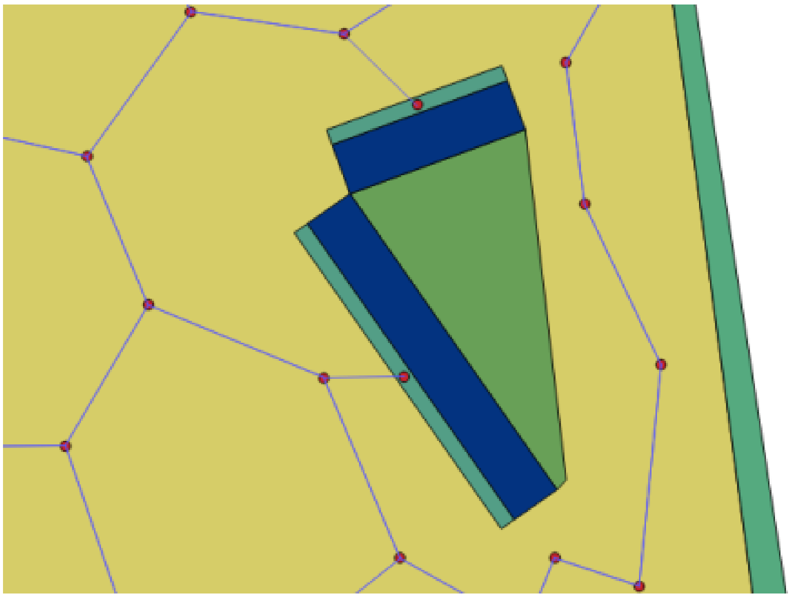


Figure 4.27: Representation of functional areas in navigation network.

Three different networks were generated for the case of RC station: navigation network without indication of functional areas, navigation network with functional areas during off-peak hour and navigation network during peak hour. Two navigation networks were generated for the case of BK faculty: navigation network without and with functional areas. The generated networks (Figure 4.28, Figure 4.29 and Figure 4.30) were stored in open source PostgreSQL database with PostGIS extension. As it was mentioned before PostgreSQL database was chosen because of its PostGIS extension which supports spatial data storage and spatial calculations. Additionally, pgRouting extension enables the shortest path calculations in the network. Networks are stored in two tables: nodes and edges. Node table contains node ID, geometry, type and name of the object. Edge table consists of edge ID, source node, target node and cost columns. Cost is indicated as Euclidian distance between two nodes.

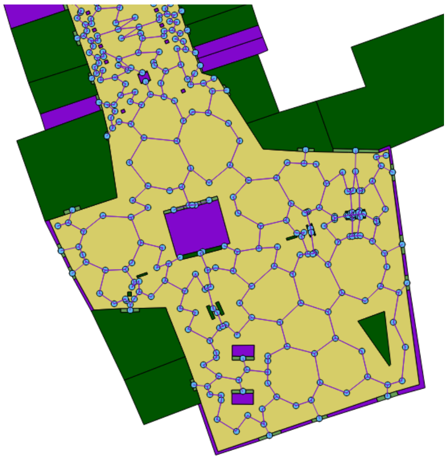
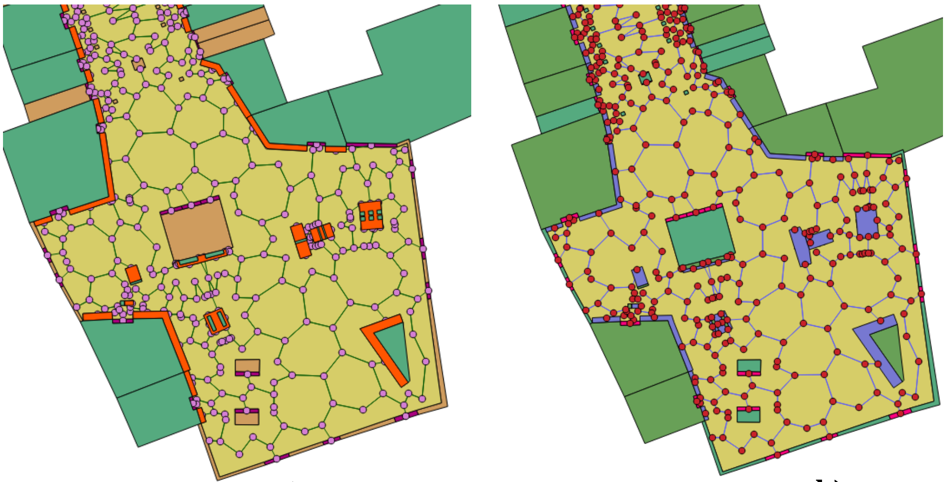
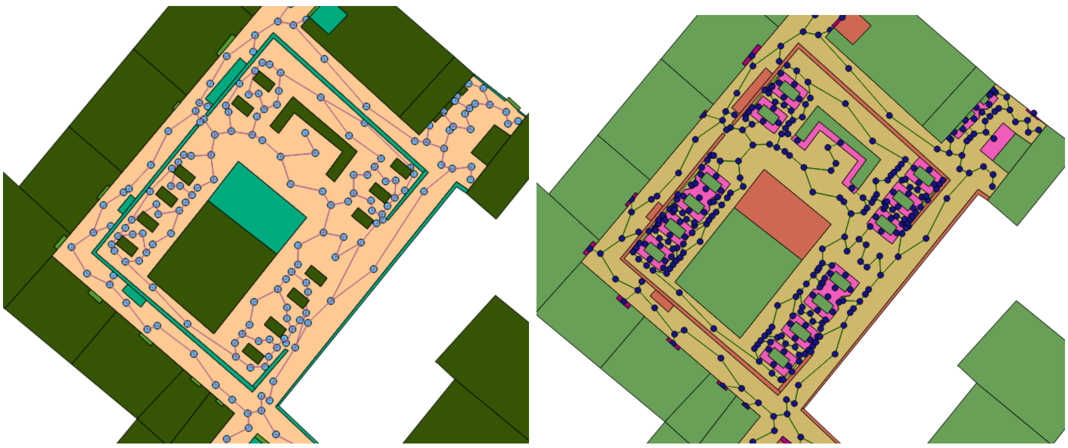


Figure 4.28: Navigation network without functional areas in RC station.



a) **b)**

Figure 4.29: Navigation network in RC station a) during off-peak hour; b) during peak hour.



a) **b)**

Figure 4.30: Navigation network in BK faculty a) without functional areas; b) with functional areas.

4.4.3 Calculations of navigation path

A* the shortest path algorithm was implemented to investigate how indication of functional areas influence the generation of navigation path and if more realistic routes are calculated. The chosen A* algorithm selects nodes that are closest to the source node and gives priority to the nodes that are closest to the destination. Thus, the computation costs are very low. A path from a source node to a destination node is said to be the shortest path if its total cost is minimum among all paths. When start and destination nodes are known the shortest path calculation query is processed, query returns sequence of nodes to be followed (Figure 4.31).

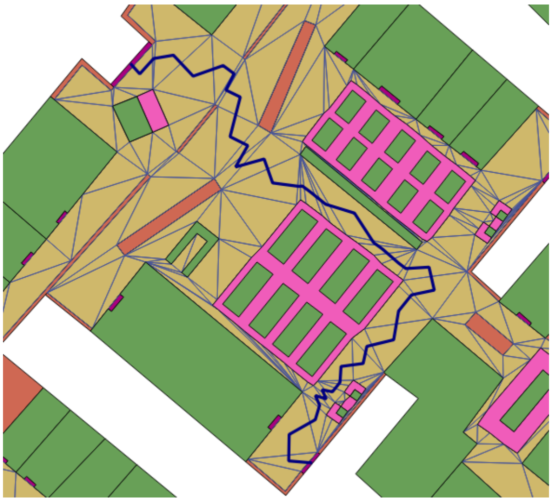


Figure 4.31: Navigation path using A* algorithm.

However, the implemented path calculation algorithm does not represent the actual human movement and produces unrealistically curved path, therefore path smoothing algorithm was developed to generate straight segments. Path smoothing algorithm adopts *divide and conquer* principle. The algorithm creates line segment between first and last node of the sequence of nodes provided by A* shortest path query. If the created line segments is within the navigable area polygon, all the nodes in between are removed. If the line segment is not within the polygon the sequence of nodes is divided in two parts. New line segment from the first node to the middle node is created and it is checked if the line is within the navigable area. If polygon contains the line, all nodes in between are removed and another line segments from the middle point to the end of initial node sequence is created. If line segment is not within the polygons it is again divided in two parts. The same actions are repeated until the majority of nodes in line of sight are removed and more realistic paths are generated Figure 4.32.

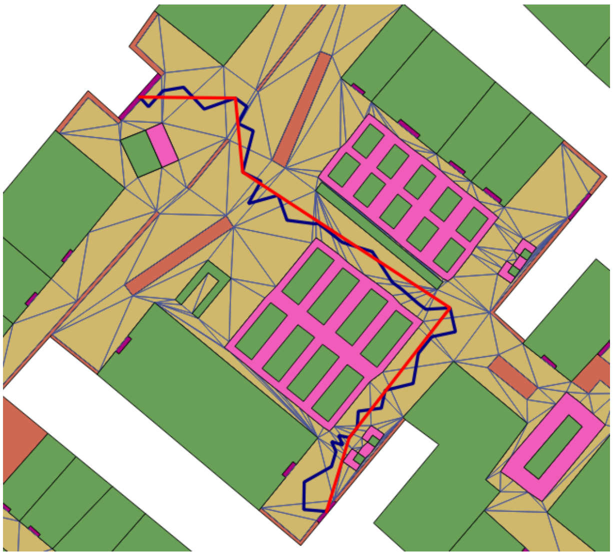


Figure 4.32: Initial (blue) and simplified (red) navigation paths.

Navigation paths from the same start point to the same target were generated using the constructed navigation networks in order to compare the results and analyse how determination of functional areas affect calculation of routes (Figure 4.33 and Figure 4.34). The generated paths illustrate that the determination of functional areas provides more realistic routes as narrow passages between objects and areas that are usually occupied by other individuals are avoided. Therefore determination of functional areas and their indication in navigation network, additionally the application of path simplification algorithm provide more realistic abstraction of the environment and navigation path which adopts principles of human natural movement.

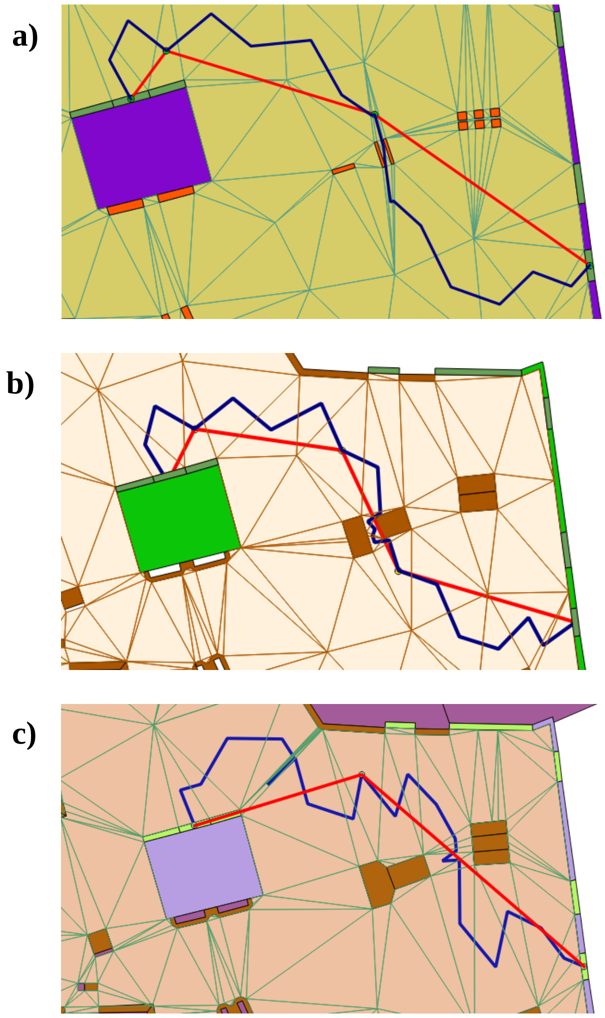


Figure 4.33: The initial (blue) and the simplified (red) paths in the navigation network of RC station a) without functional areas, b) with functional areas during off-peak hour and c) with functional areas during peak hour.

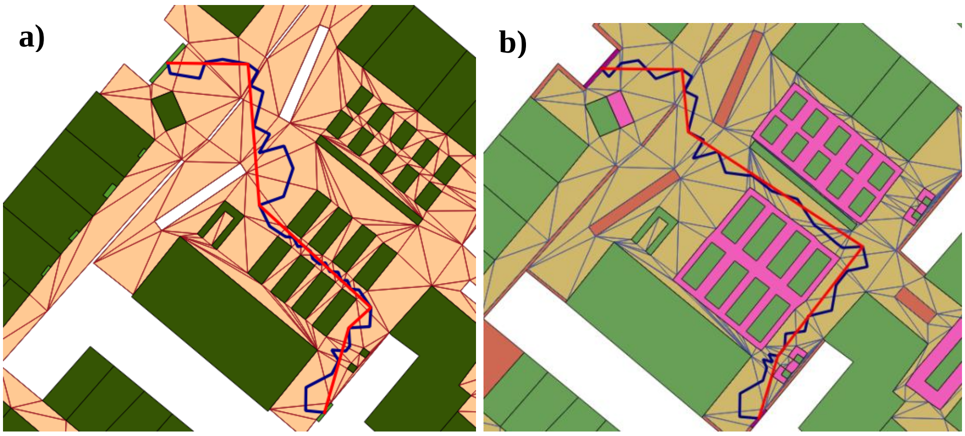


Figure 4.34: The initial (blue) and the simplified (red) paths in a navigation network a) without functional areas, b) with functional areas in the BK faculty.

5. VALIDATION

The proposed conceptual framework for indoor space subdivision in Section 3 was verified using images. Functional areas of objects with different properties were tested. Functional areas of ticket machines, information screen, shop and benches at RC station and desks in the BK faculty were analysed using images and compared to model based estimations presented in Section 4. Photographs at RC station were taken during peak (8:00-9:00) and off-peak (9:30-10:30) hours on 29th of August, 2014 and the photographs at the Orange Hall in BK were taken on 28th of August, 2014. The locations for taking images were selected so that functional areas of the selected objects could be observed and at the same time people within indoor environments would not be disturbed and their movement trajectories would not be affected (Figure 5.1).

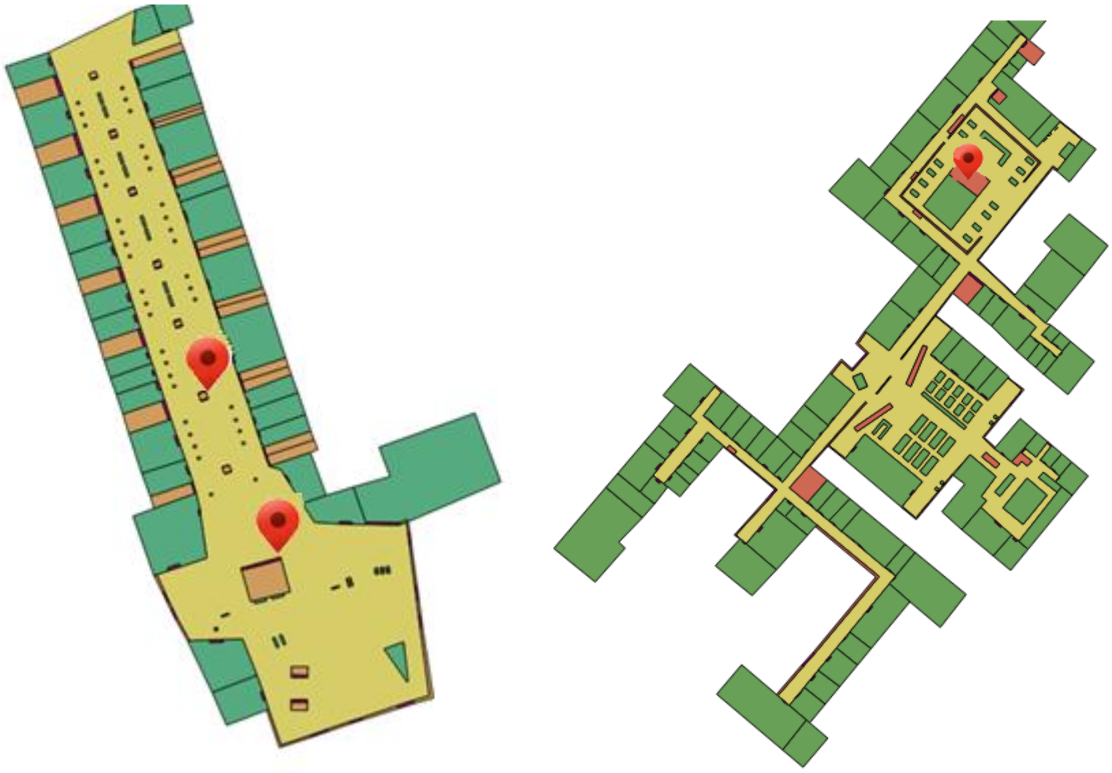


Figure 5.1: Locations of camera.

Functional areas of objects were determined by measuring areas occupied by people around the objects and distances that people keep between each other and objects. Taken images were processed using image processing software Photoshop. In order to make measurements in photographs, image scale had to be set. It means that information in pixels had to be converted to other units, in this case meters. In order to scale the image, lengths of certain objects were measured and these measurements were used to set the scale of the image. The reference objects are clear and visible in all images. Length of information stand, width of bench, width of ticket machine in RC station and width of desk in BK faculty were used as reference distances (Figure 5.2).

Figure 5.2: Reference length of object used for image analysis.

5.1 Functional area of the ticket machine

Distance from ticket machines to the end of queue of people was measured in images in order to determine functional areas of ticket machines in RC station during off-peak and peak hour (Figure 5.3). In total 120 photographs were collected to analyse people distribution around ticket machines.

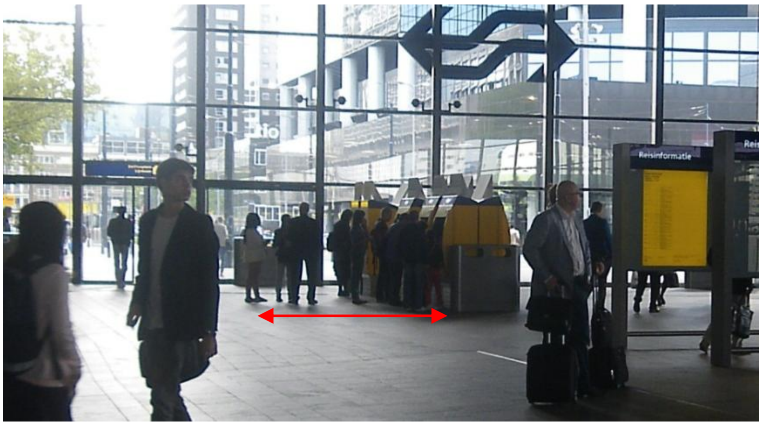


Figure 5.3: Distances measured to determine functional area of the ticket machine.

Calculations based on the proposed model indicate that functional area of the ticket machines during off-peak hour is equal to 2.10 meters. The analysis of collected images indicates that the median is equal to 1.46 meters but 83 per cent of observations fall in the range from 0.1 to 2.5 meters, therefore the calculation of the functional using the proposed model are considered to be partly supported (Figure 5.4).

However, it was observed that during off-peak hour range of distances was larger compared to observations derived from the peak hour. The findings of image analysis suggest that functional areas of ticket machines are larger during off-peak hours and do not support calculation of functional area during peak hour derived using the proposed subdivision model which was equal to 3.0 meters (Figure 5.5). According to the observations from images the median of the functional areas of ticket machines during peak hour is 1.30 meters and 80 per cent of observations fall in the range from 0.1 to 2 meters. The possible argument why the model based calculations were not supported and instead the larger distances during off-peak hour were observed might be that during rush hours majority of passengers are employees or students who use public transportation daily, therefore in order to save time, online banking system is used to pay for the services and avoid buying ticket at the station. Whereas occasional travellers tend to travel in off-peak hours and buy tickets using ticket machines.

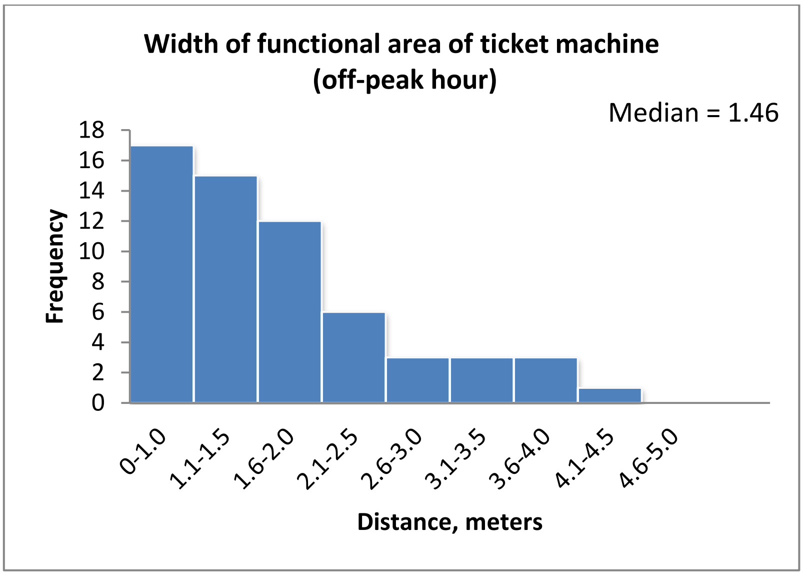


Figure 5.4: Distance distribution representing width of functional area of ticket machines (off-peak hour).

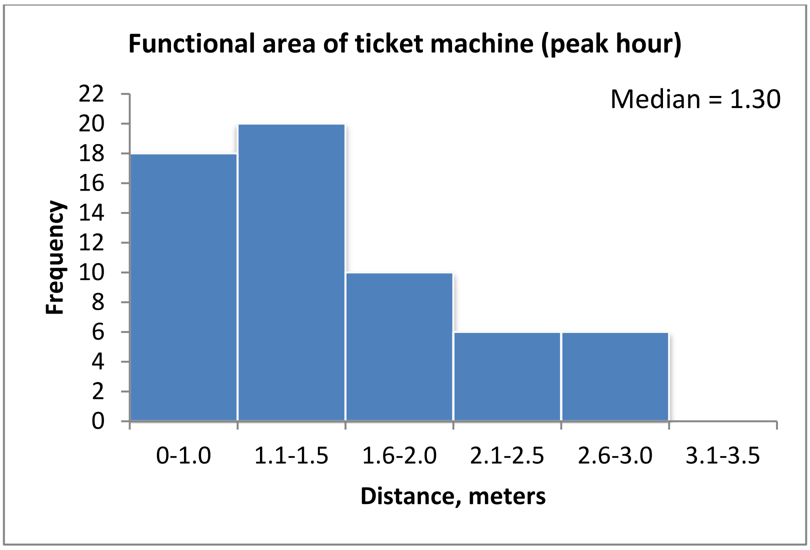


Figure 5.5: Distance distribution representing width of functional area of ticket machines (peak hour).

5.2 Functional area of the shop

In order to determine functional areas of shop, the smallest distances that people keep to pass the shop windows in the passage were measured (Figure 5.6). In total 58 images were captured and processed, the results are shown in the histograms in Figure 5.4 and Figure 5.5.

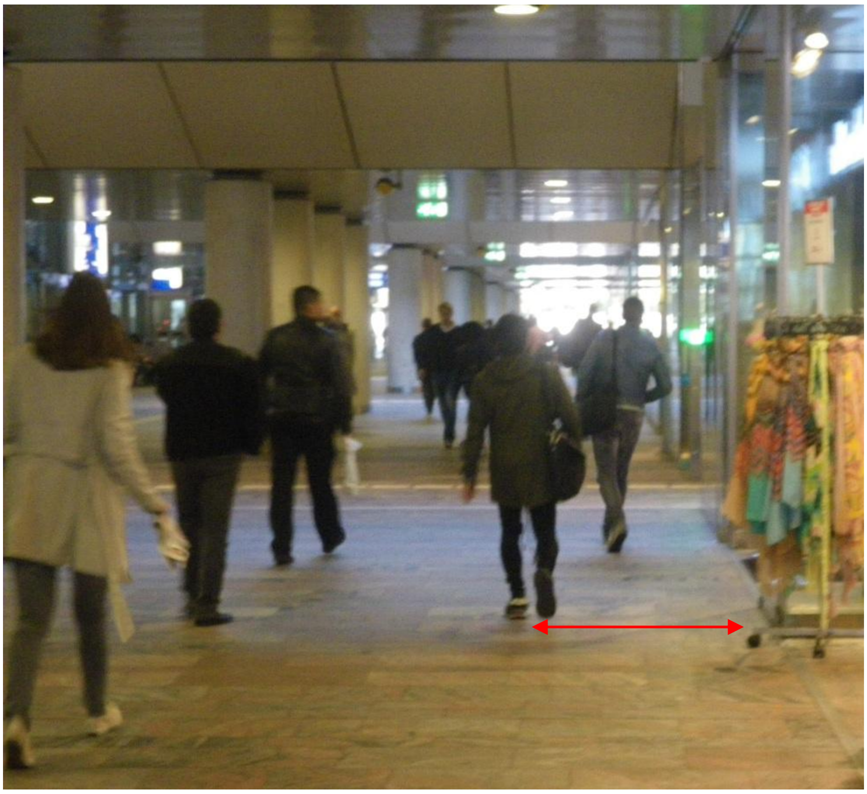


Figure 5.6: Distances measured to determine functional area of the shop.

The findings of image analysis can be considered to be in line with the estimations based on the proposed model. As it was expected functional areas of shops are larger during off-peak hour and smaller during peak hour. The image analysis shows that during off-peak hour the most frequent distance interval that appears is from 2.1 to 2.5 meters and the median is 2.1 meters (Figure 5.7). Thus the findings support the estimation based on the proposed model which is equal to 2.1 meters.

Furthermore according to the results of image analysis the most frequent distances during peak hour fall within range of 0.6-1.0 meters and the median is approximately 1 meter while shop's functional area of 1.7 meters was estimated applying the proposed model (Figure 5.8). The possible reason why the observed distances do not fully support the model based calculations is inaccurate estimation of total number of people at this period of time and its influence on attractiveness and importance of the object. Another reason might be a high value of closeness parameter used in the calculation of the functional area of the specific shop which might have distorted the result.

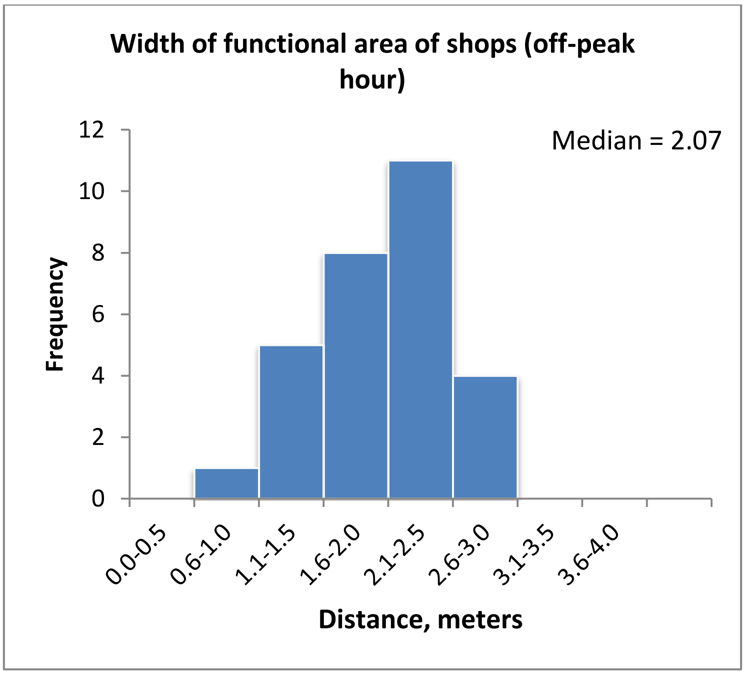


Figure 5.7: Distance distribution representing width of functional area of shops (off-peak hour).

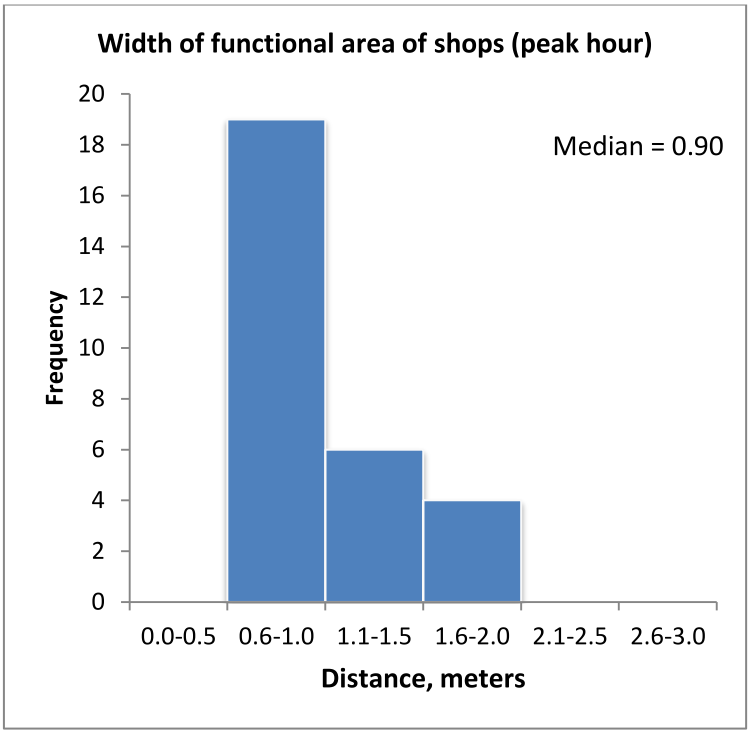


Figure 5.8: Distance distribution representing width of functional area of shops (peak hour).

5.3 Functional area of the information screen

Furthermore the functional area of information screen was inspected using photographs (Figure 5.9). In total 76 photographs were taken to analyse the functional area of information screen during off-peak and peak hours.

Figure 5.9: Distances measured to determine functional area of the information screen.

The findings of image analysis support the estimations based on the proposed model by indicating that functional area of information screen becomes larger during peak hour as the distance values shift from 1.6-6.5 meters to 2.1-8.0 meters.

Applying the proposed model it was estimated that the functional area of the information screen during off-peak hour is equal to 5.20 meters. The image analysis shows that the median is 3.8 meters, however 84 per cent of observations fall in range from 2.10 to 5.00 meters, thus it can be stated that observations partly support the model based estimations (Figure 5.10).

Furthermore, the results of the image analysis demonstrate that the most frequent distance interval during peak hour is between 4.1 and 4.5 meters and the median is 4.9 meters, but even 84 per cent of observations are within range of 2.1 – 6.5 meters (Figure 5.11). Thus, the outcome of the observations suggests that the model based estimations (6.5 meters) are partly supported. The reason why on average lightly smaller functional areas were observed during peak hour than expected might be the higher number of trains in use during rush hours which is done in order to avoid congestion.

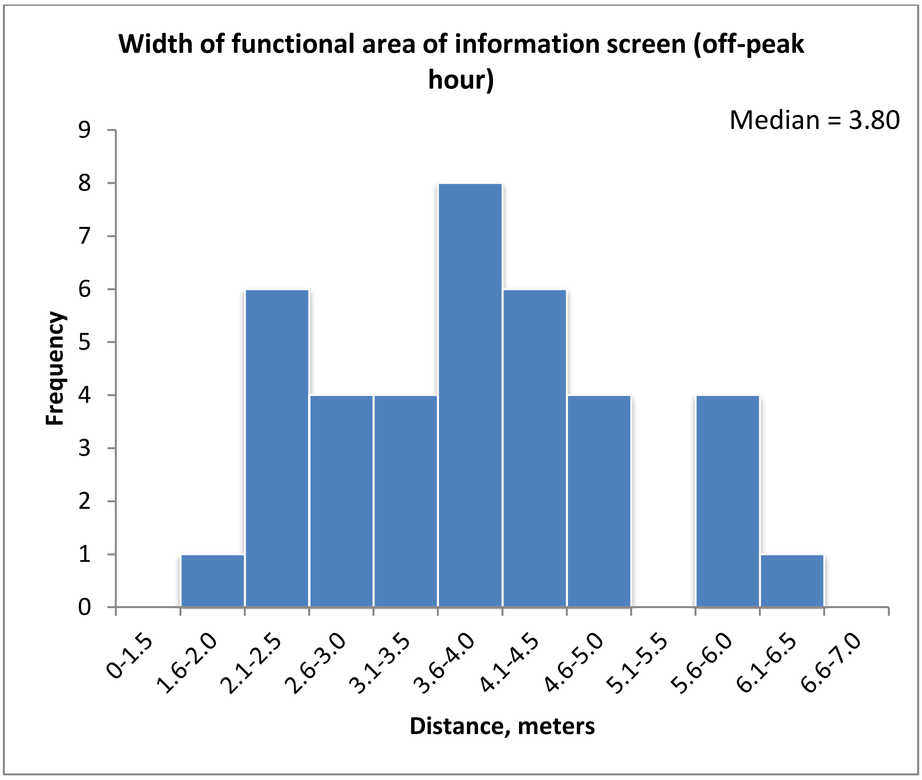


Figure 5.10: Distance distribution representing width of functional area of information screen (off-peak hour)

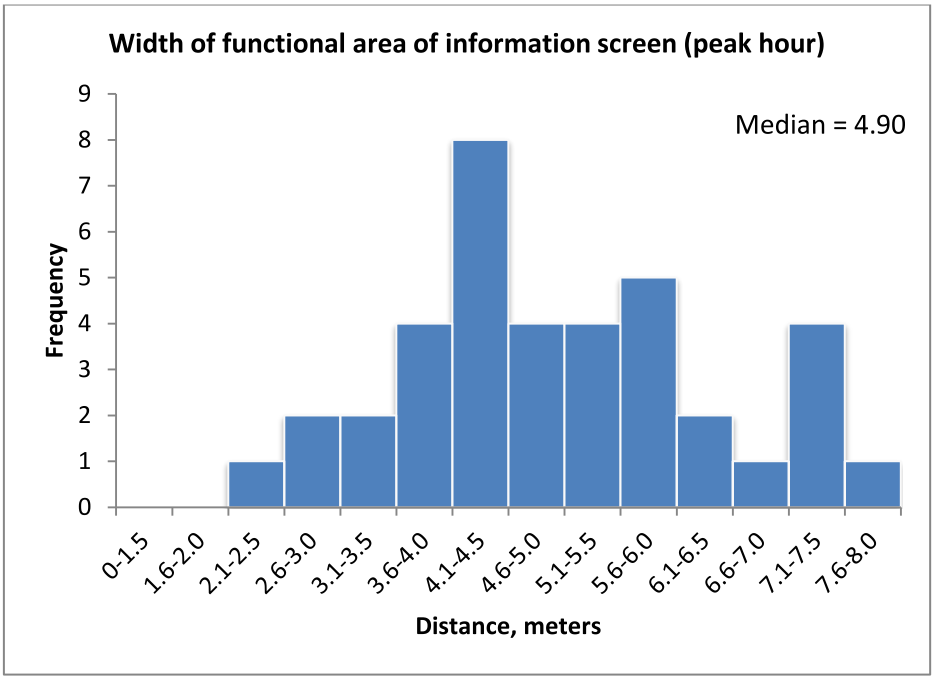


Figure 5.11: Distance distribution representing width of functional area of information screen (peak hour)

5.4 Functional area of the benches

In addition, the functional areas of benches were estimated using images. Small sample set of images was used to observe the smallest distances that people keep to bypass other passengers sitting on benches in the station (Figure 5.12). Images were taken when people cross the passage in the station; it means that from one side of the station's passage people move to the other side. In these cases the smallest distances that people keep from sitting people were estimated. Only 15 photographs were captured as it was noticed that people try to avoid coming close to sitting people and tend to select other routes to their destination which supports findings of Helbing and Molnar (1995). Figure 5.13 depicts distance measures that were obtained from image analysis. Observations suggest that people majority of people keep distance from 0.7 to 0.9 meters to bypass sitting individuals and the median is 0.98 meter. Therefore the observations confirm the model based calculations (0.9 meters).

Figure 5.12: Distances measured to determine functional area of the benches.

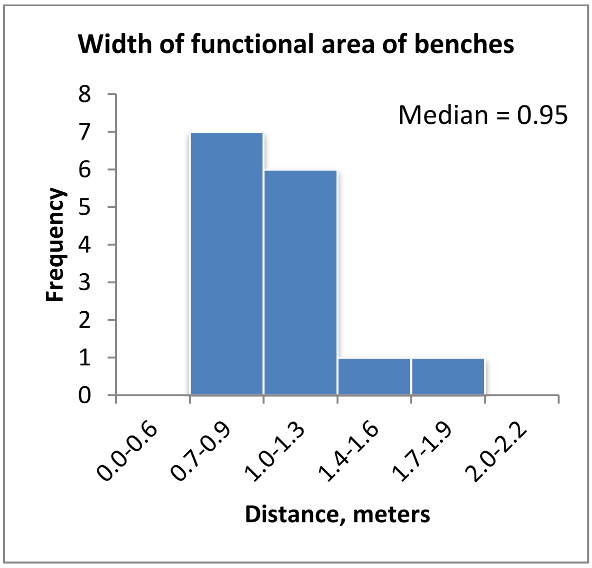


Figure 5.13: Distance distribution representing width of functional area of benches.

5.5 Functional area of the desks

Furthermore, the functional areas of desks in BK faculty were investigated using image analysis. It was analysed at what distance people pass the desks located at the Orange Hall, 34 photographs were taken and the results of the image analysis are illustrated in Figure 5.14. The findings suggest that distances between 0.8 and 1.0 meters were the most frequent and the median is 0.94 meters. Therefore the observations do not correspond to the expected distance of 1.2 meters. However, the model based calculations are considered to be partly supported as the image analysis suggests that the functional area of the desk is approximately constant. The possible reason why smaller distances within the open spaces in the faculty were observed than it was expected might be that individuals in this working environment consider themselves as co-workers thus personal and not social distances are kept from each other (Hall, 1969). Another reason might be that in the smaller environment (open space in BK is smaller compared to RC station) people keep smaller distances which supports findings of Helbing and Molnar (1995). The observations of width of functional areas of desks in BK faculty and benches in RC station suggest that distances between people depend on the origin of the environment.

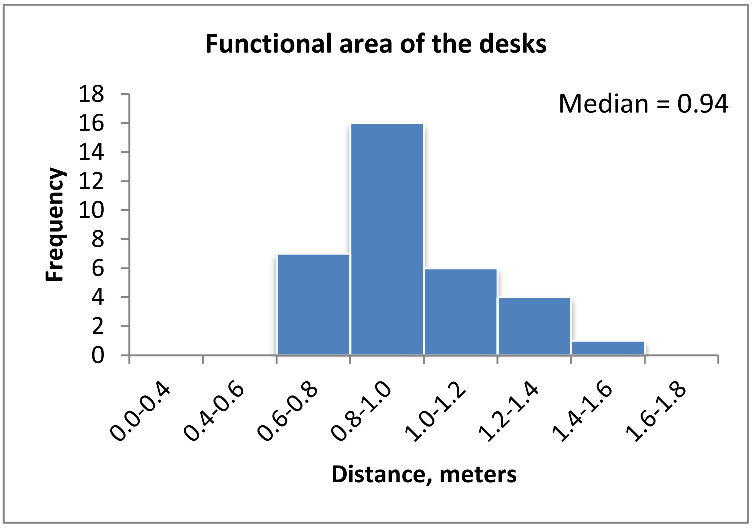


Figure 5.14: Distance distribution representing width of functional area of desk.

5.6 Overview

The summary of image analysis results is presented in Table 5.1. The performed analysis of photographs showed that majority of model based calculations were supported or partly supported and only one case was not confirmed. In the performed statistical analysis it was decided to use not only the average value of the observations (median) as a measure to evaluate the model, but also to take the overall distribution of observations into consideration. In cases when the range of the distances is large the use of a single measure in order to evaluate the validity of the model might be unreliable. Therefore, in cases when the model based calculations of functional areas are evaluated as partly supported, the median of image based observations does not fully correspond to the model estimations but high percentage of observations fall within a certain range. If the model based computations are not supported, the median and the overall distribution of image based observations are very different from the model estimations.

Table 5.1: Model validation results.

Object		Number of photos	Average functional area from images (m)	Calculated functional area (m)	Result	Remarks
Ticket machine	Off-peak	60	1.5	2.1	Partly supported	83% of observations fall in range from 0.1 to 2.5 m
	Peak	60	1.3	3.0	Not supported	
Shop	Off-peak	29	2.1	2.1	Supported	
	Peak	29	1.0	1.7	Partly supported	Functional area decreases during peak hour
Information screen	Off-peak	38	3.8	5.2	Partly supported	84% of observations fall in range from 2.10 to 5.00 m
	Peak	38	4.9	6.5	Partly supported	84% of observations fall in range from 2.10 to 6.50 m
Bench		15	0.9	0.9	Supported	
Desk		34	0.9	1.2	Partly supported	Functional area is approximately constant

5.7 Video analysis

Additionally, people movement trajectories between tables using video material were analysed in order to observe preferences for path selection and their changes when the layout of the environments is modified. Video recordings at the Orange Hall of BK faculty were made and analysed. The records were made using four cameras: two security cameras and two personal cameras. During the experiment every participant was asked to travel from the entrance of the Orange Hall to the furthest corner of the sofa placed in the hall. In total 16 participants took part in the experiment. Configuration of tables was changed twice in order to investigate preferences for the navigation path. In the first configuration tables were located further away from each other in order to provide wider passage. In the second configuration the tables were placed closer to each other. However, do to time limitation accurate coordinated movement trajectories could not be extracted from the videos, thus the video records were visually inspected and the navigation behaviour was analysed. The observations of videos show that all participants selected the shortest routes to the target point and preferred straight paths (avoided turns). In addition it was observed that when the desks were placed closer to each other, part of participants were inclined to choose a little longer path but with wider passages.

6. DISCUSSION

The research aimed to develop a conceptual model for determination of special areas within indoor space and to illustrate how the determined functional areas can be incorporated in a navigation model to facilitate wayfinding process. The results of the research have led to important final remarks which are drawn with respect to the main research question and research sub-questions raised in the introduction. The research findings are discussed in detail with the reference to the research sub-questions.

> *In which manner should the indoor space be subdivided to support more realistic abstraction of an indoor environment and generation of a navigation path while taking account of human perception of the environment and social aspects of human interaction?*

The research proposes a two-step indoor space subdivision in order to support more realistic abstraction of an indoor environment and provide a more realistic navigation path. The research suggests that firstly the semantic indoor space partition has to performed where the indoor space is divided into navigable and non-navigable areas by determining separate functional areas within the space. Separate functional areas within the indoor space with respect to human perception of the environment have to be delineated as people gather around certain objects in space and in turn obstruct areas for walking. In the second step the geometric space subdivision has to be conducted – the navigable space is further subdivided to build a navigation model which enables computations of a navigation path. Additionally, the determined functional areas should also be indicated in the navigation model for more accurate localization, navigation and guidance services.

1. *How properties of indoor environment influencing human distribution inside buildings can be applied for derivation of functional areas?*

This research successfully integrates the findings of previous studies with new concepts introduced in this research to develop the model for the determination of functional areas of objects. The designed model suggests that in order to support more realistic abstraction of indoor environment and generation of a navigation path certain properties of spatial objects and human interaction rules have to be taken in consideration. The model proposes that functional area of an object can be determined by examining its properties: its level of attractiveness, necessity, possession of transition zone, possession of limited capacity, object’s closeness to other locations within the environment. Additionally, the model introduces private space concept in order to embed human social interaction rules in the process of determination of functional areas. The research adopted definition of the object's attractiveness from the study of Frankenstein et al. (2010), closeness parameter was calculated adopting network centrality principles presented by Sevtsuk and Mekonnen (2012) and private space criterion was measured with respect to the findings of the previous research of Hall (1969) and Sommer (1969) while other criteria were introduced by this research. The performed image analysis indicates that these properties of spatial elements and private space concept can be used as measures to determine functional areas within indoor space. Human projection on a horizontal plane weighted with the values of the characteristics of spatial object provides reliable results to determine abstract borders of functional areas within indoor space. The verification of the model indicated that in most of the cases the estimations based on the designed model were supported by the results of image analysis.

The statistical analysis verified that navigable space within indoor environment changes over time, thus attractiveness and necessity values of indoor objects are time dependent. However, the image analysis illustrated that functional areas of objects during peak hour in RC station were only partly supported or not supported, thus the change of attractiveness and necessity values was not correctly adjusted. The findings suggest that in order to accurately estimate the time impact on the properties of indoor objects, different factors have to be taken into account such as occurring events in the environment, total number of people within the environment, habits of people.

Furthermore, previous studies of spatial planning and urban analysis indicate that object's closeness to other locations influence distribution of individuals (Hillier and Iida, 2005; Kazerani and Winter, 2009). As a result in this research the object's closeness to the central point of the location was used as one of the criteria to delineate functional areas. However, the results of the image analysis exposed that object's closeness to the central location of the environment is not the most appropriate approach to define distribution of people within an indoor space. For instance, in this research the objects near the main entrance of the BK faculty were considered to be the closest to the central point in the network while in case of the RC station the central point appeared to be in the middle of the passage. Since the middle of the passage is usually used as a transition area and not that many people stop there, the performed closeness analysis might have created unreasonably large functional areas of objects in the middle of the passage. For this reason, object's closeness to the specific location such as the main entrance, information point or other important location should be established to provide better results.

2. *How rules that people tend to follow during navigation inside buildings and their social interaction can be applied to generate navigable and non-navigable areas within indoor space?*

The research showed that human social interaction rules can be successfully embedded in the navigation systems by introducing private space concept which indicates the distance that people keep during their interaction with other individuals. In this research the private space concept was used to determine functional areas of objects with limited capacity. The results of image analysis confirmed that functional areas of objects with limited capacity are approximately constant – do not shrink or expand, and people keep approximately the same distance to bypass the objects. Therefore, the private space criterion is an appropriate measure to delineate functional areas of objects with limited capacity. However, the outcome of the site observations indicates that private space values have to be carefully chosen taking into consideration type of the environment and people acting within it. As the case study in the BK faculty shows that although the indoor environment is static and Hall's (1969) introduced social distances between strangers were expected, people within indoor space kept the smaller distances instead as they consider themselves as co-workers.

Furthermore, the results of performed experiments in the BK faculty in order to observe preferences for path selection are in line with previous research of Christenfeld (1995), Conroy Dalton (2003) and Hochmair and Frank (2002) which suggest that people tend to choose paths with the least number of routes and prefer routes with straight segments and wider passages. Therefore the implementation of aggregation of functional areas that are at a marginal distance and compose narrow walkable passages is an appropriate method to provide better abstraction of the navigable area. The performed path calculation tests show that route trajectories that are similar to human natural movement can be generated when the narrow passages are eliminated.

3. *How to incorporate functional areas in a navigation model and provide more accurate navigation path?*

In order to perform geometric space subdivision and to build a navigation model the network abstraction was chosen due to its high flexibility (insertion and deletion of network nodes), easy maintenance, fast navigation path computations and the most importantly – ability to encompass geometric, topologic and semantic information. The navigation networks were constructed applying constrained Delaunay triangulation which covers the whole navigable space and provides dense network with many options for path computations. The functional areas were represented as network nodes with a single link so that these nodes would not be included in navigation paths unless it is requested. However, the performed path computation tests showed that the navigation networks produce navigation paths with unrealistic turns. Therefore, further processing was needed to obtain more realistic navigation route. Path simplification algorithm had to be developed to represent a more natural human movement in space. The navigation network together with the path simplification algorithm provided the navigation path that adopts principles of human natural navigation behaviour: movement along line of sight, straight line segments, less turns and avoidance of narrow passages (Conroy Dalton, 2003; Hillier et al., 1993; Hochmair and Frank, 2002).

Therefore results of the research suggest that functional areas can be represented as *dead-end nodes* in the navigation network in order to avoid areas that are usually occupied but the path simplification algorithm should be run in order to provide more realistic navigation path without strange turns. In order to derive proper navigation paths using only navigation network, the navigation network with respect to the visibility criterion might be derived. The visibility graph is considered to be another approach that can derive reasonable navigation paths in open areas. However the main disadvantage of the navigation network based on the visibility criterion is that it might provide paths close to the obstacles and in environments with large number of obstacles it might require lot of storage space.

7. CONCLUSIONS AND FUTURE WORK

The research can be seen as having contributed to the existing research on indoor navigation systems by providing empirically supported model for indoor space subdivision. The developed model for the determination of functional areas provides basis for conceptualisation of indoor space in order to provide more realistic abstraction of the environment for navigation and localization purposes. The proposed model is particularly designed for complex buildings with irregular layout where wayfinding process is challenging, however, the model might also be used in a spatial design process for large open spaces. The indication of functional areas within indoor space may let to analyse the use of indoor facilities and improve the functionality of the indoor space.

Through this research it has been demonstrated that the determination of separate functional areas within the indoor environment and incorporation of the separate functional areas in a navigation model can enhance the understanding of the environment, indoor resources and activities and improve the navigation services. The proposed model for determination of functional areas provides users of the navigation system with descriptive information of the location, enables navigation of users to these separate functional areas and enables avoidance of spaces that are usually occupied by other people. Furthermore, the designed indoor space subdivision model facilitates orientation within indoor space as semantic information is stored in the navigation model and more precise guidelines along the path can be given.

The research integrated findings of previous studies and introduced new concepts for the determination of functional areas of objects. The designed model suggests that in order to support more realistic abstraction of the environment and generation of a navigation path certain properties of spatial objects and human interaction rules should be considered. Therefore object's attractiveness (Frankenstein et al., 2010) and necessity, object's closeness to surrounding locations (Sevtsuk and Mekonnen, 2012), object's possession of the transition zone and limited capacity together with the private space concept (Hall, 1969; Sommer, 1969) were defined as criteria for delineation of functional areas. The designed model for determination of functional areas was implemented in two case studies and applied to objects that have different functions and contain different properties. In order to verify the proposed model site observations were carried out – photographs of certain objects were taken to compare the sizes of estimated and observed functional areas.

The results of image analysis indicate that out of eight observed functional areas only one case was not supported. Therefore the performed image analysis illustrates that the selected criteria to define functional areas of objects provide reliable results and are appropriate to define abstract borders of functional areas. However, there are some aspects that can be improved in the model. The results of image analysis show that in most of the cases the model based calculations were partly supported, therefore the ranges of criteria should be further investigated in order to derive better results. Ranges of the attractiveness and necessity criteria values may be expanded. Furthermore, the findings prove that functional areas of objects are not constant, therefore attractiveness and necessity values have to be modified over time. However in order to derive finite number of space subdivisions for different periods of time, different aspects such as occurring events in the environment, total number of people within the environment, habits of people have to be analysed and combined to evaluate change of attractiveness and necessity values correctly. In addition, the validation results imply that additional attention should be given to the improvement of closeness analysis. The site observations showed that object's closeness to the central location of the environment cannot be applied to every case. Therefore the closeness measurement to the main entrance or closeness to a specific room should be introduced in order to derive more reliable results, which are suitable in different cases. Furthermore, although the image analysis indicated that objects with limited capacity have constant functional areas which can be determined by private space concept, the values of the private space criterion have to be chosen with respect to the type of the environment and people acting within it.

The research demonstrates that the aggregation of functional areas and their indication as nodes in the navigation network provide more realistic abstraction of the navigable area. However, although the navigation network model based on the constrained Delaunay triangulation together with the path simplification algorithm generates more accurate navigation path which adopts principles of human natural movement, the navigation network alone does not provide satisfactory results. Therefore in the future research different navigation models could be built such as navigation network based on a visibility graph or grid based navigation model, in order to investigate which approach provides better results. Moreover, the repulsive effects of indoor features such as distance that people keep from walls may be introduced in the process of determination of a navigable area in order to improve its representation. What is more, video records could be made to extract accurate people movement trajectories. Video coordinates could be converted to reference coordinate system and displayed together with the generated navigation paths for the comparison.

In this research in order to implement the proposed model GIS spatial analysis tools were used. The determined functional areas are represented as line buffers and the results are stored in shapefiles while the navigation network is stored in a database. Majority of the steps was implemented in Python, however the closeness analysis and aggregation of functional areas were performed using the ArcGIS software. The manual data preparation can hardly be avoided but in order to fully automate the derivation of functional areas, the algorithm in Python for aggregation of functional areas should be developed. Furthermore, in the future research it can be investigated how the derived functional areas might be represented in a 3D environment, for instance, how these functional areas could be stored in a CityGML data model.

References

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

Allen, G. L. (1999). Spatial abilities, cognitive maps, and wayfinding. *Wayfinding behavior: Cognitive mapping and other spatial processes*, 46-80.

Bailenson, J. N., Shum, M. S., & Uttal, D. H. (2000). The initial segment strategy: A heuristic for route selection. *Memory & Cognition*, *28*(2), 306-318.

Becker, T., Nagel, C., & Kolbe, T. H. (2009a). A multilayered space-event model for navigation in indoor spaces. In *3D Geo-Information Sciences* (pp. 61-77). Springer Berlin Heidelberg.

Becker, T., Nagel, C., & Kolbe, T. H. (2009b). Supporting contexts for indoor navigation using a multilayered space model. In *Mobile Data Management: Systems, Services and Middleware, 2009. MDM'09. Tenth International Conference on* (pp. 680-685). IEEE.

Borovikov, I. (2011). Navigation Graph Generation . "Navigation Graph Generation" at GameDev.net

Brown, G., Nagel, C., Zlatanova, S., & Kolbe, T. H. (2013). Modelling 3D topographic space against indoor navigation requirements. In *Progress and New Trends in 3D Geoinformation Sciences* (pp. 1-22). Springer Berlin Heidelberg.

Brunyé, T. T., Mahoney, C. R., Gardony, A. L., & Taylor, H. A. (2010). North is up (hill): Route planning heuristics in real-world environments. *Memory & cognition*, *38*(6), 700-712.

Carmona, M., Heath, T., Oc, T., & Tiesdell, S. (2003). Public spaces. Urban spaces.

Christenfeld, N. (1995). Choices from identical options. *Psychological Science*, *6*(1), 50-55.

Conroy Dalton, R. (2003). The Secret Is To Follow Your Nose Route Path Selection and Angularity. *Environment and Behavior*, *35*(1), 107-131.

Curtis, S., Snape, J., & Manocha, D. (2012, March). Way portals: efficient multi-agent navigation with line-segment goals. In *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games* (pp. 15-22). ACM.

Downs, R. M., & Stea, D. (1973). Cognitive maps and spatial behavior: Process and products. *Image and Environment. Chicago: Aldine*, 8-26.

Emo, B., Hölscher, C., Wiener, J. M., & Dalton, R. C. (2012). Wayfinding and spatial configuration: evidence from street corners. In *Proceedings of the Eight International Space Syntax Symposium, Santiago de Chile*.

Frankenstein, J., Büchner, S. J., Tenbrink, T., & Hölscher, C. (2010). Influence of geometry and objects on local route choices during wayfinding. In *Spatial cognition vii* (pp. 41-53). Springer Berlin Heidelberg.

Franz, G., Mallot, H., Wiener, J., & Neurowissenschaft, K. (2005, August). Graph-based models of space in architecture and cognitive science-a comparative analysis. In *Proceedings of the 17th International Conference on Systems Research, Informatics and Cybernetics* (pp. 30-38).

Furtado, A. S., Fileto, R., & Renso, C. (2013). Assessing the Attractiveness of Places with Movement Data. *Journal of Information and Data Management*, *4*(2), 124.

Gärling, T., Böök, A., & Lindberg, E. (1986). Spatial orientation and wayfinding in the designed environment: A conceptual analysis and some suggestions for postoccupancy evaluation. *Journal of architectural and planning research*.

Giannotti, F., Nanni, M., Pinelli, F., & Pedreschi, D. (2007, August). Trajectory pattern mining. In *Proceedings of the 13th ACM SIGKDD international conference on Knowledge discovery and data mining* (pp. 330-339). ACM.

Gibson J. (1979). *The Ecological Approach to Visual Perception.* Houghton Mifflin Company, Boston.

Goetz, M., & Zipf, A. (2011). Formal definition of a user-adaptive and length-optimal routing graph for complex indoor environments. *Geo-Spatial Information Science*, *14*(2), 119-128.

Golledge, R. G. (1999). Human wayfinding and cognitive maps. *Wayfinding behavior: Cognitive mapping and other spatial processes*, 5-45.

Hall, E. T., & Hall, E. T. (1969). *The hidden dimension* (Vol. 1990). New York: Anchor Books.

Haq, S., & Zimring, C. (2003). Just down the road a piece the development of topological knowledge of building layouts. *Environment and behavior*, *35*(1), 132-160.

Helbing, D., & Molnar, P. (1995). Social force model for pedestrian dynamics. *Physical review E*, *51*(5), 4282.

Helbing, D., Molnar, P., Farkas, I. J., & Bolay, K. (2001). Self-organizing pedestrian movement. *Environment and planning B*, *28*(3), 361-384.

Henderson, L. F. (1974). On the fluid mechanics of human crowd motion.*Transportation research*, *8*(6), 509-515.

Hillier, B., & Hanson, J. (1984). *The social logic of space* (Vol. 1). Cambridge: Cambridge university press.

Hillier, B., & Iida, S. (2005). Network and psychological effects in urban movement. In *Spatial information theory* (pp. 475-490). Springer Berlin Heidelberg.

Hillier, B., Penn, A., Hanson, J., Grajewski, T., & Xu, J. (1993). Natural movement-or, configuration and attraction in urban pedestrian movement. *Environ Plann B, 20*(1), 29-66.

Hochmair, H., & Frank, A. U. (2000). Influence of estimation errors on wayfinding-decisions in unknown street networks–analyzing the least-angle strategy. *Spatial Cognition and Computation*, *2*(4), 283-313.

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., & Knauff, M. (2006). Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, *26*(4), 284-299.

Hu, H., & Lee, D. L. (2004). Semantic location modeling for location navigation in mobile environment. In *Mobile Data Management, 2004. Proceedings. 2004 IEEE International Conference on* (pp. 52-61). IEEE.

Huang, L., Li, Q., & Yue, Y. (2010, November). Activity identification from GPS trajectories using spatial temporal POIs' attractiveness. In *Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Location Based Social Networks* (pp. 27-30). ACM.

Jiang, B., Claramunt, C., & Batty, M. (1999). Geometric accessibility and geographic information: extending desktop GIS to space syntax. *Computers, Environment and Urban Systems*, *23*(2), 127-146.

Kallmann, M., & Kapadia, M. (2014, July). Navigation meshes and real-time dynamic planning for virtual worlds. In *ACM SIGGRAPH 2014 Courses* (p. 3). ACM

Kaplan, S. (1983). A model of person-environment compatibility. *Environment and behavior*, *15*(3), 311-332.

Kazerani, A., & Winter, S. (2009). Can betweenness centrality explain traffic flow. In *Proceedings of the 12th AGILE International Conference on GIS*.

Khan, A. A., & Kolbe, T. H. (2012, November). Constraints and their role in subspacing for the locomotion types in indoor navigation. In *Indoor Positioning and Indoor Navigation (IPIN), 2012 International Conference on* (pp. 1-12). IEEE.

Khan, A. A., & Kolbe, T. H. (2013). Subspacing Based on Connected Opening Spaces and for Different Locomotion Types Using Geometric and Graph Based Representation in Multilayered Space-Event Model (mlsem). *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *1*(1), 173-185.

Kikiras, P., Tsetsos, V., & Hadjiefthymiades, S. (2006). Ontology-based user modeling for pedestrian navigation systems. In *ECAI 2006 Workshop on Ubiquitous User Modeling (UbiqUM), Riva del Garda, Italy*.

Kim, H., Jun, C., Cho, Y., & Kim, G. (2008). Indoor spatial analysis using space syntax.

Kuipers, B. (2000). The spatial semantic hierarchy. *Artificial Intelligence, 119*(1), 191-233.

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

Lertlakkhanakul, J., Li, Y., Choi, J., & Bu, S. (2009, August). GongPath: Development of BIM based indoor pedestrian navigation system. In *INC, IMS and IDC, 2009. NCM'09. Fifth International Joint Conference on* (pp. 382-388). IEEE.

Liu, L., & Zlatanova, S. (2011, May). A door-to-door pathfinding approach for indoor navigation. In *Proceedings of GeoInformation For Disaster Management Conference 2011* (pp. 3-8).

Lorenz, B., Ohlbach, H. J., & Stoffel, E. P. (2006). A hybrid spatial model for representing indoor environments. In *Web and Wireless Geographical Information Systems* (pp. 102-112). Springer Berlin Heidelberg.

Lynch, K. (1960). The image of the city (Vol. 11). MIT press.

Michalowski, M. P., Sabanovic, S., & Simmons, R. (2006). A spatial model of engagement for a social robot. In *Advanced Motion Control, 2006. 9th IEEE International Workshop on* (pp. 762-767). IEEE.

Mount D. (2013). *Geometric Data Structures for Games: Geometric Graphs.* [PDF document]. Retrieved from http://www.cs.umd.edu

Nagel, C., Becker, T., Kaden, R., Li, K., Lee, J., & Kolbe, T. H. (2010). *Requirements and space-event modeling for indoor navigation*. Tech. Rep. OGC 10-191r1, Open Geospatial Consortium Discussion Paper.

Nakauchi, Y., & Simmons, R. (2002). A social robot that stands in line. *Autonomous Robots*, *12*(3), 313-324.

Neufert, E., & Neufert, P. (2012). *Architects' data*. John Wiley & Sons.

Passini, R. (1992). Wayfinding in architecture. New York: Van Nostrand Reinhold.

Peponis, J., Zimring, C., & Choi, Y. K. (1990). Finding the building in wayfinding. *Environment and behavior*, *22*(5), 555-590.

Public Works and Water Managements. (2010). *Public Transport in the Netherlands*.

Raubal, M., & Worboys, M. (1999). A formal model of the process of wayfinding in built environments. In *Spatial information theory. Cognitive and computational foundations of geographic information science* (pp. 381-399). Springer Berlin Heidelberg.

Richter, K. F., Winter, S., & Ruetschi, U. J. (2009, May). Constructing hierarchical representations of indoor spaces. In *Mobile Data Management: Systems, Services and Middleware, 2009. MDM'09. Tenth International Conference on* (pp. 686-691). IEEE.

Sevtsuk, A., & Mekonnen, M. (2012). Urban network analysis. A new toolbox for ArcGIS. *Revue Internationale de Géomatique*, *22*(2), 287-305.

Sommer, R. (1969). Personal Space. The Behavioral Basis of Design.

Stoffel, E. P., Lorenz, B., & Ohlbach, H. J. (2007). Towards a semantic spatial model for pedestrian indoor navigation. In *Advances in Conceptual Modeling–Foundations and Applications* (pp. 328-337). Springer Berlin Heidelberg.

Timpf, S., Volta, G. S., Pollock, D. W., & Egenhofer, M. J. (1992). A conceptual model of wayfinding using multiple levels of abstraction. In Theories and methods of spatio-temporal reasoning in geographic space (pp. 348-367). Springer Berlin Heidelberg.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological review*, *55*(4), 189.

Tsetsos, V., Anagnostopoulos, C., Kikiras, P., & Hadjiefthymiades, S. (2006). Semantically enriched navigation for indoor environments. *International Journal of Web and Grid Services*, *2*(4), 453-478.

Uchino, A., Furihata, T., Tanaka, N., and Takahashi, Y. (2005). Some Contribution toward Spatial Urban Dynamics. In *Proceedings of the System Dynamics Conference*. Boston, USA, pp. 1–7, 2005.

Van Toll, W., Cook, A. F., & Geraerts, R. (2011, September). Navigation meshes for realistic multi-layered environments. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on* (pp. 3526-3532). IEEE.

Weisman, J. (1981). Evaluating Architectural Legibility Way-Finding in the Built Environment. *Environment and behavior, 13*(2), 189-204.

Wiener, J. M., Büchner, S. J., & Hölscher, C. (2009). Taxonomy of human wayfinding tasks: A knowledge-based approach. Spatial Cognition & Computation, 9(2), 152-165.

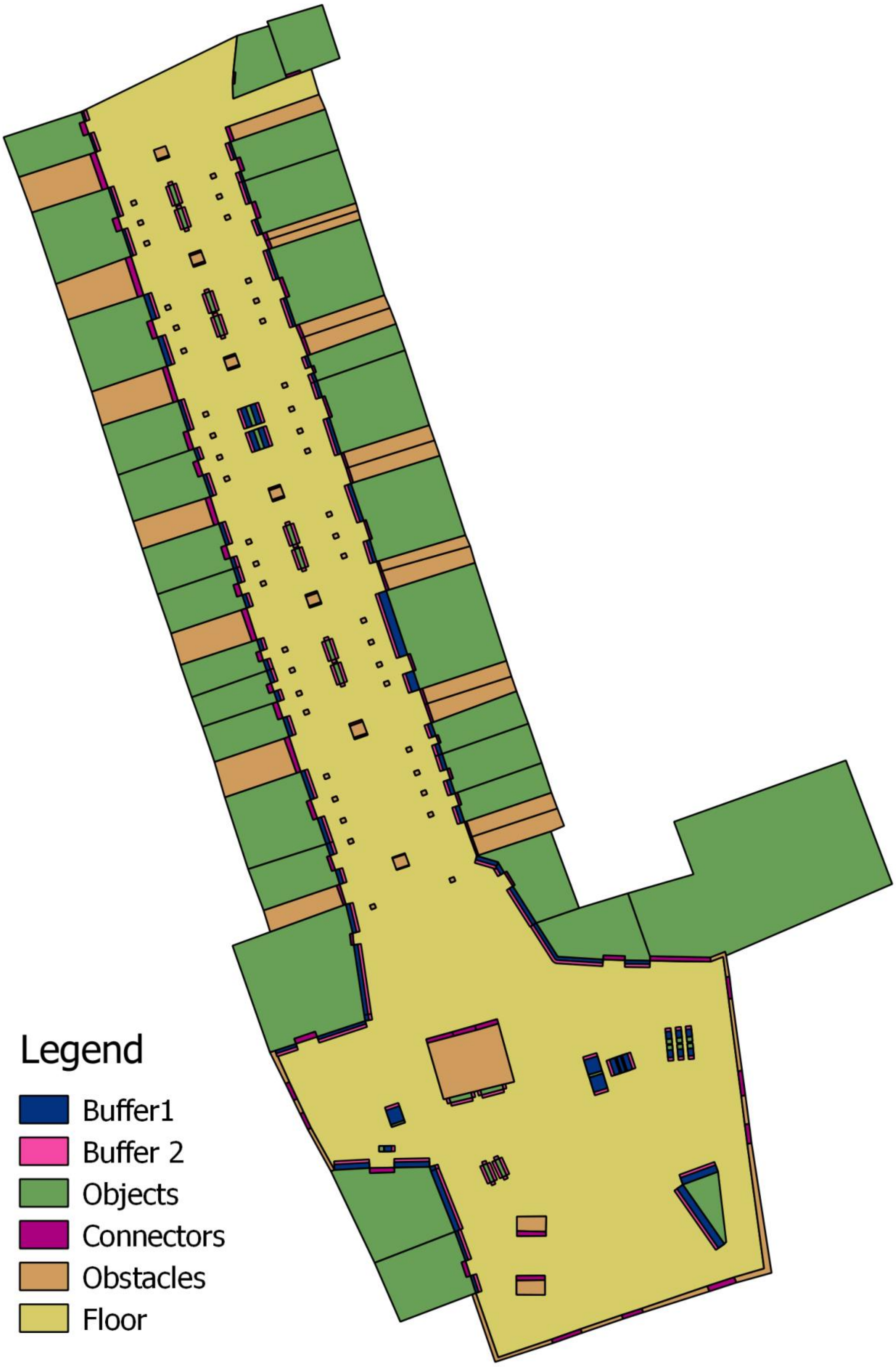
Worboys, M. (2011, November). Modeling indoor space. In *Proceedings of the 3rd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 1-6). ACM.

Zlatanova, S., Liu, L., & Sithole, G. (2013). A Conceptual Framework of Space Subdivision for Indoor Navigation.

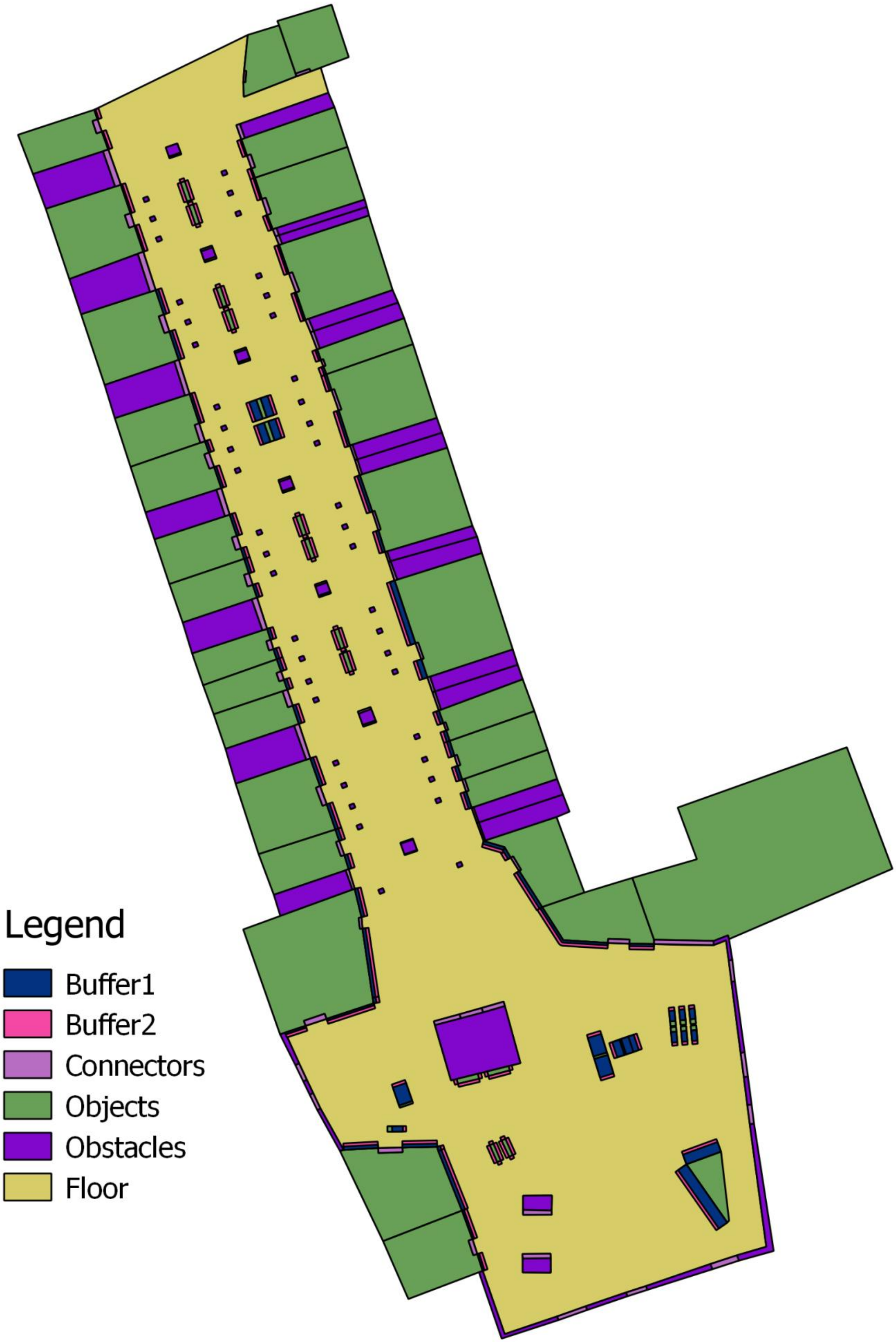
Appendices

Appendix A.

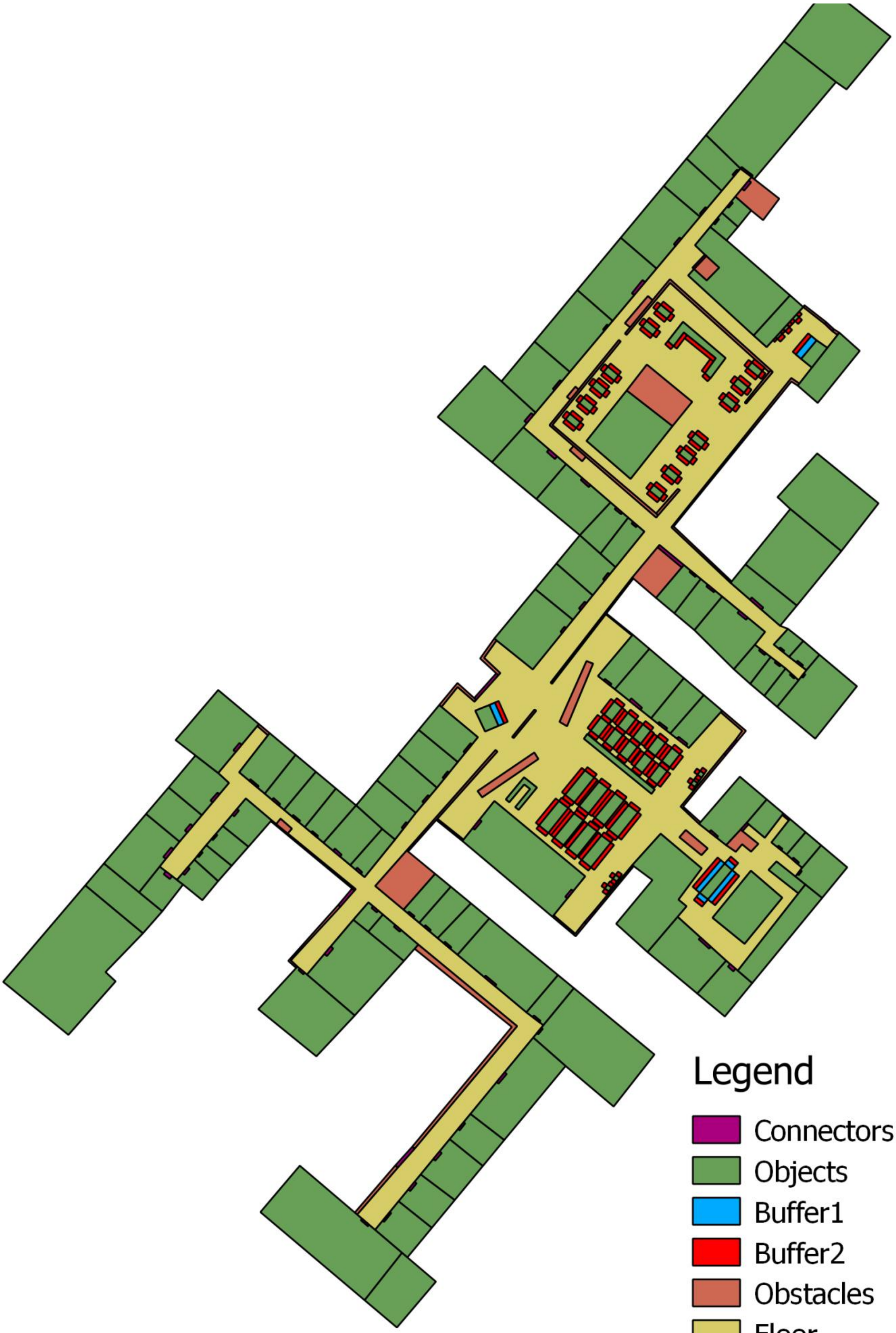
Initial functional areas in RC station during off-peak hour.



Initial functional areas in RC station during peak hour



Initial functional areas in BK faculty.

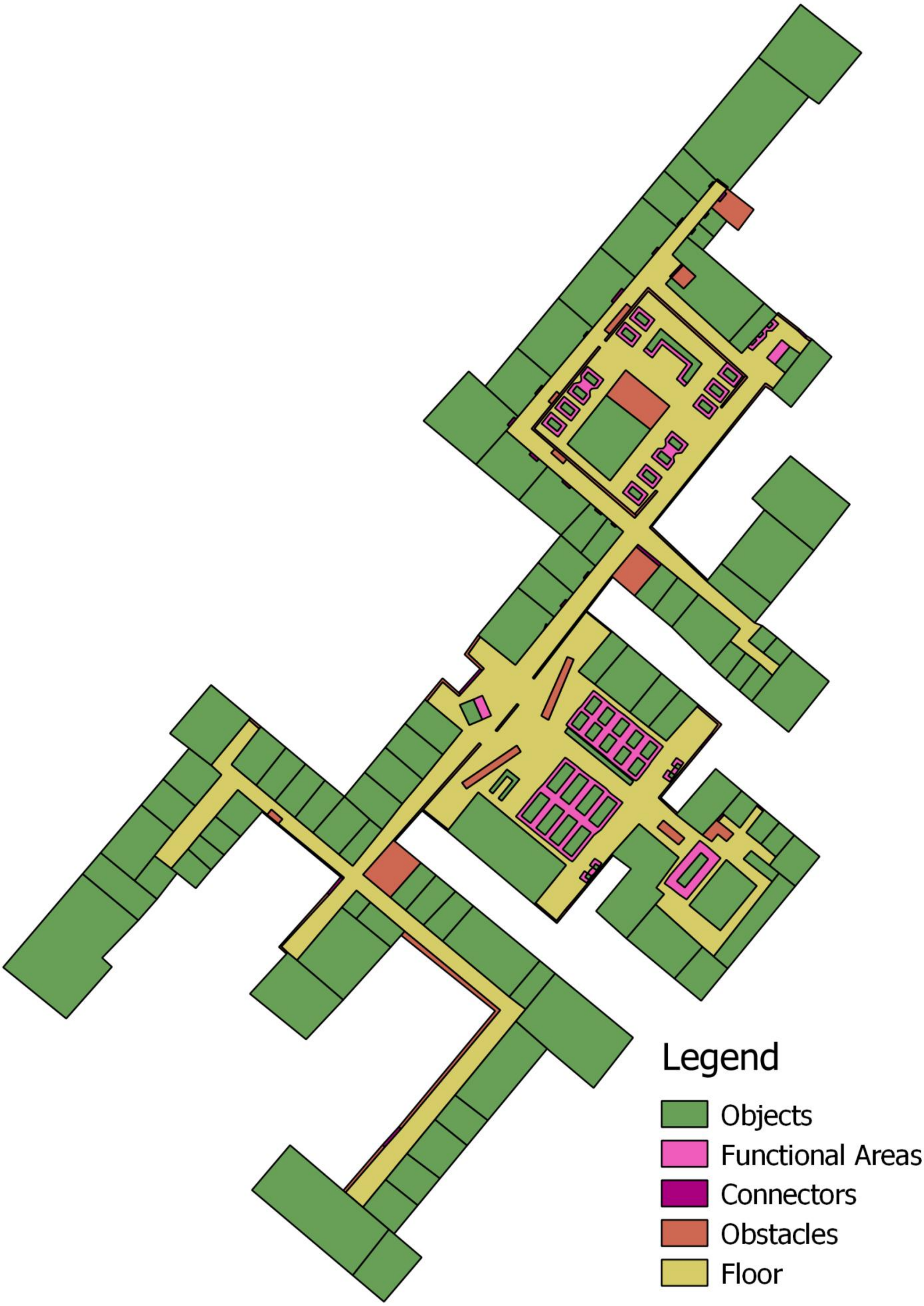


Appendix B.

Functional areas in RC station during off-peak hour

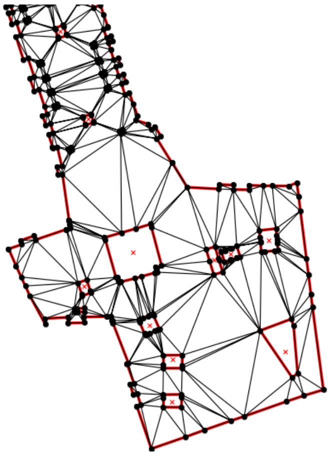
Functional areas in RC station during peak hour

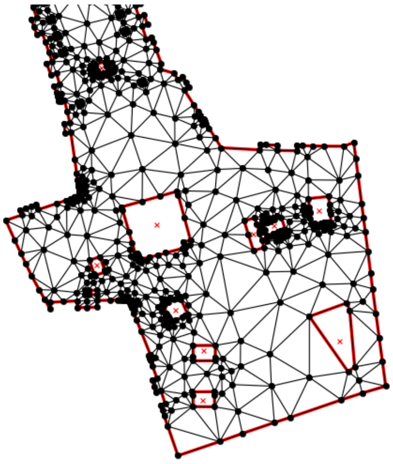
Functional areas in BK faculty



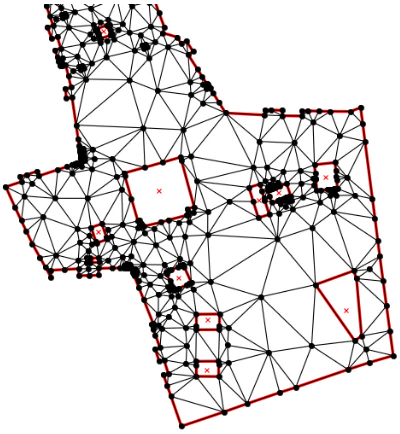
Appendix C.

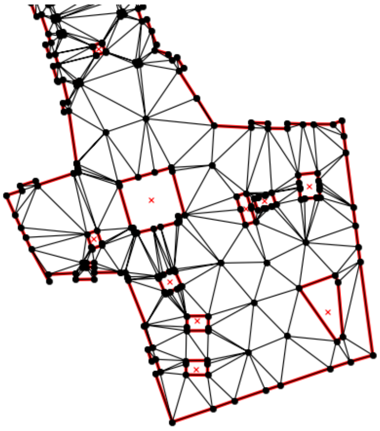
Left: CDT without any extra constraints. Right: CDT with minimum angle of 25° constraint in RC station.



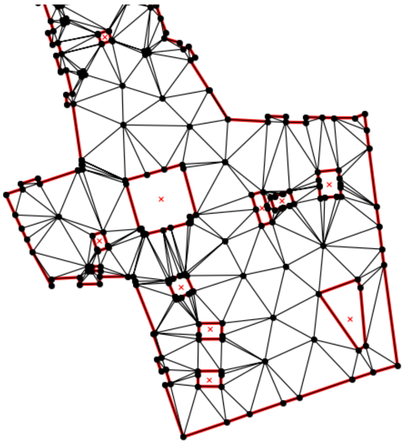


Left: CDT with maximum area of 350 (system units) constraint. Right: CDT with maximum area of 250 (system units) constraint in RC station.

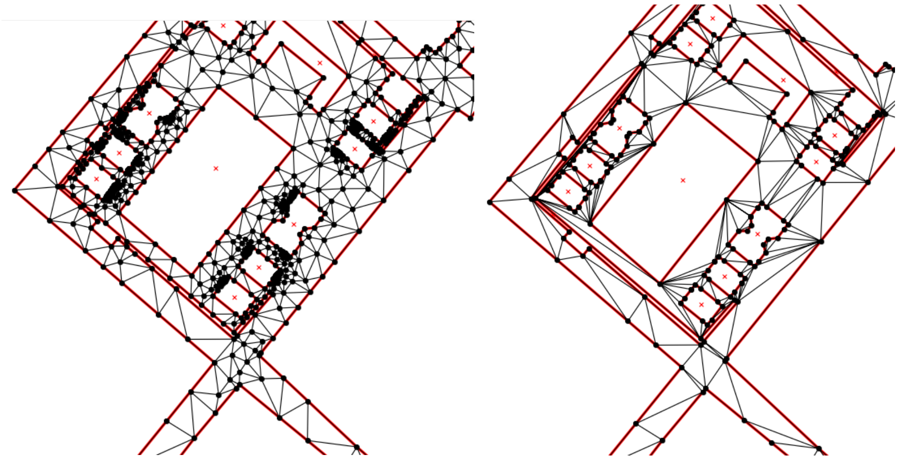




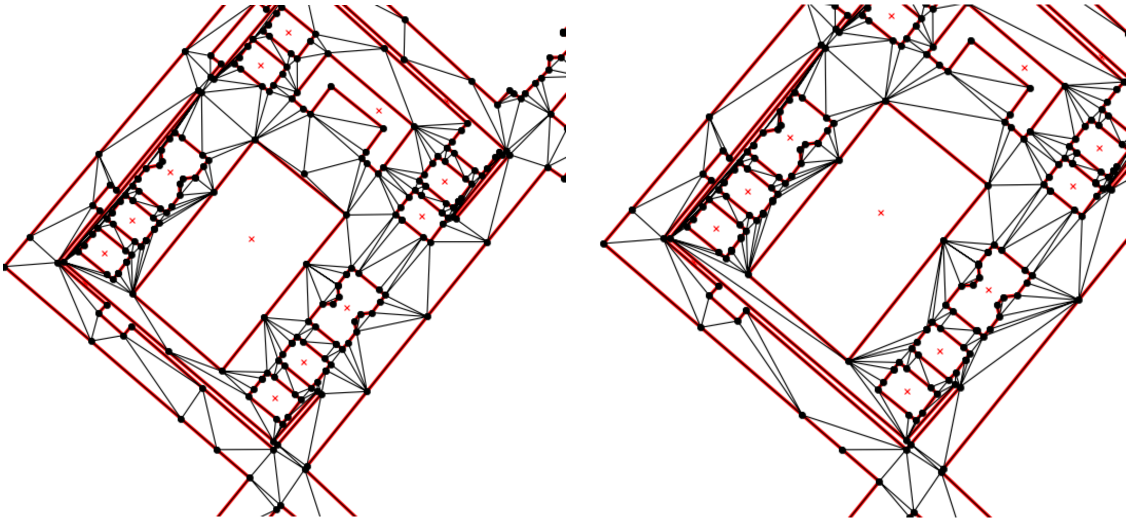
CDT with maximum area of 200 (system units) constraint in RC station.



Left: CDT with minimum angle of 25° constraint in BK faculty. Right: CDT with maximum area of 70 (system units) constraint in BK faculty.



Left: CDT with maximum area of 50 (system units) constraint in BK faculty. Right: CDT with maximum area of 100 (system units) constraint in BK faculty.



Appendix D.

Creation of buffers (parts)

```
# Create buffer column according to the properties of objects
with fiona.collection('Line_feature', 'r') as lines:
   # copy of the schema of the original file to the output
   # create new column for buffer calculations
   schema = lines.schema.copy()
   schema['properties']['buffer2'] = 'float'
      with fiona.collection('line_with_buffer', 'w', 'ESRI Shapefile', schema) as output:
         for ln in lines:
            res = {}
            res['properties'] = ln['properties']
            if ln['properties']['limited_cap'] == "no" and ln['properties']['trans_zone'] == "no":
               res['properties']['buffer2'] = ln['properties']['projection'] *
(ln['properties']['attractive']+ln['properties']['necessity']+ln['properties']['closeness'])+ln['properties']['private']
            elif ln['properties']['limited_cap'] == "no" and ln['properties']['trans_zone'] == "yes":
               res['properties']['buffer2'] = ln['properties']['trans_dist'] + ln['properties']['projection'] *
(ln['properties']['attractive']+ln['properties']['necessity']+ln['properties']['closeness'])+ln['properties']['private']
            else:
               res['properties']['buffer2'] = ln['properties']['private']
            output.write(res)

# Create buffers
from shapely.geometry import CAP_STYLE, JOIN_STYLE
class CAP_STYLE(object):
   round = 1
   flat = 2
   square = 3
class JOIN_STYLE(object):
   round = 1
   mitre = 2
   bevel = 3

with collection("lines_with_buffer.shp", "r") as input:
   schema = input.schema.copy()
   bufferDistance = input['properties']['buffer2']
   with collection (
   "Subspaces_buffer.shp", "w", "ESRI Shapefile", schema) as out:
      for line in input:
         out.write(
               {'properties':line['properties'],'geometry':mapping(shape(line['geometry']).buffer(bufferDistance, 1,2)}
               )
```

Removal of overlaps (parts)

```
with fiona.open(filename, 'r') as buffers:
   fiona_lst = list(c)
polygons = []
   polygon_id = 0
   for geom in fiona_lst:
      coords = geom['geometry']['coordinates']  #coordinates for geometry
      for ring in coords:
            polygons.append( [polygon_id, Polygon(ring[0:-1])  ,  geom['properties']['OBJECTID']] )
         polygon_id += 1
   #BBOX neighbours:
   neighbours = []
   for i in range(len(polygons)):
      neighbours.append([polygons[i][0],[]])
      bds = polygons[i][1].bounds
```

```
      p_bbx = box(bds[0],bds[1],bds[2],bds[3])
      for j in range(i+1,len(polygons)):
         if i==j: continue
         if polygons[j][1].intersects(p_bbx):
            neighbours[-1][1].append((polygons[j][0]))
      if not neighbours[-1][1]: #if polygon has no neighbours, remove it from list
         neighbours.pop(-1)
   overlaps = []
   for poly in neighbours:
      for neigh in poly[1]:
         if polygons[poly[0]][1].overlaps(polygons[neigh][1]):
            overlaps.append((poly[0],neigh))
   todelete = []
   for over in overlaps:
      if fiona_lst[over[0]]['properties']['Name'] == fiona_lst[over[1]]['properties']['Name']:
         removal = polygons[over[0]][1].union(polygons[over[1]][1])
         fiona_lst[over[0]]['geometry']['coordinates'] = [removal.exterior.coords[:]]
         todelete.append(over[1])
         fiona_lst[over[0]]['properties']['Shape_Area'] = float(removal.area)
      else:
         if fiona_lst[over[0]]['properties']['weight'] > fiona_lst[over[1]]['properties']['weight']:
            removal = polygons[over[1]][1].difference(polygons[over[0]][1])
            fiona_lst[over[1]]['geometry']['coordinates'] = [removal.exterior.coords[:]]
            fiona_lst[over[1]]['properties']['Shape_Area'] = float(removal.area)
         elif fiona_lst[over[0]]['properties']['weight'] < fiona_lst[over[1]]['properties']['weight']:
            removal = polygons[over[0]][1].difference(polygons[over[1]][1])
            fiona_lst[over[0]]['geometry']['coordinates'] = [removal.exterior.coords[:]]
            fiona_lst[over[0]]['properties']['Shape_Area'] = float(removal.area)
         else:
            if fiona_lst[over[0]]['properties']['Shape_Area'] < fiona_lst[over[1]]['properties']['Shape_Area']:
               removal = polygons[over[1]][1].difference(polygons[over[0]][1])
               fiona_lst[over[1]]['geometry']['coordinates'] = [removal.exterior.coords[:]]
               fiona_lst[over[1]]['properties']['Shape_Area'] = float(removal.area)
            else:
               removal = polygons[over[0]][1].difference(polygons[over[1]][1])
               fiona_lst[over[0]]['geometry']['coordinates'] = [removal.exterior.coords[:]]
               fiona_lst[over[0]]['properties']['Shape_Area'] = float(removal.area)
   output_geom = []
   for i in range(len(fiona_lst)):
      if i not in todelete:
         output_geom.append(fiona_lst[i])
   with fiona.collection("planar_partition_buffer2_BK.shp", "w",  crs=c.crs,
                  driver="ESRI Shapefile", schema=c.schema.copy()) as out:
      for g in output_geom:
         out.write(g)
```

Difference operation between initial navigable space and aggregated functional areas (parts)

```
floor = fiona.open("floor.shp")
fareas = fiona.open("aggregated.shp")
schema = floor.schema.copy()
with fiona.open('navigable.shp', 'w', 'ESRI Shapefile', schema) as difference:
   for geom in [shape(i['geometry']).difference(shape(j['geometry'])) for i,j in zip(list(floor),list(fareas))]:
      if not geom.is_empty:
         difference.write({'geometry':mapping(geom)})
```

Appendix E.

Navigation network generation and path calculation.

```
def simplifypath(pntlist, polygon):
   indxS = 0
   indxE = len(pntlist)-1
   while indxS<indxE:
      ls = LineString([pntlist[indxS][1:],pntlist[indxE][1:]])
      if ls.within(polygon):
         pntlist[indxS:indxE+1] = [pntlist[indxS],pntlist[indxE]]
         indxS +=1
         indxE = len(pntlist)-1
      else:
         indxE = int(len(pntlist[indxS:indxE+1]) / 2) + indxS
   return pntlist

floor = fiona.open(FILE)
connectors = fiona.open(FILE_CONNECTORS)
subspace = fiona.open(FILE_SUBSPACE)
dictGeom = []
triList = []
doors = []
polygonList = []
for each in floor:
   prop = each['properties']
   geom = each['geometry']
   v = geom['coordinates']
edges = []
holePoints = []
start = 0
# Determination of outerring and innerring of polygon
for ind, ring in enumerate(v):
   if start >0:
      pg = Polygon(ring)
      hole = pg.representative_point().coords[:]
      holePoints.append(hole)
   elif start == 0:
      polygonList.append(Polygon(ring))
   v[ind] = ring[0:-1]
   length = len(v[ind])
   for i in range(0, length):
      edges.append([start + i, start + ((i + 1) % length)])
   start = start + length
# Merge allpoints in the inner and outer ring in one list
pointsMerged = list(itertools.chain(*v))
# Store results
if holePoints:
   dictGeom.append(dict(vertices=array(pointsMerged), segments=array(edges),
holes=array(holePoints)))
else:
   dictGeom.append(dict(vertices=array(pointsMerged), segments=array(edges)))
# Peform Constrained Delaunay Triangulation and store triangles in the list
for ind, d in enumerate(dictGeom):
   t = triangle.triangulate(d, 'pa200')
triList.append(t)
# Find edges of trianglges
neighbors = []
triPolygons = []
triLines = []
centroidPointsList = []

for tri in triList:
   points = []
   polyTriList = []
   LineTriList = []
   vertList = tri['vertices']
   triInd = tri['triangles']
   centroidPoints = []
   for t in triInd:
```

```
        points = vertList[t].tolist()
        points.append(points[0])
        lines = LineString(points)
        L = lines.coords[:]
        LineTriList.append(L)
    triLines.append(LineTriList)

# Calculation of central points of triangles
for tri in triList:
    points = []
    polyTriList = []
    vertList = tri['vertices']
    triInd = tri['triangles']
    centroidPoints = []
    for t in triInd:
        points = vertList[t].tolist()
        points.append(points[0])
        polygon = Polygon(points)
        polyTriList.append(polygon)
        cPoint = polygon.centroid
        c = cPoint.coords[:]
        centroidPoints.append(c[0])
    triPolygons.append(polyTriList)
    centroidPointsList.append(dict(vertices=array(centroidPoints)))

ng =[]
for ind, polygon in enumerate(polyTriList):
    for otherInd, otherPolygon in enumerate(polyTriList):
        if not (ind == otherInd):
            mPolygon = MultiPolygon([polygon, otherPolygon])
            if not mPolygon.is_valid:
                ng.append([ind, otherInd])
neighbors.append(ng)
networkPoints = []
networkEdges = []
informationNetworkPoints = []
for ind, each in enumerate(centroidPointsList):
    lengthNetwork = len(networkPoints)
    vertices = each['vertices'].tolist()
    edges = neighbors[ind]
    for e in edges:
        e[0] = e[0] + lengthNetwork
        e[1] = e[1] + lengthNetwork
        networkEdges.append(e)
    networkPoints.extend(vertices)

# Link connectors to the network
lengthNetwork = len(networkPoints)
connectorPoints = []
connectorNodeIDs = []
infoType = []
infoName = []
for each in connectors:
    prop = each['properties']
    v = each['geometry']['coordinates']
    infoType = each['properties']['Type']
    infoName = each['properties']['Name']
    connectorsPolygon = Polygon(v[0])
    con = connectorsPolygon.representative_point().coords[:]
    connectorPoints.append(con)
for ind, con in enumerate(connectorPoints):
    shortestDistance = float("inf")
    winner = 0
    for ind2 in range(0, lengthNetwork):
        np = networkPoints[ind2]
        dis = Point(con).distance(Point(np))
        if dis < shortestDistance:
            winner = ind2
            shortestDistance = dis
    index = ind+lengthNetwork
    networkEdges.append([index, winner])
```

```
    networkPoints.extend(con)
    connectorNodeIDs.append(index)

#Calculation of centroids of subspaces
lengthNetwork = len(networkPoints)
subspacePoints = []
subspaceNodeIDs = []

for each in subspace:
    prop = each['properties']
    v = each['geometry']['coordinates']
    subspacePolygon = Polygon(v[0])
    sub = subspacePolygon.representative_point().coords[:]
    subspacePoints.append(sub)

for ind, sub in enumerate(subspacePoints):
    shortestDistance = float("inf")
    winner = 0
    for ind2 in range(0, lengthNetwork):
        np = networkPoints[ind2]
        dis = Point(sub).distance(Point(np))
        if dis < shortestDistance:
            winner = ind2
            shortestDistance = dis
    index = ind+lengthNetwork
    networkEdges.append([index, winner])
    networkPoints.extend(sub)
    subspaceNodeIDs.append(index)

# Calculate the cost of each edge by using the distance between two points
costEdges = []
for e in networkEdges:
    sPoint = Point(networkPoints[e[0]])
    tPoint = Point(networkPoints[e[1]])
    cost = sPoint.distance(tPoint)
    costEdges.append(cost)

connection = psycopg2.connect(database = DBNAME, user = USERNAME,
password = PASSWORD, host = HOST, port=PORT)
cursor = connection.cursor()
cursor.execute('TRUNCATE nodes')
cursor.execute('TRUNCATE edges')
#cursor.execute('TRUNCATE subspaces')
for nodeID, np in enumerate(networkPoints):
    SQL = "INSERT INTO nodes (nodeID, the_geom, name, type) VALUES (%s, ST_PointFromText(%s, 3857), %s, %s)"
    pointText = asPoint(array(np)).wkt
    data = [nodeID, pointText]
    cursor.execute(SQL, data)

for edgeID, ne in enumerate(networkEdges):
    SQL = "INSERT INTO edges (edgeID, source, target, cost) VALUES (%s, %s, %s, %s)"
    data = [edgeID, ne[0], ne[1], costEdges[edgeID]]
    cursor.execute(SQL, data)
connection.commit()
SQL = "SELECT nodeID, ST_X(the_geom), ST_Y(the_geom) FROM (SELECT id1 FROM pgr_astar('SELECT edgeID \
as id, source, target, cost, x1, y1, x2, y2 FROM (SELECT edgeid, source, target, cost, x1, y1, st_x(the_geom) as x2, \
st_y(the_geom) as y2 FROM (SELECT edgeid, source, target, cost, st_x(the_geom) as x1, st_y(the_geom) as y1 \
FROM edges JOIN nodes ON source = nodeID) AS test JOIN nodes ON target = nodeID) AS test2', \
777, 779, false, false)) AS test3 JOIN nodes ON id1 = nodeID;"
cursor.execute(SQL)
rows = cursor.fetchall()
print rows
cursor.close()
connection.close()
poly = list(groundfloor)[0]['geometry']['coordinates']
if len(poly) > 1:
    walkableAREA = Polygon(poly[0],poly[1:])
else:
    walkableAREA = Polygon(poly[0])
newrows = simplifypath(rows, walkableAREA)
print [x[0] for x in newrows]
```