Indoor Signposting and Wayfinding through an Adaptation of the Dutch cyclist Junction Network System

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Master thesis

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Delft, January 2015

Terms and Definitions

Conforming Delaunay Triangulation: A triangulation type where the initial constrained segments are subdivided into several edges by the insertion of additional vertices called Steiner points in order to preserve for all the generated triangles the Delaunay criterion (empty circumcircle)

Constrained Delaunay Triangulation: It is a constrained triangulation which is as much Delaunay as possible. The constraints are in terms of edges - certain required segments are forced into the triangulation. The circumscribing circle of any facet of a CDT contains in its interior no data point visible from the facet.

Decision Point: Nodes where re-orientation is required and where a choice among several possibilities has to be made.

Delaunay Triangulation: A triangulation is called Delaunay when the circumscribing circle of any facet of the triangulation contains no vertex in its interior.

Landmark: any salient object, which is easily identified and in contrast to its environment.

Medial Axis Transform: The medial axis of a polygon is the set of points internal to a polygon that are equidistant from and closest to at least two points on the polygon's boundary (*Lee, 1982*). Because of its shape, the medial axis of a figure is also known as its skeleton or symmetric axis.

Mesh: A mesh is a partition of a given region into simplices whose shapes and sizes satisfy several criteria. The domain is the region that the user wants to mesh. It has to be a bounded region of the region and it is defined by a PSLG.

Planar Straight Line Graph (PSLG): It is a set of segments such that two segments in a set are either disjoint or shape an endpoint. The segments of a PSLG are constraints that will be represented by a union of edges in the mesh. The PSLG can also contain isolated points which appear as vertices of the mesh. A **graph** that can be embedded in the plane without crossings in which every edge in the graph is a straight line segment. It is sometimes referred to as planar subdivision or map.

Triangulation Axes: An algorithm which serves as an alternative of the Medial Axis Transform that creates a skeletal structure of a polygon with straight-line elements.

Wayfinding: It is the process of determining and following a path or route between an origin and a destination. It is a directive, purposive and motivated activity.

Abstract

Finding one's way in complex indoor settings can be a quite stressful and time-consuming task, especially for users unfamiliar with the environment. There have been several different approaches to provide wayfinding assistance in order to guide a person from a starting point to a destination, ranging from traditional maps and signposting systems to the most recent developments of navigation systems displaying direction information on a mobile device screen. However, so far none of them has emerged to be efficient enough in order to act as a uniform solution for the wayfinding problem in indoor environments. Moreover, referencing to landmarks is not widely employed by wayfinding assistance systems despite the fact that landmark-based navigation is the most common way for people to navigate themselves through unfamiliar environments.

The aim of this work is to propose a new wayfinding assistance method for indoor environments that makes use of the landmark concept. The method to achieve it is by translating the main principles of an already existing outdoor system named Junction Network System, which applies successfully for providing guidance to cyclists in The Netherlands. The most important parameter of the system is that assistance is provided to users where they actually need to make a directional choice. The first step is to automatically define the locations, i.e. the decision points, where wayfinding assistance is needed in indoor settings and the second is to supply them with a special type of landmark which will have the form of a signpost that provides all the necessary information. A graph based representation of the indoor setting is generated in order to extract the decision points and create the network of all possible routes in the environment.

The conceptual framework for the determination of the decision points is implemented in two case studies: GeoFort main building and the Faculty of Architecture and the Built Environment (BK) of TU Delft. Two different building cases are used in order to gain an insight on how the system can be applied in different indoor environments. The part of the navigable indoor space where movement mainly occurs when people are in search of a destination was subdivided according to a geometric criterion (Constrained Delaunay Triangulation) while also the semantics of the space were taken into account in order to determine the decision points. By connecting all the decision points and the destinations a network of all the possible routes is created. A route is followed by referring to the sequence of numbers corresponding to the nodes of the network.

The proposed system was verified based on a human-based survey. The proposed landmark-signs were installed at part of the faculty of Architecture and users were asked to find their way in the building relying only on them. The time to reach the destination and the number of detours were

counted, while a questionnaire-based survey was used in order to further investigate the feelings and views of participants regarding the effectiveness of the system. The findings of the experiment are quite promising, as the performance of the participants in both measures was very good. Additionally, the results of the questionnaire indicate that users consider the system simple and comprehensive and they are in general satisfied by the provided assistance. However, further implementation and testing in more indoor space cases is needed in order to draw an indisputable conclusion about its effectiveness. Nevertheless, an important contribution of the research is the generation of a conceptual model in order to automatically determine the decision points in indoor environments that this can be applied invariable to other wayfinding assistance systems.

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1. Introduction

In recent years, navigation has become a very active research area with a wide range of application fields. Navigation, also called as finding one's way, whether in real or electronic world, is a fundamental but also complex human activity (*Burnett, Smith & May, 2001*). Two different approaches are usually employed by people when they are navigating in a space; path integration and landmark-based navigation (*Fallah et al., 2012*). In the first one people orient themselves relative to a starting position using proprioceptive data, while in the second one they rely upon perceptual cues combined with an external or cognitive map. In landmark-based navigation, users change from one reference point (landmark) to another reference point as they navigate in the environment, taking into account the relative positions of the landmarks. In this case the individual uses a physical or cognitive map of the environment. By recalling from memory the landmarks and their spatial relationships, their current position and orientation can be estimated based on the distance and angles relative to one or multiple landmarks.

Navigation can be conceptualized as consisting of two components: wayfinding and locomotion. Wayfinding refers to the requirement to know where to go and how to get there and forms the goal-directed and planning part of navigation while locomotion refers to the real-time part of navigation, in which the move is executed successfully in the intended direction while avoiding injuries and obstructions (*Montello & Sas, 2006*). Successful wayfinding requires that people are firstly capable of orienting themselves in space, namely to know where they are located and in which direction they are facing. Then, planning a route and following the planned route while maintaining a real-time understanding and heading is necessary. In all these three stages, which are depicted in figure 1.1, people access stored knowledge about the space or employ wayfinding aids or do both.

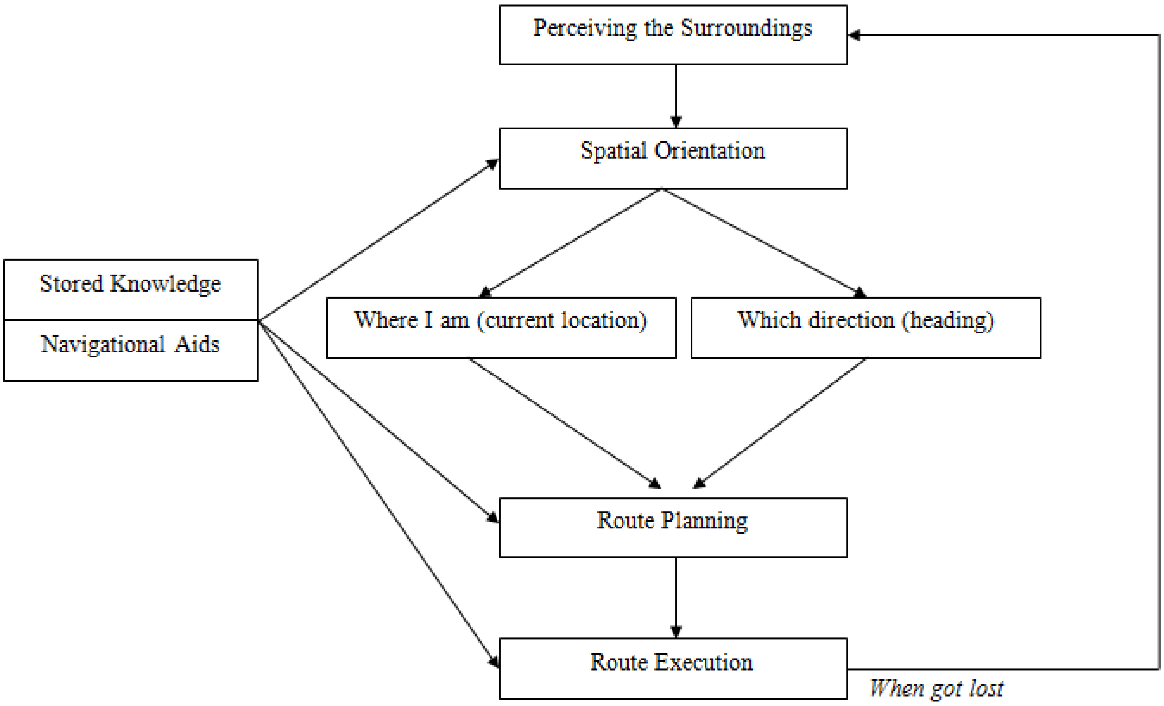

Figure 1.1: Stages involved in wayfinding process (*Ishikawa et al., 2008*)

1.1 Motivation

Finding their way through an environment is for some people an effortful task as the perception and comprehension of the surroundings may differ significantly among individuals (*Allen, 1999; Ishikawa et al., 2008*). Thus, people are used to employ various wayfinding assistance means in order to facilitate the wayfinding experience. External support in order to enhance wayfinding is available for cars and motorbikes as well as for bicycles and pedestrians. Despite the fact that navigation systems have primarily been developed for vehicles, wayfinding in indoor environments has emerged to be a significant field of interest as people spend most of their times indoors. Searching for a destination in a complex indoor setting is a process that people repeatedly go through in their daily life. This process may be as easy as moving from one room to another or as difficult as trying to escape a building on fire. Therefore, indoor spaces should be effectively navigable and people need to know how to find the way from their current location to their destination. This implies that people need to know their current location in the indoor space, the layout of the building and the location of their destination in order to formulate their action plans.

Without the support of external navigation aids people have to rely on common knowledge about the structure of buildings, on their previous experience and on the visual input they encounter while moving in the building (*Holscher et al., 2007*). However, this is not always an easy task. The conceptualization of wayfinding as spatial problem solving incorporates information processing, decision making or planning and decision execution (*Passini, 1992*). Wayfinding requires solving problems involving explicit decision-making, such as selecting routes to follow, orienting towards non-perceptible landmarks and scheduling trips (*Montello & Sas, 2006*). Moreover, the sense of orientation in indoor spaces is affected by several parameters. Firstly, indoor space is characterized by the existence of the third dimension which is expressed though the different floor levels (*Brunner-Friedrich & Radoczky, 2006*). Vertical movement can have a serious impact on the wayfinding performance. Moreover, indoor environments are composed of smaller, fragmented spaces, with a limited field of view and change of direction is imposed more often than outdoors.

Consequently, people encounter significant difficulties in the pursuit of their destination target when they are navigating in unfamiliar indoor environments. Especially in semi-public buildings, such as airports and train stations, hospitals, offices or university buildings, individuals often fail to find their way immediately or under time pressure without external information and would, therefore, benefit from a well-established system offering wayfinding assistance (*Millonig & Schechtner, 2007*). Humans depend mainly on wayfinding directions, either provided by other people or given by maps or other wayfinding services. People use landmarks when they give route directions to anchor actions in space or to provide confirmation that the right track is still being followed (*Michon & Denis, 2001*). However, while it is proved that directions provided by people are based on using landmarks as references, especially at decision points, the directions given by wayfinding services are generated based on the geometry of the space.

In the past decades, empirical research has established the importance of landmarks in our understanding of and communication about space (*Lynch, 1960; Michon & Denis, 2001; Raubal & Winter, 2002; Snowdon & Kray, 2009*). Landmark-based navigation is the most natural concept for humans to navigate themselves through their environment, especially in new and unfamiliar environments where wayfinding may be a time consuming and even challenging task, as in this type of navigation people choose a readily-identifiable feature of the general landscape and use it as a base. They can move out from the base to explore, return to the base whenever they get lost or whenever they want to start over and explore in a different direction. When they become familiar with an area, they may move from one landmark to another in order to navigate through larger spaces. It has already been proved by empirical research that by using landmarks the wayfinding task can be significantly simplified (*May et al., 2003*). The outcome of spatial-cognition studies reveal the importance of salient objects for orientation and navigation. Wayfinding process based on landmarks relies on the presence of landmarks at each point along a route where wayfinders might need assistance. More research is necessary in the field of landmark integration in wayfinding assistance task in indoor environments.

Signposts can play a special role when they are used as landmarks. They have the potential of serving as distinctive, recognizable and salient landmarks while at the same time they can provide additional information (*Fontaine & Denis, 1999; Millonig & Schechtner, 2007*). Therefore, it will be advantageous for wayfinding assistance systems to refer to signposts for routing purposes. It is a common fact that signage is the most commonly employed physical means of enhancing wayfinding efficiency in indoor environments. Most building complexes posses wayfinding systems in the form of building and room names, directional signs or other graphical elements. Various types of signage systems are encountered in our daily experience in order to support wayfinding process in indoor environments. However, there is no common reference regarding the type, language and nomenclature used in the signs or the locations of providing assistance. Additionally, several limitations can be detected regarding the comprehensibility, legibility, amount of presented information, language, change of direction marking and position of placement.

Airports, train stations, hospitals, university and office buildings are some of the building cases where an effective signage system can significantly contribute to a better organization of the space and its resources and the facilitation of visitors experience. For example, airport signs are the primary means of guidance of passengers in the environment, as they are needed to show the way for finding the gates, transfers, toilets or even the coffee corners. However, there is no standard regarding the signs that are used in the various airports throughout the world. Schiphol airport in Amsterdam with the characteristic yellow-coloured signposts (Figure 1.2) is now considered as a benchmark upon which other airport signage systems are judged. Even in this case that the design is carefully planned, there are many people complaining that they are getting lost. Among the limitations that can be mentioned is that many information is provided in one sign so that people spend a lot of time trying to read it, that people in the airport have no indication of their position and they cannot orient themselves in space and that finding their way back at the entrance hall is not well-signed.

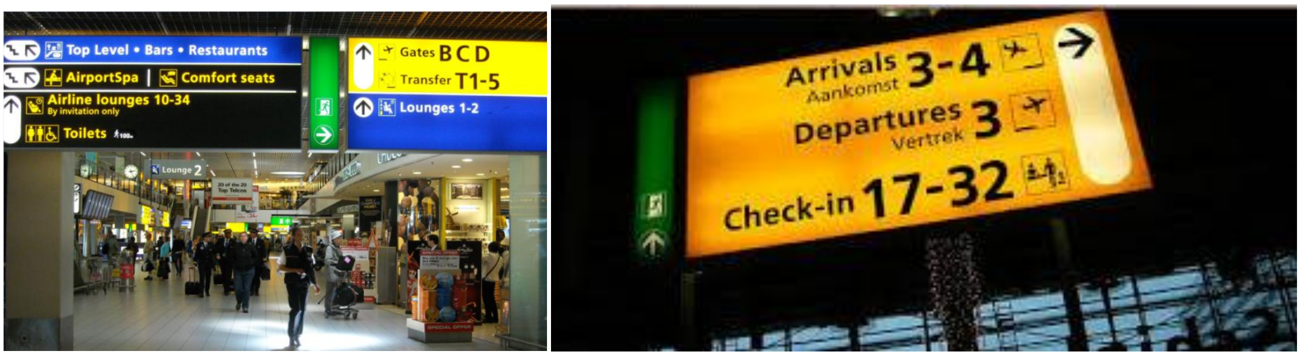

Figure 1.2: Schiphol airport signage system

University buildings is another example of indoor spaces where wayfinding assistance is organized around signposts. Also in this case there is a diversity in the types of signposts. Different types are encountered even among the faculties of the same university. In TU Delft faculties there is no consistency of their wayfinding assistance systems. In figures 1.3 and 1.4 the signage systems employed in some of the university faculties are illustrated.

Figure 1.3: Wayfinding signage system in 3mE faculty

At the faculty of 3mE the signs are ceiling-hung and they contain an inventory of the important rooms at every direction. One disadvantage of this system is that there is no confirmation sign that the right track is followed and it is not clearly signalled the point where the change of direction occurs. Moreover, the legibility of the sign is impeded by the fact that there is too much text in a considerable height. At the faculty of Architecture wall-mounted signs are identified throughout the entire building. In this building there is a better guidance, provided through a sequence of signs leading to some of the rooms. But this is not the case for all the parts of the building. Additionally, the Dutch language is used, which might be confusing for the international students. Finally, there is no strong contrast between the sign and the background resulting in a difficulty to be identified by first time visitors.

Figure 1.4: Wayfinding signage system in Architecture faculty

1.2 Objectives and Research Questions

The ultimate goal of this research is to propose a wayfinding assistance system that can be applied to several indoor environments in order to direct users to a pre-determined destination by incorporating the concept of landmark. The term landmark in this research is used to indicate prominent physical objects that can be used in order to indicate people's location in complex buildings and guide them to their destination. The emphasis is given not only on the visual attributes of objects but mainly on the importance of the location of their presence as fundamental parameter for the provision of direction instructions to facilitate the wayfinding task.

Consequently, in this work a wayfinding system which makes use of physical objects is presented. This pragmatic solution avoids challenges that are associated with mobile indoor navigation assistance (e.g., positioning technologies). The first objective of the research is the determination of the decision points in indoor environments, which are the points along a route where people need wayfinding assistance. A computational model is proposed in order to automatically calculate the decision points. Special signposts are proposed to be installed at the decision points in order to provide location and directional information. Therefore, the second objective is to create a special type of landmark for indoor environments which will be in the type of signposts and which can be easily recognized and remembered. The signs in indoor environments serve as landmarks in human's perception; and landmarks can be used to mark the way. Consequently, the main concept of the system is that pedestrians will follow a sequence of graphical-given instructions delivered at key points along a set of routes in order to reach a destination.

The method to achieve the development of a successful indoor wayfinding system is by reviewing the current theory and practices regarding wayfinding and landmarks and by translating the principles of an outdoor wayfinding system which applies successfully for the case of providing directional instructions to cyclists and adapting it to the case of indoor space.

RESEARCH QUESTIONS

The main question that is to be answered in this work is stated as:

How can the principles of the Junction Network System be applied in order to enhance wayfinding in the context of indoor navigation?

In order to address all the parameters regarding the main question a list of sub-questions follows, which gives also an overview of the steps that are going to be performed in order to reach to the final result.

1. What are the principles of Junction Network System as it is applied for cyclists?

2. How can the decision points be determined in indoor environments and how will they be connected?

3. Where should the landmark-signs be located in order to become prominent objects?

4. What kind of landmark-signs will be used and how many different types of them are needed in order to make the system applicable?

5. How many landmark-signs are needed in order to provide a full coverage of the indoor space without confusing the user?

6. What are the principles of the Junction Network System for Indoor Environments?

7. What is the reliability of the proposed approach?

1.3 Research Methodology

The ultimate target of this work and at the same time the final product to be derived is an indoor wayfinding assistance system , which will be based on the presence of physical objects at landmark locations so that all possible routes to be easily determined. In order to achieve the expected result, the research process was split into four main phases, as outlined below.

1. **Literature Review**: through literature study the properties of indoor space and the information requirements of pedestrians concerning the wayfinding task are examined in order to gain an insight in their spatial and temporal behaviour. Current approaches of outdoor and indoor wayfinding are investigated. The literature review particularly elaborates on the "knooppuntensysteem" or 'Junction Network System' approach in order to obtain a deep understanding of the system and its benefits and limitations. Moreover, a significant interest in this initial phase lies on the role of landmarks and signposts in wayfinding task and the practices already used in order to support a person in finding his way in a complex environment. The acquired knowledge from the literature review serves as a basis in order to understand the basic concepts and apply them for the purpose of indoor wayfinding.
2. **Design of Junction Network System for Indoor Environments Principles**: the whole set of rules of how the system should look like for indoor environments is defined. All the important decisions related to how the system is formed are taken and the working principles of the system are clarified. The indoor wayfinding system presented in this work is founded on a framework of rules derived by the translation of the principles of the original outdoor Junction Network System to the case of indoor wayfinding. The navigable indoor space of interest for this approach is defined and a computational model for the decision points determination is developed. Additionally, the design of the landmark-sign to be used is specified.
3. **Implementation of the System**: the proposed system is implemented by applying the theoretical concept to two different building cases. 2D floor plans of the buildings and QGIS software is used in order to visualize indoor space and locations of landmarks-signs. The navigable indoor space for the purpose of this approach is subdivided according to the Constrained Delaunay Triangulation criterion, considering also the semantics of the objects, and a network of the possible routes in the building is created. The decision points are determined based on the above mentioned space partitioning and the system is completed by

placing the proposed landmarks-signs at the decision points. Thus, a network of landmark-signs is created to map out any desired route.

4. **Verification of the reliability**: The system is tested in Architecture Faculty building in TU Delft by installing the proposed landmarks-signs in parts of the building. The deployment of the landmarks-signs follows the rules set for the decision points. In order to prove that the proposed conception is applicable, a human based survey is conducted. The aim of the survey is to observe people while moving in the building and get information about their behaviour and more specifically the role that the installed landmarks-signs play in their decisions. The time to reach the destination and the times of getting lost are the main measures to assess the performance of the system. Additionally, a questionnaire-based survey is used to reveal participant's personal opinion on the usability of the system. In that way the reliability of the proposed landmarks-signs in order to provide guidance is practically examined.

1.4 Structure

The remainder of the report is structured according to the discrete stages of the abovementioned methodology. The second chapter provides a thorough literature review on the human wayfinding process and the current wayfinding approaches in indoor space, the landmark theory and the use of route directions in wayfinding process. Later on, in chapter 3 the original Junction Network System is presented and its main principles are discussed. In chapter 4 the framework of rules for the proposed Junction Network System for Indoor Environments is discussed, while chapter 5 contains that implementation of the proposed concept in two building cases. Chapter 6 presents and analyses the results of the validation test of the adapted indoor system in the Faculty of Architecture and the Built Environment. Finally, the last two sections discuss the findings with respect to the initial research questions and provide the conclusions and the contribution of this work and recommendations for further investigation.

2. Related Work

Wayfinding is the process of determining and following a path or route between an origin and a destination. It is a purposive, directed and motivated activity (*Golledge, 1999*). Landmarks are used in two distinct contexts in studies of spatial development. The first one is spatial orientation and processes of wayfinding. The other one is the representation of spatial knowledge (*Presson & Montello, 1988*).

The inclusion of landmarks in wayfinding instructions requires two steps: a) the identification of features that can act as references and b) the integration of these objects into the generated direction instructions. Often these two approaches are seen as independent (*Richter, 2013*). In this section the relevant literature on human wayfinding research and common used wayfinding approaches for outdoor and indoor environment, as well as landmark characteristics and their use in wayfinding processes is reviewed.

2.1 Human Wayfinding

The term wayfinding was firstly introduced by the architect Kevin Lynch in 1960 in his book named 'The Image of the City', where he identified that the five principal elements that people use in order to organize their images about the city are: paths, landmarks, regions, edges (barriers) and nodes (intersections). According to his research the imageable or memorable features of the space like landmarks, regions and nodes are employed by humans in order to enhance wayfinding. Landmarks are memorable locations that help to orient the navigator; regions are distinct areas that place him in one part of the environment; and nodes mark points where wayfinding decisions are made. Since a navigator uses these features to record his past route-following experiences, a designed space that employs them should be more effectively navigable. Lynch also identifies maps, street numbers, directional signs and other elements as 'wayfinding devices'. His book is considered to be the foundation of human wayfinding research.

Passini and Arthur (*1992*) describe wayfinding as a two-stage process during which people have to solve a wide variety of problems in architectural and urban spaces that involve both 'decision making' (formulating an action plan) and 'decision executing' (implementing the plan). It is common the term navigation to be used synonymously with the term wayfinding by researchers. However, the term wayfinding is broader than the term navigation, which refers to the specific means by which people find their way.

Human wayfinding research investigates the processes that take place when people orient themselves and navigate through space (*Raubal and Egenhofer, 1998*). Several theories have been developed in order to address issues such as how people find their ways in the physical world, what they need in order to find their way, how they communicate directions and how their abilities affect wayfinding. Successful wayfinding means that a goal or destination is being reached efficiently. In order to be achieved this goal, people need to have spatial knowledge and various cognitive abilities (*Raubal and Egenhofer, 1998*). McNight, Dillon and Richardson (*1993*) summarize the three primary ways that people employ in order to find their way: landmark-navigation, in which people select easily identifiable points of reference in the environment and use them as a base, route-navigation, in which they put the landmarks in a sequence creating navigation paths and they navigate in the space by learning routes between locations, and map-navigation in which people create a general frame of reference (mental/cognitive map) containing the spatial relationships between objects and use it to navigate. People's perception of the real world develops gradually through these three levels by recording information about the environment. Accordingly, for successful wayfinding information about the environment - what is in the environment and where it is - are required.

Wayfinding is basically about effective communication, and relies on a succession of communication clues delivered through peoples sensory system of visual, audible, tactile and olfactory elements (*Apelt et.al, 2007*). Numerous types of environmental information can help people when they try to find their way within buildings. Weisman (*1981*) distinguished four classes of environmental variables which influence the wayfinding process. His results were configured by other researchers (*O'Neill, 1991*). These four categories are:

a. visual access to familiar cues or landmarks;
b. the degree of architectural differentiation between different parts of a building;
c. use of signs or room numbers; and
d. plan configuration.

The influence of each one of the abovementioned variables or of combinations of them on people's wayfinding performance has been examined in several studies. Some of them were focused on the relationship between floor plan complexity and wayfinding performance. More specifically, Weisman (*1981*) illustrated through a survey conducted with students in university buildings, that people are getting lost less frequently in buildings with simpler floor plans. O' Neill (*1991*) proved that when the floor plan complexity is increased, people's understanding of the spatial layout is decreased and consequently wayfinding performance. Additionally, from his study it is demonstrated that wayfinding performance is increased with the presence of signage. Another important conclusion made about signage is that while graphic signs increase the rate of travel, textual signs produce smaller amount of wrong turns and backtracking. However, the presence of signage is not able to compensate for the complexity of floor plans. The study of Garling, Lindberg and Mantyla (*1983*) demonstrated the importance of visual access as a factor of influence of the orientation and the wayfinding performance. Visual access refers to the degree to which different parts of the environment can be seen by different viewpoints (*Montello and Sas, 2006*). When visual access is restricted, orientation becomes difficult and wayfinding performance is decreased.

According to the degree of familiarity with the building the wayfinding strategy of the people can be changed. Hölscher et al. (2006) have proposed a categorization of the different wayfinding strategies which people use to employ in multi-level buildings. According to their research, inexperienced wayfinders rely mostly on a central point strategy by sticking as much as possible to a central part of the building even if it entails more detours (*Hölscher & Brösamle, 2007*). On the other hand wayfinders familiar with the environment use mainly the direction strategy or the floor strategy in order to find their way. The first one corresponds to choosing routes that head and lead directly at the horizontal position of the destination target irrespective of level-changes, while the second one focus on firstly finding the floor of the destination and later on the horizontal position (*Hölscher & Brösamle, 2007*).

Orientation is one of the fundamental requirements in order to achieve a successful wayfinding. Orientation refers to the ability of humans to be aware of their location relative to their destination and to other places or objects (*Montello and Sas, 2006*). The orientation requirements for a wayfinder can be quite coarse; it is important to know what is essential in order to reach the destination effectively and to avoid getting lost. Geographic disorientation can generate anxiety and frustration to the wayfinder. Humans can orient themselves in an environment through landmark-based and dead reckoning processes (*Montello and Sas, 2006*). The presence of landmarks aid place recognition while dead reckoning (or path integration) only provides information about the location of a place relative to the location of another place at which one was recently located. Dead reckoning processes are prone to errors as they can be accumulated if they are not corrected via landmark-based processes.

The information requirements of pedestrians in order to navigate successfully through an unfamiliar outdoor urban environment were investigated by May et.al (*2003*). The outcome of this research reveal the dominant place of landmarks as wayfinding assistance tools. This applies especially for objects that are visually prominent and familiar and are located on the pedestrian route. Another significant result of the research was that information is needed at key navigation decision points (i.e. nodes) but also between them in order to provide confirmation that the correct route is being followed and to maintain wayfinder's confidence and trust.

2.2 Wayfinding Approaches

People perform wayfinding tasks in unfamiliar environments relying on common-sense knowledge of the geographic space and their previous obtained experience. Wayfinding is a natural skill that people develop throughout their lives (*Raubal and Egenhofer*, *1998*). People find their way by trying to understand what the environment contains and how it is organized. However, in cases of complex environments people's natural wayfinding skills are not adequate in order to help them find their way. External information can simplify the wayfinding task. Therefore, several systems have been developed in order to provide wayfinding assistance. The most common way of navigating in indoor spaces is by using the information systems of the building comprising by maps and signs, while for outdoor environments there are several approaches according to the mode of locomotion, such as car navigation systems, signposts for aiding cars, bicycles and pedestrians. A successful wayfinding system should provide information to users to confirm they are at the correct start or finish point of an individual journey, to identify their location within a building or an external space, to reinforce they are travelling to the right direction, to orient themselves within a building or an external space, to understand the location and any potential hazards, to identify their destination on arrival and to escape safely in an emergency case (*Apelt et.al, 2007*).

One way of supporting someone on finding his way is by providing him with a verbal description of the decisions to be taken along a route orally. This is a useful method for simple routes and when the wayfinder is going to search his way immediately thereafter and the decisions are not too complex. One important disadvantage of this method is that the wayfinder may interpret the verbal description in a different way, especially when there is no unambiguous reference in the space to anchor the decision (*Freksa*, *1999*). Verbal descriptions are economical when there is only one route that is taken by all users. However, when the aim is to support finding different destinations from a given location, it makes sense to provide wayfinders with a map.

Maps are fundamental tools in the wayfinding process. Traditional paper map is the oldest mean of supporting wayfinding. They are extremely useful in orienting users to the space and they can become the first step of forming a mental representation of the environment. A route can be planned almost completely in advance. However, the route should be memorized and the progress should be verified by consulting the map regularly. Additionally, a map which is misaligned with respect to the current orientation of the wayfinder can be detrimental. This forms a common and usually encountered drawback of floor maps of buildings. Nowadays, digital maps and route descriptions on mobile devices are becoming more and more popular with the wide-spreading of smartphones and Google Maps applications as well as GPS maps. Various presentation formats of spatial information have been developed, such as verbal navigational instructions, static and interactive maps, 3D visualizations and animations. Although all these digital maps are frequently used in every day wayfinding, they do not provide the orientation of the direction of heading and sometimes the amount of details that is presented is more than what is necessary in order to avoid confusion. Ishikawa et.al (*2007*) conducted a research in order to compare the wayfinding behaviour and the acquired route knowledge received by humans navigating an environment using a GPS-based navigation system and maps and direct experience. It was found that people navigating using the GPS-based system travelled longer distances, stopped more times while searching for their destination and finally rated the wayfinding task more difficult than map-users did. The possible reasons of failure of GPS-based navigation system are the small size of the screen of the device compared to the paper map and the fact that people were focused only on the screen due to the continuously updated information presented and not to the surrounding space globally. Additionally, digital maps in mobile devices can act as a wayfinding support tool only for users familiar with technological advancements who possess a wireless mobile device. These systems are not helpful for inexperienced users.

Signage is a common used mean of enhancing wayfinding process, especially in indoor spaces with complex floor configuration. Different types of signage exist such as labels, room numbers, arrows, you-are-here maps and text directions. Several studies indicated the positive relationship between signage and wayfinding performance. For example, according to Best (*1970*), signs placed at decision points in buildings improve the wayfinding performance. Additionally, wayfinding performance is also improved by the addition of signage in the reception area of complex buildings. Navigating by signs is very straight-forward and no information is to be memorized (*Hölscher et.al, 2007*). However, there are studies that find signage less than effective in wayfinding support. According to Weisman (*1987*), people rely more on architectural features rather than on signs in order to find their way. Moreover, other research indicated that people may have problems to understand the signs or even confusion is generated when there are too many signs. Despite these limitations of signage systems it is the primarily employed means of wayfinding support in indoor environments.

The performance of the previously mentioned approaches in supporting wayfinding in indoor environments can be evaluated according to certain criteria, having as an ultimate objective the quest of the most suitable approach to become a uniform solution. These criteria are the following:

a. successfully reach the destination without getting lost
b. indisputable interpretation of the information
c. provide confirmation that users are on the correct start or finish point
d. identification of the location of the user in the space
e. provide confirmation that users travel on the right direction
f. users are able to orient themselves in space
g. recognition of the destination upon arrival

Criteria/Approach	Route directions given by humans	Traditional maps	Signage Systems	Digital wayfinding services
a	-	-	-	-
b	-	-	-	-
c	-	-	+	-
d	-	+	-	+
e	-	-	-	-
f	-	+	-	+
g	-	-	+	-

- not sufficiently effective; + effective

From the table it becomes obvious than none of the above mentioned approaches is able to fulfil all the criteria in order to dominate over the rest and become an overall solution. Route directions is the less effective of all as none of the criteria is fulfilled. Each one of the rest has advantages over the others at different points. The strong points of traditional maps and digital wayfinding services are the fact that they provide also location information to the user and they facilitate the orientation in the space, even if it is difficult for some users to orient themselves in space especially when using paper maps. On the other hand signage systems confirm that the user is located at a certain location in the building and also the arrival at a destination.

2.3 Landmarks

Presson and Montello define landmarks as features that are relatively well-known and which define the location of other points. According to them anything that sticks out from the background can serve as a landmark (*Presson and Montello, 1988*). Landmarks are stationary, distinct, and salient objects or places, which serve as cues for structuring and building a mental representation of the surrounding area. Any object can be perceived as a landmark, if it is unique enough in comparison to the adjacent items (*Millonig and Schechtner, 2007*). From the previous definitions it becomes evident that the concept of landmark is bound on the prominence of an object in the environment.

Landmarks can be classified from various points of view. Sorrows and Hirtle (*1999*) categorize landmarks based on their visual peculiarities (visual landmarks) as well as their use or meaning (semantic landmarks) and their structural properties. The characteristics that define the salience of an object are according to Sorrows and Hirtle:

- singularity, i.e., contrast with surroundings;
- prominence of spatial location;
- content, i.e., meaning or cultural significance.

A landmark is structurally attractive if it plays a major role or has a prominent location in the structure of the spatial environment (*Raubal & Winter, 2002*). From a structural point of view they can be categorized into global and local landmarks based on their location in the environment. In a wayfinding context, global landmarks are typically used for conveying directional information; they are at a distance, or off the route. Local landmarks are typically used for conveying positional information; they are close to the route, and are sometimes further categorized into landmarks at decision points, landmarks at potential decision points, and on-route landmarks along segments (*Klippel et al., 2005; Lovelace et al, 1999*).

As it has already been mentioned landmarks are important in creating a mental representation of the space. Communication about an environment is facilitated by using landmark references. Landmark-based navigation is particularly important when people navigate through unfamiliar environments. Landmarks support clarity of a specific route. Route directions enriched with landmark references lead to less wayfinding errors. Therefore, incorporating landmarks along a route is a crucial task of navigation systems in order to provide more efficient and reliable guidance.

There have been several approaches for the identification and integration of landmarks in outdoor navigation services. However, today's navigation systems still give guiding assistance in terms of metric distances, based on the current position and the underlying digital map. The only commercial system using landmarks so far is the Australian routing service WhereiS (*Richter, 2013*). On the contrary, landmark identification and utilization for supporting indoor wayfinding is not a highly investigated area so far. It makes no sense to adopt the current concepts of vehicle navigation to mobile applications for indoor environments as people are free to move in the open space of a building and not tied to a very specific network such as the road network.

In order for landmarks to be beneficial for navigation purposes, proper criteria can be applied for determining the features that make a landmark useful. The research of Burnett et al. (*2001*) defines the generic characteristics of a 'good' landmark, that makes it suitable for vehicle navigation purposes. It is believed by the authors that such knowledge will be beneficial for the analysis of landmarks in other navigational contexts e.g. pedestrians or indoor spaces. The attributes that are valued as important for landmarks are:

- permanence - the likelihood of the object being present
- visibility - whether the object can be clearly seen in all conditions
- usefulness of location - whether the object is located close to navigational decision points
- uniqueness - the ability to be easily distinguished
- brevity - the conciseness of description, it should have a simple description

These generic characteristics can be useful under particular conditions but there are also other parameters to be considered like the way of measuring them and the available information sources.

Landmark identification is performed by specifying the area in which landmarks have to be sought and then identifying the features that act as outliers in the area, i.e. finding salient features (*Richter, 2013*). The salience of a feature does not depend on its individual attributes but on the distinction to attributes of close features: being a landmark is a relative property (*Nothegger et al., 2004*); the same object can lose the attribute of acting as a landmark after changing environment. For instance, a multi-storey building is an excellent landmark for a small city but the same building would be useless as a navigation aid in a city like New York.

Nothegger, Winter and Raubal (*2004*) proposed a computational model in order to measure the salience of features at decision points and automatically select the most appropriate of them to act as landmark, which is the one closest to human choices of landmarks at these points. It was found from this research that semantic attraction and visibility are the parameters that have the greatest influence on landmark selection. However, in this approach only one class of features in urban environments (facades of buildings) was considered and decision points were arbitrarily selected. Elias (*2003*) used data mining methods in order to automatically derive landmarks from existing spatial databases. But she is also limited to a specific category of features and her identified features are local to a route but not at the decision points.

While the previous mentioned works are focused on the identification of salient objects to act as landmarks and the definition of their visual and semantic characteristics that make them salient with respect to their surroundings, the structural salience of landmarks has been neglected. Klippel, Richter and Hansen (*2005*) investigated the potential of different types of intersections to act as landmarks due to their functional role for the route. The location of a landmarks is taken into account in this approach. Caduff and Timpf (*2005*) proposed an algorithm that generates a route through a network based on the presence of landmarks at decision points (nodes). The main focus of this approach is to integrate landmarks in the route generation process and to navigate a wayfinder along a route that has a landmark at every decision point, rather than extracting landmarks from databases.

The determination of objects or places of an environment that can be used as landmarks is influenced by several factors. Among others, such as saliency and modes of navigation, individual preferences are of great importance. The gender, age and social and cultural background have an impact on the choice of objects that are identified as landmarks. For example, adults and children tend to select different environmental features as reference points along a route as it has been proved by experiments carried out by Allen et al. (*1979*) in order to investigate developmental differences in the ability to select and use environmental landmarks for cognitively organizing distance information along a route.

2.4 Route Directions in Wayfinding

Often people give and follow directions to facilitate wayfinding. Route directions is a primary mean to guide someone in finding one's way. It can also refer to instructions on how to follow a route providing the actions to be carried out in order to reach the destination (*Richter & Klippel, 2005; Richter, Tomko & Winter, 2008*). The structure of the environment influences the kind of instructions that can be given. Route knowledge is an understanding of the environment described in terms of paths between locations, and relative to locations along those paths. Route directions provide 'a set of procedures and descriptions that allow someone using them to build an advance model of the environment to be traversed' (*Richter, 2013*).

To successfully navigate, wayfinders need to know which directions to turn to at the crucial spots along their way where they have to make a decision on how to move further, namely the decision points (*Richter, Tomko & Winter, 2008*). If the environment is unfamiliar, wayfinders need assistance in taking these decisions. This assistance needs to communicate all information that is necessary to reliably enable wayfinders to perform the right actions, but should refrain from providing any excess information as this aggravates correctly interpreting the assistance. A variety of details can be given when providing directions for wayfinding, such as landmarks, cardinal directions, street names, distances and turn descriptions (*Hund & Padgitt, 2010*). In human route directions we almost never find numerical references to distances or turning angles, instead people use landmarks to anchor actions in space or to provide confirmation that the right track is still being followed (*Michon and Denis, 2001; Richter, 2013*). Route directions enriched with local landmarks are easier to understand, or more useful, than directions based solely on geometry and place names (*Nothegger et al., 2004*).

Klippel makes a distinction between path and route (*Richter & Klippel, 2005*). He defines path as a linear, unbounded feature of the environment upon which movement occurs, while he states route as a behavioural pattern, which has an origin and destination and it is directed and bounded. According to this definitions, a path is demarcated by a route by determining these parts of the path that are traversed when a route is followed. These parts are called path-segments, their meeting points are called branching points and a graph structure of the street network to represent the geometric layout of the paths is used for the generation of route directions in Richter and Klippel (*2005*).

More specifically, in Richter's approach landmarks are integrated into an abstract specification of route directions that follow cognitive principles of direction giving. In this approach a route is represented as a number of decision point/action pairs. The generated route directions support this conceptualization of route as a mental representation of an expected decision point sequence with their accompanying actions. Instructions are influenced by the environment, the route itself, path annotations and landmarks that are visible along the route (*Richter and Klippel, 2005*). A computational process, called GUARD, has been developed for generating context-specific route directions. GUARD stands for Generation of Unambiguous, Adapted Route Directions and it consists of four steps, as it is illustrated in figure 2.1 (*Richter, 2008*).

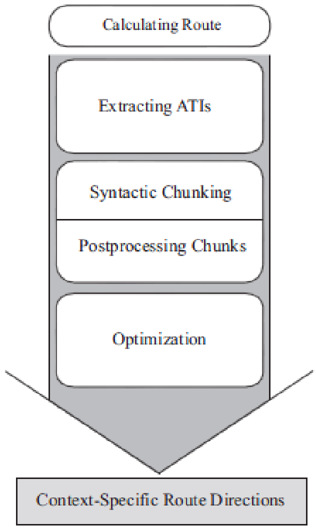

Figure 2.1: GUARD process of generating context-specific route directions (*Richter, 2008*)

In general, the outcomes of research about the use of landmarks in route directions reveal that there are no uniform references to landmarks along routes, but they are mainly concentrated to critical points. These points, called decision points, are nodes where re-orientation is required and where a choice among several possibilities has to be made (*Fontaine & Denis, 1999; Michon and Denis, 2001; Raubal & Winter, 2002*).

People represent spatial knowledge, such as distances and directions, qualitatively. The processing and representation of angular (direction) information is essential for wayfinding and route planning. Directional relations are used in several respects in route directions: they state the location of entities encountered along the route (like landmarks) with respect to the wayfinder or other entities; they announce a change of heading at decision points, i.e. represent turning actions; and they may relate these actions to an entity's location to better anchor them in space. In general, it can be stated that wayfinding can be characterized as following a route segment up to a decision point, making a directional choice, following the next route segment up to the next decision point, making a directional choice, and so on.

In research on qualitative spatial reasoning, several qualitative direction models have been proposed. These models divide the two-dimensional space into (labelled) regions. These sectors map all possible angular bearings by a usually small, discrete set of categories (*Richter, 2008*). Against homogeneous four-sector and eight-sector direction models, Klippel et al. (*2005*) empirically elicited such a heterogeneous direction model for turning actions in wayfinding - qualitative direction's model (Figure 2.2).

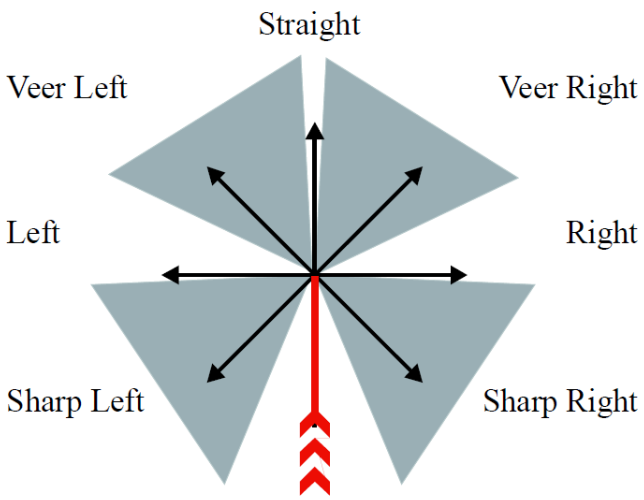

Figure 2.2: Revised direction model for the generation of verbal route directions and the schematization of maps (*Klippel et al., 2005*)

3. The 'Junction Network System'

The Junction Network System (or originally 'knooppuntensysteem'), which was developed by Hugo Bollen, a former Belgian mining engineer, is a special approach of providing direction instructions that help cyclists plan and follow a route. This system is an innovative signposted cycle network based on numbered junctions (='knooppunten' in Dutch) having as a goal to make wayfinding easier for cyclists. The Junction Network System is mainly used in recreational routes, where people are mainly interested in exploring the region while there is no time stress. For every region there are recommended thematic tours that incorporate part of the sights of the area. Having gained user's recognition and acceptance, the system has started appearing also in cities, overcoming the fact that built environment is characterized by a larger number of junctions.

The main focus is given on the intersections or junctions where two or more cycling paths cross one another, which are the points where cyclists should make a decision on how to go further. By giving to the most relevant of these junctions a specific number, a network is created, as it is illustrated in figure 3.1. Thus, the main concept of the system is that the users rely on a network of nodes, which is created by exploring the locations where the cycling paths intersect and placing a sign containing a unique number and directional information to the next encountered nodes at all possible directions of moving. Along the cycling paths, there are indications to lead to the next numbered node and just before the node there is a signpost to signal that the cyclist is approaching it.

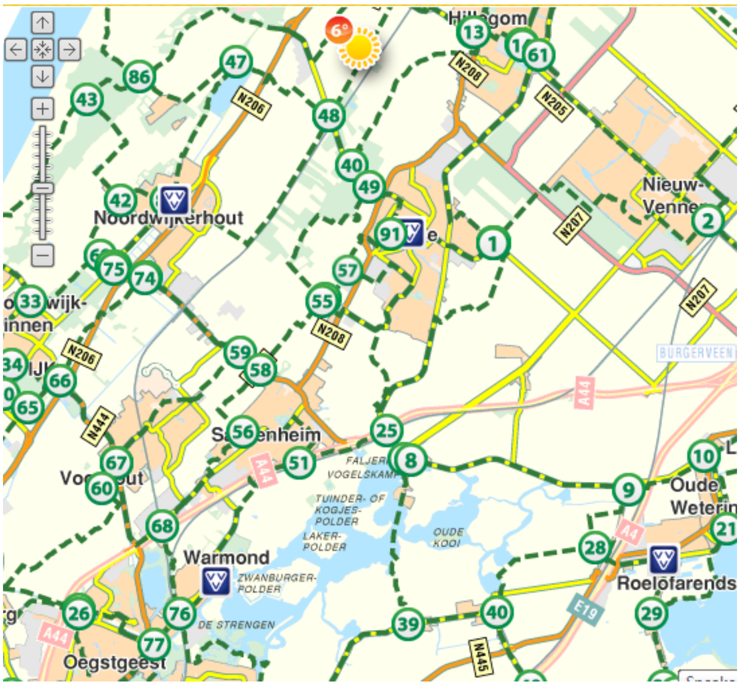

Figure 3.1: Junction Network

The only thing that cyclists have to do is to remember the sequence of numbers that corresponds to a specific route and watch for the signposts with numbers, which indicate the direction to go. This system makes it easier to explore a region from any node of the network. At special points in every region, special maps are standing that provide an overview of the surrounding area in order for the cyclists to plan or confirm their routes. Moreover, there is a website with the complete node network for every region for the case that the cyclist wants to plan the trip in advance. Separate paper maps are available at the local offices of every region. Cyclists can note down the numbers for recommended routes and follow them. The length of them is also indicated.

The value that the system provides to the users is twofold; firstly, it directs them to a destination and secondly, it provides information about their relative location in the environment as the numbered nodes create a type of reference system. Having a topographic or schematic map of the area with all the numbered nodes the cyclists can get a quite precise indication of their location in the space and the travelled distance. Additionally, among the advantages of the system is the flexibility that offers to the user. Everyone composes on his own the route to follow and determines the travel distance, which can be changed according to the prevailing conditions (weather, time, energy). Furthermore, a route can be followed in either direction as the signs are double-side-marked.

The signage system that dominated is a green sign with the node numbers in a white circle (Figure 3.2), which is now also used in many parts of Belgium, gaining in that way international recognition. These signs have emerged to be a special type of landmarks along the cycling paths as they are recognized and easily identified by cyclists.

Figure 3.2: Signage of Junction Network System

To summarize the main principles of the original system:

- The points where the cycling paths cross each other are the locations of the nodes (junctions).
- A system based on numbers is created by assigning a unique (at least for a certain region) number to each one of the nodes.
- At the nodes of the system, signs displaying the current number and directional arrows to the next numbered nodes of the network in the possible directions of moving are situated.
- By creating a sequence of numbers a user-specified route is determined.
- These signs have emerged to be a special type of landmarks along bicycle lanes as they have gained cyclists acceptance. They are not only easily identified but also cyclists are searching for them.
- Signage is available in both directions; cyclists can return to their starting point by following the same sequence of numbers in an inverse way

The Junction Network System is a signposting system for providing wayfinding assistance to cyclists. The acceptance and success of the system is attributed to the incorporation of many important concepts related to the wayfinding task into one physical object. However, the system is not perfect. There are several limitations with respect to its functionality and performance as a wayfinding assistance tool. The strong points and limitations of the Junction Network System will be discussed profoundly in the following paragraphs.

First of all, two of the main wayfinding approaches, i.e. signage system and maps, are combined in this system so that the benefits of each one of them are adopted. More specifically, by only referring to the number of the node of presence the user is able to estimate his relative location in the network. He can also confirm his arrival at a destination node. However, the topographic space is not a network and the knowledge of the location in the network's reference system is not always adequate. Therefore, by advising the special maps at various points along the routes the user can derive his relative location in the topographic outdoor space. The maps provide also to the cyclists the potential of orienting themselves in space. The problem is that these maps are not placed everywhere. Consequently, if the cyclist finds himself at a point which is not signalled not only he is unable to infer his location in the network or the topographic space reference system but also he cannot plan his trip. He has then to backtrack or randomly search for a sign or map.

Secondly, the signs act as landmarks along the cycling paths as they concentrate many of the characteristics that make an object salient according to the landmark theory. The fact that they have gained cyclist's recognition is an important aspect that attach importance in the landmark attribute of the signs. The most important parameter of the Junction Network System in terms of wayfinding purpose is that assistance is provided to the users where they need to make a decision on how to go on, in the points where two or more cycling paths intersect. Junctions have a high salience value as they are functionally important locations for following a route. However, not all junctions are populated by signs. The selection of the junctions where signs stand is arbitrary and there is no method to select the most salient or relevant of them. This fact generates misunderstandings in the instructions and increases the possibilities of turning wrong and eventually getting lost.

A special unique enumeration is the technique that the system employs to provide all the information to the users. Route instructions are given to cyclists through the numbers displayed on the signs and routes are conceptualized as paths between numbered nodes. Direction instructions are provided in terms of a sequence of numbered nodes and turning actions are expressed by referring to the upcoming node. By not using semantically-given references, such as 'turn left in 5 meters' or 'turn right in the next corner,' misunderstandings concerning the interpretation of turning instructions are eliminated. Moreover, there is no need to state explicitly the semantics of the space in order to reach a destination as the whole route is represented by numbered nodes.

The integration of all the previously mentioned characteristics in one system makes it a promising solution for aiding other locomotion cases, such as pedestrians. Indoor wayfinding is one of the cases where a proper adaptation of the system could lead to an effective assistance tool. There are certain points to support the assumption that the indoor adaptation of the system will overcome some of the shortcomings of the existing indoor wayfinding systems. The creation of routes that include the most important points of the space, the unique enumeration which minimizes the need to make use of the semantics of the space, the conceptualization of turning instructions as paths between numbered nodes that makes the interpretation of information indisputable and the fact that the user knows where he moves and can identify his destination in the network space are among these points.

4. The 'Junction Network System for Indoor Environments' - Conceptual Framework

Having already introduced the main principles of the system that serves as a base for this approach and having revised the most important points of the landmark theory as well as the attributes that make an object easily identifiable, the conceptual framework of the new indoor wayfinding system is introduced in this chapter. The proposed system, 'Junction Network System for Indoor Environments', is registered as a first attempt of translating and applying the main principles of the original Junction Network System in indoor space, having as a target group pedestrians of all age groups, with no physical impairment that prefer to be independent from a mobile navigation system. The whole concept and main principles of the proposed system derive from a direct mapping of the main principles of the Junction Network System to the case of indoor wayfinding.

In terms of wayfinding communication, the system should be able to respond to three major questions in order to be effective: what information should be presented, where will the information be provided, and in what form. In this case a physical object is employed in order to communicate all the necessary information, which for the case of indoor wayfinding is the location of the user and directional information in order to reach the desired destination. This information is provided to the users at the locations where they actually need assistance in order to take a decision on the direction to follow. More specifically, the proposed approach is based on the creation of a network of landmark locations, equipped with a special type of signpost containing a unique number for every location and directional arrows to the other numbered locations in the vicinity of it. In that way any possible route in an indoor setting is mapped out.

The system is formed by two main components and their interrelationships. These components are illustrated in figure 4.1. One of the main building blocks of the system is the presence of the physical object, named landmark-sign from now on, throughout the entire indoor space. The landmark-signs signal the occurrence of the decision points, which are the crucial points where people need assistance in order to proceed further (junctions of the original system). Moreover, the location and directional information are revealed through the landmark-signs. By giving each one of them a unique number, the closest destination spaces to this sign are automatically registered and attached to it. So, when the wayfinder is located at sign number 5, he can infer his relative location in the network. Additionally, directional assistance is also provided by the signs as they contain directional arrows indicating the closest numbered decision points or the arrival at a destination space in all possible directions of moving. The destination spaces are also marked with a unique number. The numbering of destination spaces starts after the numbering of the decision points and it could be useful the first digit to reveal the floor level. The location of the landmark-signs makes easier the conceptualization of turning instructions, enhancing the understanding of direction instructions.

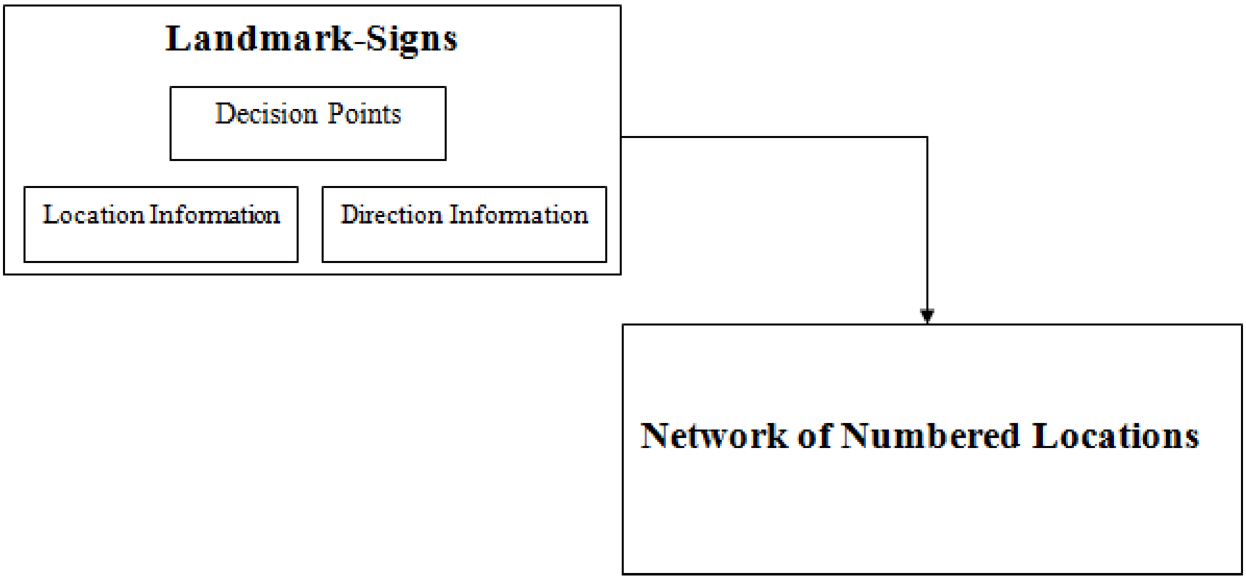

Figure 4.1: System components and their interrelationships

The connections between the landmark-signs and the destinations attached to each one of them create the whole network of nodes that provides all possible combinations of routes between starting points and destinations. A route is followed through the network based on the presence of the landmark-signs at every decision point. This is the second important constituent of the system. The basic representation underlying the system is a sequence of numbered decision points with their accompanying actions. Guidance is given by referring to numbers of landmark-signs and anchoring actions to them. The network of nodes has a twofold role: firstly, it acts as a wayfinding/routing system that enhances the successfully reach of destination while secondly, it plays the role of a referencing system which provides a location indication to the users.

4.1 Landmark-Signs

The landmark concept is the departing point in the design of the system as the most important request is the generation of a wayfinding system that incorporates the basic principles of the landmark theory in the task of provision navigational assistance. As it has been deduced through the literature review, landmarks may have particular visual characteristics, a unique purpose or meaning or may be in a central point or prominent location that make them effective as landmarks. The salience of an object results from the combination of its visual, semantic and structural characteristics. Most of the landmarks possess one or two of these salient characteristics. In this research, the desire is to create a special type of landmark containing all these three features.

The selection of signposts as a suitable object to act as landmark in this approach is firstly supported by the unambiguously evident that graphical signs is traditionally the most commonly employed means in order people to navigate themselves in unfamiliar environments. Hence, this object can be easily recognized and detected throughout the indoor setting. According to Viaene (*2013*) study on landmark identification in indoor environments, it is indicated that objects or areas in a building appointed with a sign increase their saliency. Additionally, all the information requirements in order to reach a destination can be covered by this unique object.

Signs in this approach become a special type of landmarks based on their visual characteristics that makes them distinguishable from the other features of the environment but also based on the attribute of existing in a location where they can be easily identified because of the aid they offer to wayfinders to reach their destination (structural characteristics). The repetition of the landmark-sign throughout the indoor setting reinforces its role as a landmark as the semantic component is added. As people are becoming familiar with the presence of this very specific object that provides navigational assistance in the space, they start searching for it. Thus, a semantic salience is assigned to the landmark-sign and complements the already existing visual and structural salience.

The visual aspects of an object which make it act as landmark are the shape, the colour, the age, the size, the material and the position and visibility in the environment. In indoor settings colour is the most cited feature when referring to a landmark and to a less extent material and size. Age is a highly subjective parameter while shape is important in the case of modern buildings with elements of special geometries. The decision about the design of landmark-signs respects the conclusions of landmark theory but is also drastically influenced by the structure of the environment. Landmarks are always defined in association with the surroundings. For example, a red blue door in a corridor where all the other doors are white has a high degree of saliency and acts as landmark. The exact same door in a corridor where all the doors are blue makes no particular difference. Therefore, the specific features of the buildings are taken into account. From everyday experience it can be stated that building's structural elements (walls, doors, windows etc.) are mostly dominated by neutral, non-striking colours such as white or grey. Therefore, the use of bright colours is desired in order to create a contrast with the environment. The selection of green colour for this approach comes from the original system but it is also in accordance with the rules regarding contrast with the surroundings.

A common element that all signs contain is the number that indicates the location of presence. This number is unique for every sign, gives an identity to each one of them and differentiate them among each other. Numbering is easier to be understood and remembered and it can communicate information to a variety of multilingual user groups. The numbering of the landmark-sign starts from the beginning for every floor of the building, especially in large multi-storey buildings, while the floor level is explicitly presented on the landmark-signs. The final design of the landmark-sign is depicted in figure 4.2. The blue colour is used to indicate the arrival at a destination.

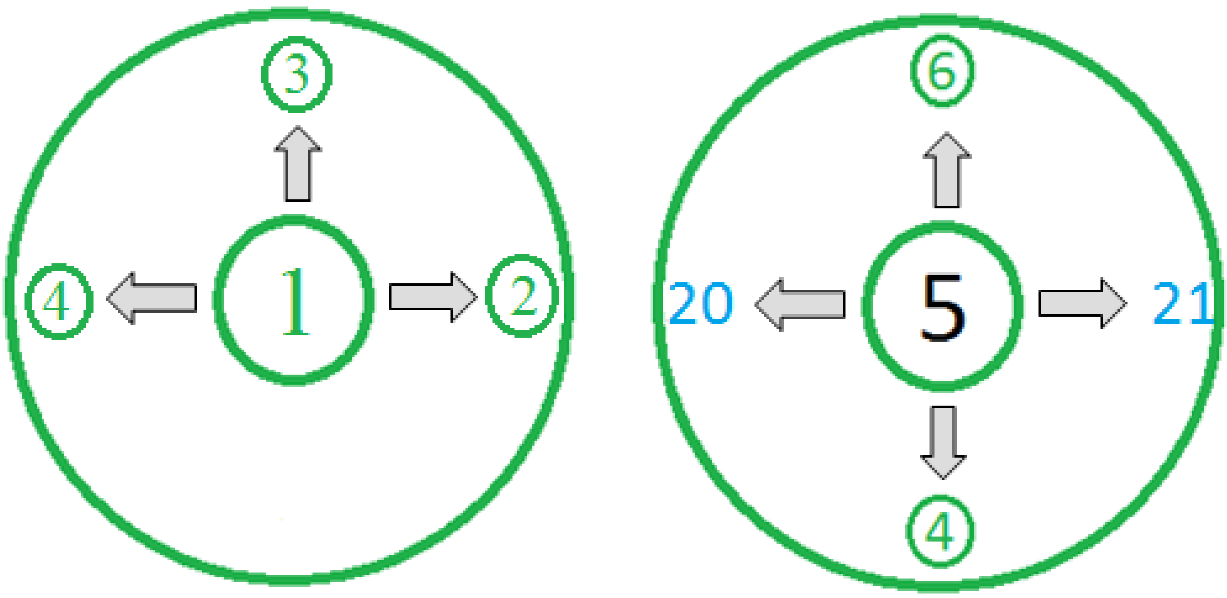

Figure 4.2: Proposed landmark-signs

The effectiveness of a signage system depends on the way users perceive, interpret and use the information conveyed by the signposts. Therefore, it is not a measure easy to be assessed. However, there are some aspects that can be considered when building a new system. Firstly, it should be ensured that the provided information achieves a good level of comprehensibility and that the critical details have a good level of legibility. The directional indications should be consistent with the intended route so that people can reach their destination. Considering the number of signs, two cases should be avoided; overload of signs and information is the first one and shortage of signs is the second one. Finally, the position of the signs should ensure that users will be able to detect them.

All the previously mentioned parameters are taken into account in the proposed system. The proposed landmark-signs are easily read and understood as all the information is provided through numbers. They are also placed in prominent spots in order to be easily distinguished by people. Floor-mounted signs are considered to be a good choice for this case. Floor-mounted signs attract wayfinders caution as they are visible from a distance and there are no important limitations regarding their size. Additionally, in the strong points of the floor-mounted landmark-signs is included the fact that they can be placed exactly at the determined points that facilitate at most the wayfinding instructions task, while they do not interfere in the configuration of the space and do not intervene in people's movement.

4.2 Decision Points

Decision points are the points where assistance is necessary for people to proceed with their trip. Decision points can be determined as functionally relevant points along a route or any physical location where the individual is presented with a navigational choice. A navigational decision is to be made at these locations as more than one alternatives of direction of moving exist. The decision points of the original system are the junctions of the cycling paths. The decision points are considered as landmark locations as everybody considers them unintentionally because of their structural salience. Therefore, an important aspect of the system is the determination of the decision points in indoor settings. The landmark-signs are placed at these decision points as the time and place an aid is required is important for an efficient wayfinding system.

Indoor space is quite different compared to outdoor environment. Indoor spaces are characterized by entities such as walls, rooms, doors, hallways etc., which imply topological constraints that enable or disable movement. The structural elements of the buildings, e.g. walls, block the free movement of people. Moreover, other elements like furniture or pillars are considered as obstacles when people navigate themselves in a building. These elements delimit the navigable space of indoor settings. Therefore, in indoor space the points where a navigational choice must be made are the points where there is no element to obstruct the free movement in multiple directions, such as intersections of corridors, exits, doorways and points of floor change such as elevators and entrances to stairways. These decision points are automatically determined in this approach by subdividing the space into smaller subspaces and checking for each one of them whether or not there are elements that block the free movement to all directions of the subspace.

4.2.1 Indoor Space Modelling

In order to determine the decision points, the indoor environment has to be organized in a way that a planar partition can be constructed. A geometric spatial model is applied as the accurate positions and distances between the entities play an important role for the determination of the decision points. According to the boundary-based models the boundaries of the objects are represented using sequences of primitive geometries like points, lines and curves. One of the most important advantages of this modelling approach is that it forms a direct way to represent the indoor space and the constraints that limit people's movement. Planar partitioning of the indoor space is used in order to represent correctly the geometry and topology of the space. The semantics of places of interest and places that have an important role in the functionality of the system are also considered in the determination of the decision points.

The topographic indoor space is subdivided into two large categories: navigable and non-navigable space. This space partitioning is influenced by physical constraints, the type of locomotion and the context of application. Normally navigable space are considered the rooms, corridors and doors of buildings while non-navigable areas are walls and obstacles. The determination of navigable and non-navigable areas is related to the used indoor space representation and affects the indoor space analysis.

In this approach, the proposed system aims at providing assistance for the simplest case of wayfinding, which is finding the way to a room when navigating in public buildings. This is though one of the most commonly repeated human activities. Therefore, the navigable space that is mainly of our interest for the purposes of this research are the connecting spaces (connectors) between other entities that act as destinations and for which people are usually in search for, e.g. rooms. People use the corridors (Figure 4.3) as the backbone of the building in order to reach their destinations. They correspond to the main orientation ring of the building and they are the first parts of the building to be experienced.

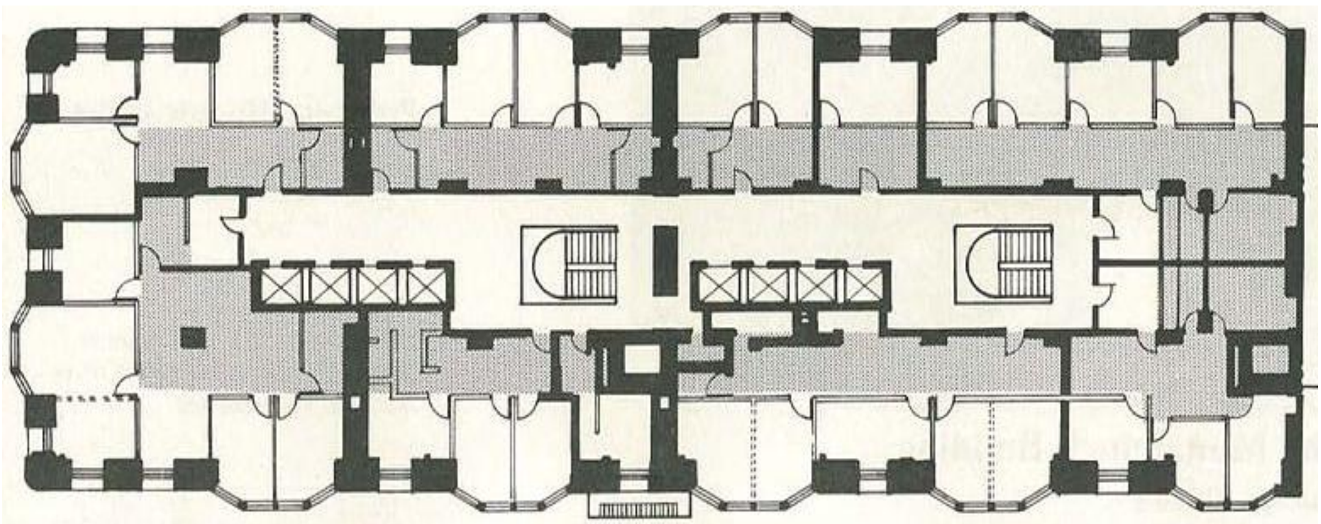

Figure 4.3: Corridor of a building act as connector between rooms (destinations)

The system is initially designed for cases of indoor space with elongated shape, such as corridors, as they have a similar geometry with the cycling paths used in the original system. However, it can be extended for the cases of large open spaces, where more than one destination points exist. For these cases identification of the walking paths is necessary. Consequently, for indoor space the areas that apply to this concept are the main ring (backbone of a building) or well-structured paths where movement occurs in big open spaces and which can arise from observation of people's flow. Well-structured paths are continuous and have a clear beginning, middle and end when viewed in each direction, as illustrated in figure 4.4. In order to identify these paths space syntax tools and techniques can be used. People's flow in indoor settings can be deduced based on spatial accessibility values of the space and the visibility criterion. A path can be created by the line of sight between entrances/exits of the open space and by the inclusion of points of interest.

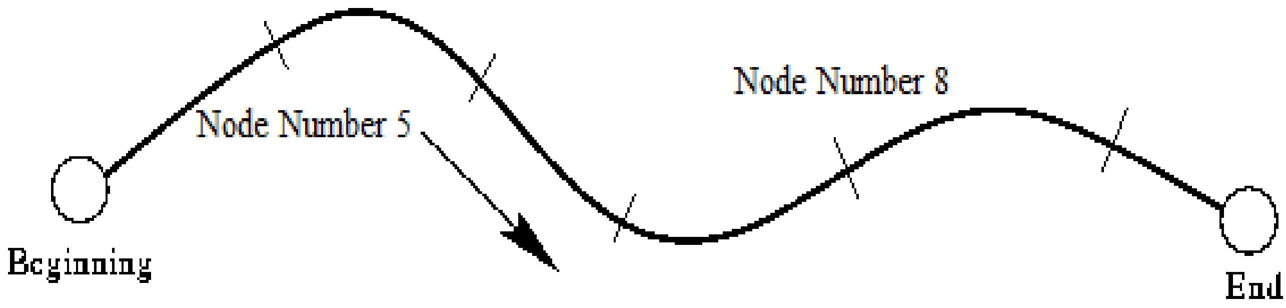

Figure 4.4: Well-structured navigation path

The determination of all the connectors of an indoor setting provides the circulation routes in the space. The points where two or more of these spaces intersect or where an intermission of the continuity of the boundary of the connector occurs are the decision points for indoor space. The intermissions/gaps indicate the presence of an opening, which also gives the opportunity of changing direction.

4.2.2 Decision Points Determination

Having defined the navigable indoor space where the decision points occur, it is further subdivided according to the Constrained Delaunay Triangulation criterion, which makes use of the geometry of the space while it respects the positions of obstacles. Obstacles are specified as constrained segments in this method. After applying the CDT the plane is subdivided into a number of triangular-shaped non-overlapping facets. From these facets two broader types are distinguished; these that are built from segments that consist part of the user-specified constraints and others that are free of these constraints. The last type of triangles are adjacent to other generated triangles from all three sides. In figure 4.5 the three types of triangles are illustrated. Type 1 corresponds to triangular subspaces without constrained segments.

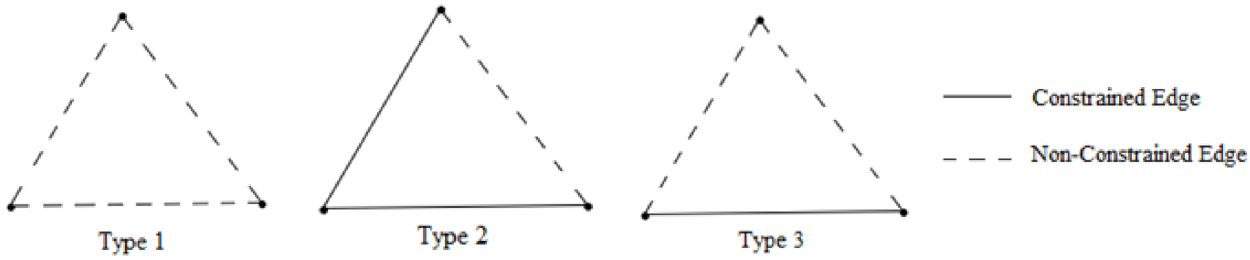

Figure 4.5: Types of triangles

Thus, people standing at these subspaces are allowed to walk to three possible directions - there are no constraints to limit them to any direction. This type of generated subspaces corresponds in reality to areas that two or more navigable connecting spaces intersect or where an opening or floor change occurs. Consequently, in these subspaces decision points are located. Therefore, by classifying the triangles the decision points are determined.

The distinction between the triangle types is based on their topological overlay relations with the originating connecting space. When the triangle does not overlap with the boundary of the connecting space then it belongs to type 1. Additionally, the triangles that are adjacent to objects that indicate the possibility of transition from one connecting space to another space, either they are doors or stairs or elevators, belong to type 1 triangles.

CASE 1

WHEN NOT *triangle(i) overlaps connecting_space.boundary*

THEN *triangle(i) = type 1*

CASE 2

WHEN *triangle(i) overlaps transition_space.boundary*

THEN *triangle(i) = type 1*

The central point of every subspace is the most representative point to act as decision point. In cases where two or more subspaces are adjacent to each other they are merged into one bigger subspace. This operation is requested in order to avoid phenomena such as overload of landmark-signs and information.

4.3 Information Provision

The kind of information given through the landmark-signs are directions and identifications. It is important that signs convey information without ambiguity and that the information is effectively transmitted to the users. The enumeration of the landmark-signs contain the information. However, similarly to the original approach this information refer to the reference system of the network of numbered nodes. People can get a rough estimation of their location in the building by correlating the number of the landmark-sign closer to them with the one closer to the entrance of the building. In the same way the relative distance they have travelled in the building is possible to be estimated. A floor plan of the building including the landmark-signs locations and numbers is necessary in order to get more precise information about the location in the building. Only by superimposing a map of the building the exact position of presence can be calculated.

Moreover, the user should be aware of the meaning of the place of the indoor setting where he is located. This is not provided by the landmark-signs as they do not reveal the semantics of the space. Therefore, an inventory of the meaning of the destinations closer to each one of the landmark-signs should be given at special points in the indoor setting. Consequently, in order to create a complete system maps of the whole building are standing at specific points in the indoor setting. These maps are accompanied by a list that correlates numbers with the semantics of the space. The amount of such maps depends on the size and the complexity of the building. However, it can be stated that they should be standing at the entrances of the building and the floor change points.

Directional assistance is provided to indicate a path to a destination. By giving to the landmark-signs a unique number, a certain sequence of numbers corresponds to a specific route. The location of a landmark-sign has an ease in the conceptualization of turning instructions and thus enhances the understanding of direction instructions. Consequently, it is possible to give guidance by referring to the numbered landmark-signs and anchoring actions to them. For example, the expression "turn left at number 5" is expressed through the landmark-sign with the unique number 5 and the arrow showing the numbered landmark-sign or the desired destination in the right direction.

Arrows are used to provide the direction of the following landmark-sign. According to Klippel's eight-direction model having a starting point there are seven potential route directions. The simplest conceptualization of this model provides only four basic possible directions. This simpler model is suitable for our approach based on the part of navigable environment which is in our interest. Consequently, some kind of information about the next encountered points in the four important directions are provided. The model is extended in order to incorporate also the vertical movement. A 3D environment can be developed by stacking multiple layers of 2D maps. The vertical connections such as stairs and elevators between different layers are incorporated. They are represented by nodes that denote the transition between floors. A special indication next to the arrow is used in order to illustrate the floor change.

4.4 Network Generation

The second important component of the system is the generation of a network that links all the decision points and the destination points. The unique number of every decision point facilitates the linkage between these locations and the creation of a network of numbered nodes which is able of guiding a person in an indoor space. The generation of the network can be easily achieved using a graph representation of the building. The decision and destination points are the nodes of the network and the links between the nodes are mapped as edges in the graph representation of the indoor space.

It is a common approach buildings' structure to be represented by a graph model for indoor navigation purposes (Figure 4.6). Historically, routing is based on graphs as road networks can be easily described as sets of nodes and edges. The graph structure of the environment is extracted in two steps: in a higher, more detailed level using the Constrained Delaunay Triangulation to further subdivide the connecting spaces, select the subspaces where any direction of movement is possible and represent them by a node; and in a coarser level by representing all destinations by a node and connecting it to the closer node of the previous step. A variation of Medial Axis Transformation constructed by using Constrained Delaunay Triangulation is applied in the connecting spaces in order to extract their middle line, which is the most representative way of depicting the human movement in these spaces (*Mortari et al., 2014*). The triangulation axes, which is an alternative structure to extract the topological skeleton of the polygons, is used to represent the geometry of the space (*Aigner et.al., 2012*).

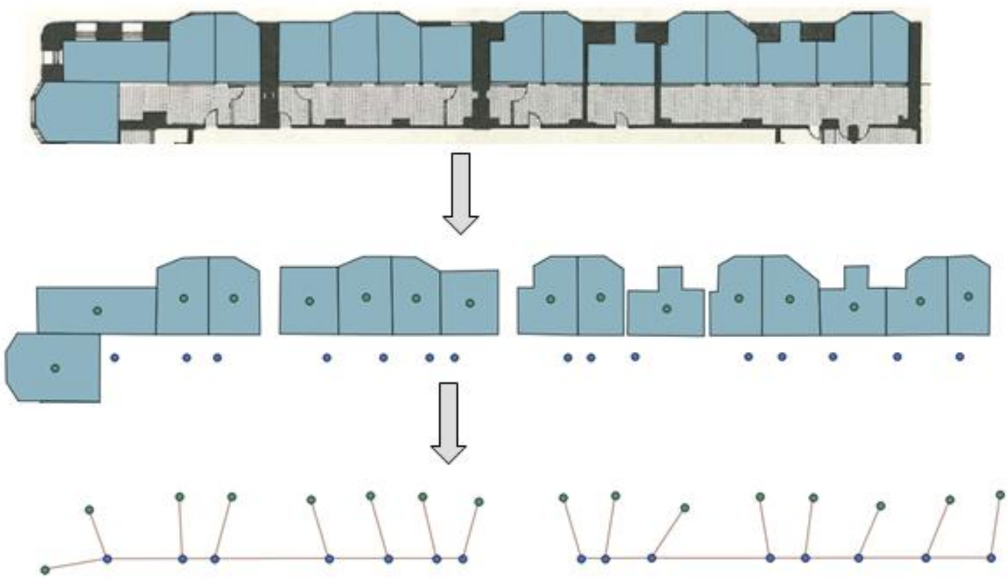

Figure 4.6: Graph Model representing part of a building

Connecting space polygons are mapped to nodes and edges of a graph, which is able to provide all possible routes. The decision points are mapped as nodes in the graph representation of the connector polygon. The other building spaces that act for this approach as destination spaces are represented by their central point, which are also components of the graph, and they are connected to the middle line of the connecting spaces at the closest decision points' node through the transition spaces (doors). These connections are implemented in order to illustrate the adjacency and connectivity relations between all the different parts of the indoor environment. In that way a network of nodes and edges is created which represents all the possible routes that humans can employ in a certain environment. The idea of a route-skeleton corresponds to the central-point strategy that people usually employ in unfamiliar environments.

Outcome: Creation of a network of numbered nodes, where the choice of changing direction is imposed.

4.3 System Overview

There are several aspects that can make the system a special approach and a useful tool for users in the wayfinding task. Firstly, it is based on an already existing and recognized system meaning that people can more easily adapt and use it. The outdoor system applies successfully not only for cyclists but also for hiking and boat guidance purposes. The fact that it is successfully applied in different navigation modes makes it a promising solution for indoor wayfinding problem. Secondly, it provides an indication of the relative position of the user in the environment. It acts not only as a routing system but also as a referencing system. Thirdly, it is based on a physical object that acts as a unique identifier and plays several roles. This unique identifier is the landmark-sign, which expresses the critical points where people need to choose direction of moving and provides location and directional information. The enumeration of the landmark-signs facilitates the interpretation of the directional information and it is easier for people to remember it. It is also a solution that with minor modifications can be applied to different indoor space cases. The basic concept of determining the nodes of the system can be used invariant to all space configurations. Finally, it is an approach that does not request the use of an additional equipment from the side of the user. Therefore, it is also suitable for people not familiar with mobile devices and digital navigation systems or for people who just do not want to use them.

Review of Rules of how the system should be applied:

1. The navigable space that is of our interest for the purposes of this research are the connecting spaces between destination spaces (rooms) for which people are usually in search.

2. Determination of the paths where movement occurs - main corridors of buildings or well-structured paths.

3. Decision points are locations where two or more connecting space intersect or locations where gaps in the boundary of the connecting spaces occur.

4. Placement of a special type of landmark-sign at the decision points at prominent locations.

5. Provision of location indication and directional information through the numbered landmark-signs.

6. Additional maps of the building at the entrance and floor change points are needed for getting precise location information.

7. Network construction by connecting the decision points using the triangulation axes approach.

8. The indoor space is mapped as a graph; i.e. a collection of nodes and their edges. All possible routes are represented by edges of the graph.

9. In cases of large multi-storey buildings the numbering starts from 1 for each one of the floors.

5. Technical Part - Implementation

The method for determining the decision points locations, which is the first and most important step for the implementation of the proposed wayfinding assistance system, is applied in two building cases. **GeoFort**, which is an educational attraction in the field of cartography and navigation in The Netherlands, was selected as a first suitable place to implement and test the reliability of the system. The park of GeoFort combines indoor and outdoor facilities. From GeoFort park facilities, the main building, which contains most of the indoor activities, is selected in order to illustrate the concept of deriving the decision points.

Advantages of GeoFort:

- the place is dedicated to geographic information and navigation, so the system can fit well to the environment and it will be in coherence with the concept of the place
- a quite large number of people can be used in order to validate the system
- the main target group is children at the ages of 4-14, which means that if they are able to follow the system everybody can do it and also they acquire experience on the system and its working principles from such an early age
- it can remain there after testing in order to receive continuous feedback on its reliability

The Faculty of Architecture and the Built Environment (BK) of TU Delft is additionally to GeoFort used in order to apply the proposed system, as it is a quite more complex building and it provides the possibility of testing the usability of the system in an environment that approximates closer most of the public indoor spaces as it includes also large open spaces where movement in all possible directions occurs. In that way more possible encountered circumstances of indoor space configurations are examined.

Advantages of Architecture building:

- more complex building
- contains large open spaces
- existing wayfinding system needs improvement
- large number of users during validation test
- opportunity to compare the proposed with the existing wayfinding system

The concepts of the proposed approach are illustrated using 2D floor plans of the main building of GeoFort (figure 5.1) and the ground floor of Architecture building (figure 5.2). The use of the ground floor only is attributed to the fact that this specific floor has a more special space configuration. while the other floors consist mainly of corridors and rooms.

Figure 5.1: Floor plan of the main building of GeoFort

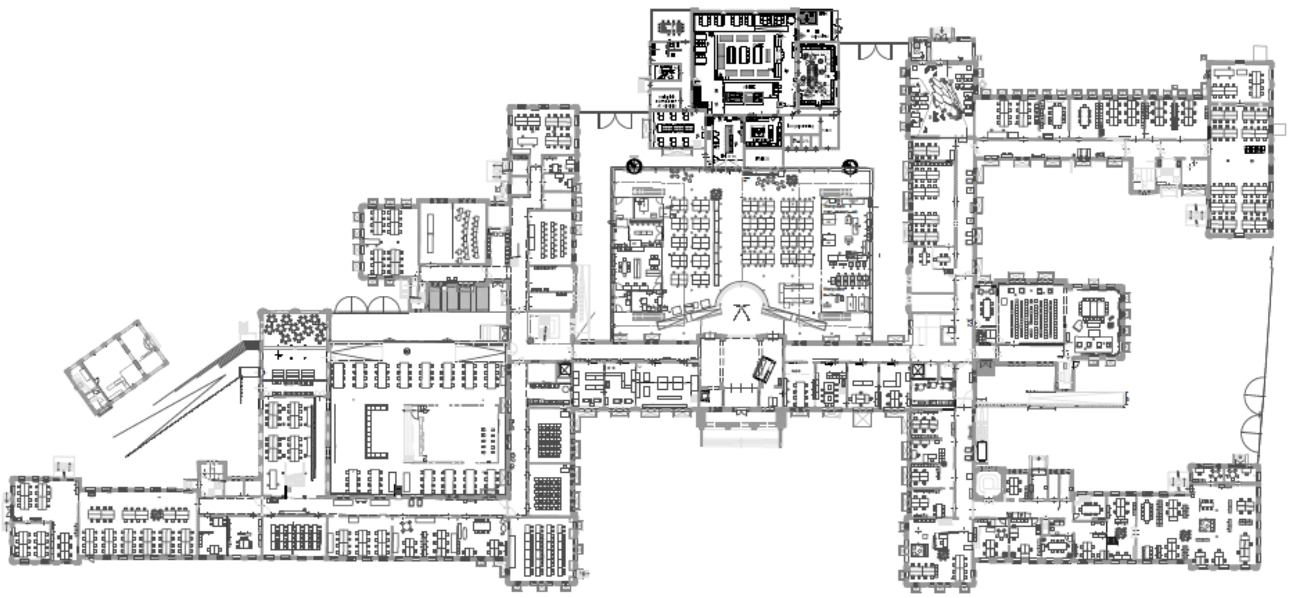

Figure 5.2: Floor plan of the ground floor of the Faculty of Architecture and the Built Environment

5.1. Software

Several software packages were used in order to execute all the processes of the implementation phase. First of all, Quantum GIS (QGIS) platform was used for data visualization throughout the whole implementation phase and for preparing the initial input data, which in this case is the floor plan, for further processing. QGIS is an open-source desktop application that provides data viewing, editing and analysis capabilities. Despite the fact that QGIS offers a considerable array of tools and components in order to analyze and manage data, it lacks the ability to chain together tools in series, or adapt the tools to satisfy specific needs. In order to improve the efficiency, extend the capabilities of the system and automate the whole process, Python programming language was used. Python scripts were generated in order to perform the space subdivision, to determine the subspaces where movement occurs in all possible directions, thereby the decision points, and to generate the network of all possible routes in the indoor environment. Python is also an open-source programming language and integrates well with GIS packages. Finally, the PostgreSQL database with the PostGIS extension for support of geographic data was used in order to store the decision points coordinates and the network. PostGIS is also an open-source program and it is common to act as a database backend of QGIS software.

5.2 Data Preparation

The first part of the implementation process is the data preparation phase. As it has already been mentioned, for this phase 2D floor plans provided by the administration of GeoFort and the Faculty of Architecture were used as an input. Georeferencing of the input data is required in order to assign real-world coordinates to each pixel of the raster image. The plans are geo-referenced in WGS84 spatial reference system as OpenStreetMap and Google Maps are used as a background basis for the process. Thus, the objects are associated with their physical locations.

All the objects of the environment are represented by polygons, which are derived from the footprints of the objects in the map. No gaps and overlaps exist between the polygons in order to build a planar partition and in that way to create correct the geometry and topology of the space. All polygons have a meaning in accordance to their role in the building and object IDs are attached to each feature. Three polygon feature classes are relevant to the purpose of the proposed system. Firstly, the connecting spaces or connectors as they are defined earlier, which are in these case studies the main corridors of the buildings and the well-structured paths where movement occurs in open spaces. The second class comprises all the rooms that act as destination spaces irrespective of their use, e.g. activity rooms or shop in GeoFort and lecture rooms, cafeterias or WCs in

Architecture. Finally, the last class consists of the transition spaces, which enhance the transition of people between the connectors and the destinations, e.g. doors, stairs, escalators. Figures 5.3 and 5.4 illustrate the representation of the environment by polygons for both case studies.

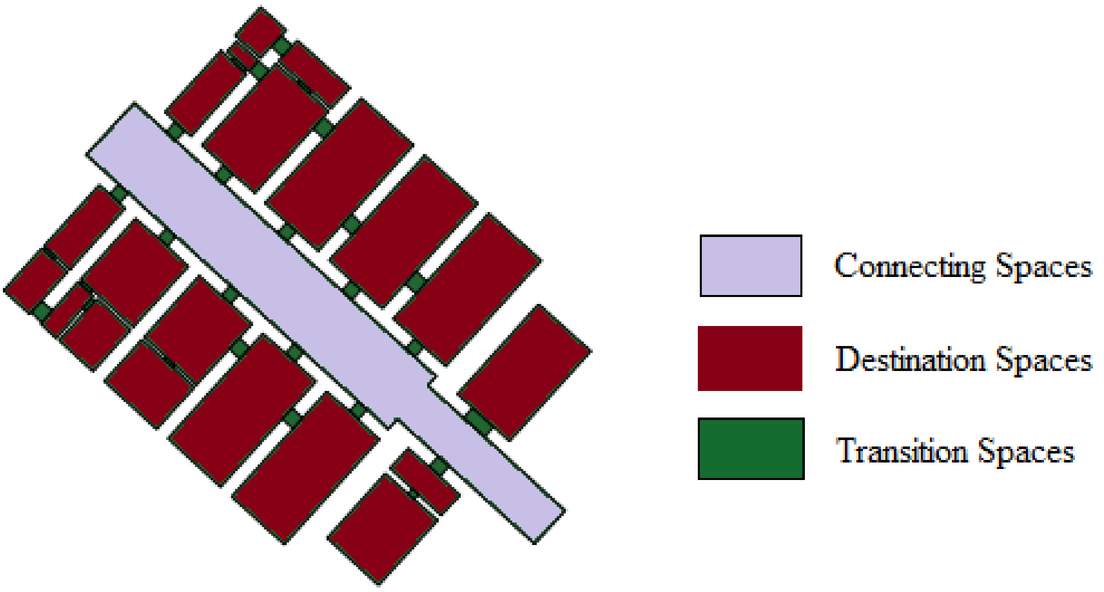

Figure 5.3: Environment Representation GeoFort building

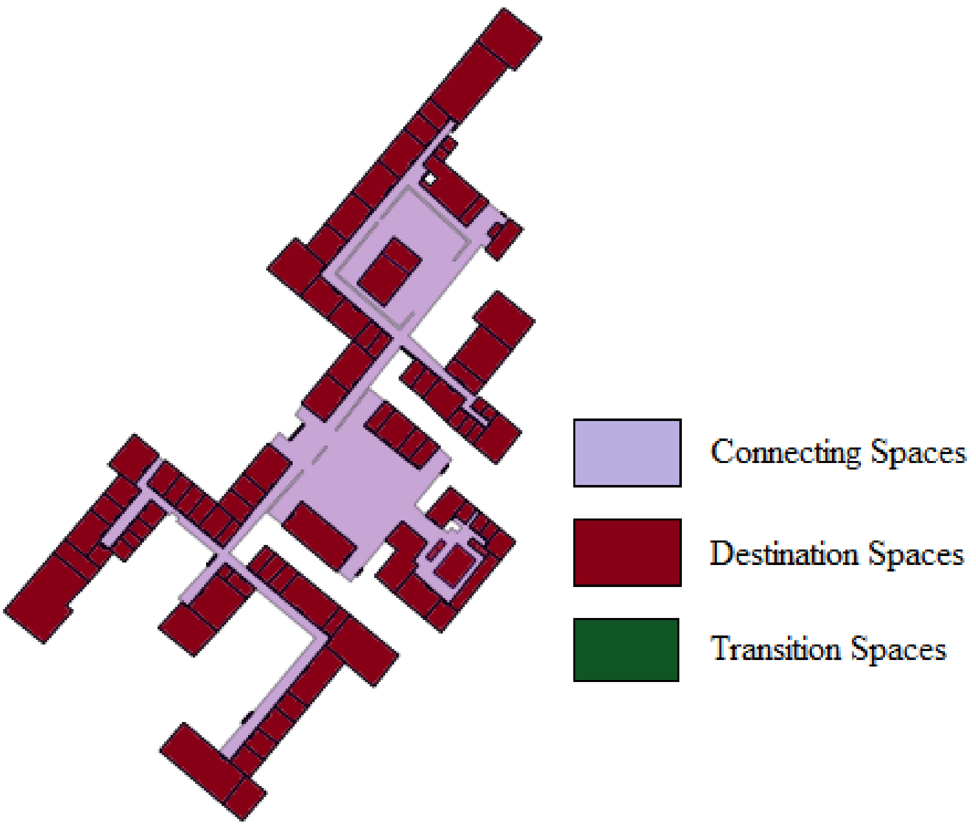

Figure 5.4: Environment Representation Architecture building

The whole preparation phase including georeferencing, digitization of polygons and entering of attribute values is a manual work which is necessary to be accomplished for every environment that the system is going to be implemented.

5.3 Navigable Space Subdivision

The connector polygons are of interest for the implementation of the proposed wayfinding assistance system as they delimit the part of the navigable space where people move when they are in search for a destination. Subsequently, these polygons are further subdivided according to a certain geometric criterion in order to derive these subspaces where people need assistance and even further the exact, accurate coordinates of the decision points. Rooms are not included in the triangulation as they act as starting points or destinations for the proposed system, as it has already been stated. They are taken into consideration only in order to infer the connectivity relationships between them and the decision points. Space subdivision is usually performed using the geometry of the indoor space. In practice, the geometry of 2D floor plans (lines or polygons) is used in order to subdivide the space according to a triangulation criterion, which is an absolute geometric criterion.

The Constrained Delaunay Triangulation (CDT) technique is used for the subdivision of the connector polygons. A CDT provides a natural way to retain the boundary information while producing a good triangulation (*Chew, 1989*). More specifically, CDT algorithm is a good solution for space subdivision when obstacles occur as it forces certain required segments in the triangulation. Obstacles are specified as constrained segments which can form an open or closed polygon in a given planar environment. Constrained segments can be perceived as entities blocking the movement in the space, e.g. walls. In this research as constrained segments are defined the walls that shape the connectors as it is impossible for people to cross them in order to reach their destination. Moreover, an important reason for the selection of CDT is the simplicity of the implementation and the precision in the resulting geometries. Triangulation is used in many game engines for path representation and planning. They are powerful structures which have been used in different ways for the purpose of computing navigation queries.

This method subdivides the plane into a number of triangular-shaped non-overlapping facets, while it retains the boundary information. The results of this operation are illustrated for the two case studies in figures 5.5 and 5.6. The Delaunay criterion imposes that the circumcircle of every triangle of the triangulation contains no vertex in its interior. In the constrained Delaunay triangulation some of the triangles might not be truly Delaunay, but all of them are constrained Delaunay meaning that the circumcircle of any triangle contains no vertex in its interior which is visible from all three nodes of the triangle (*Chew, 1989*). The constrained segments act as visibility blockers.

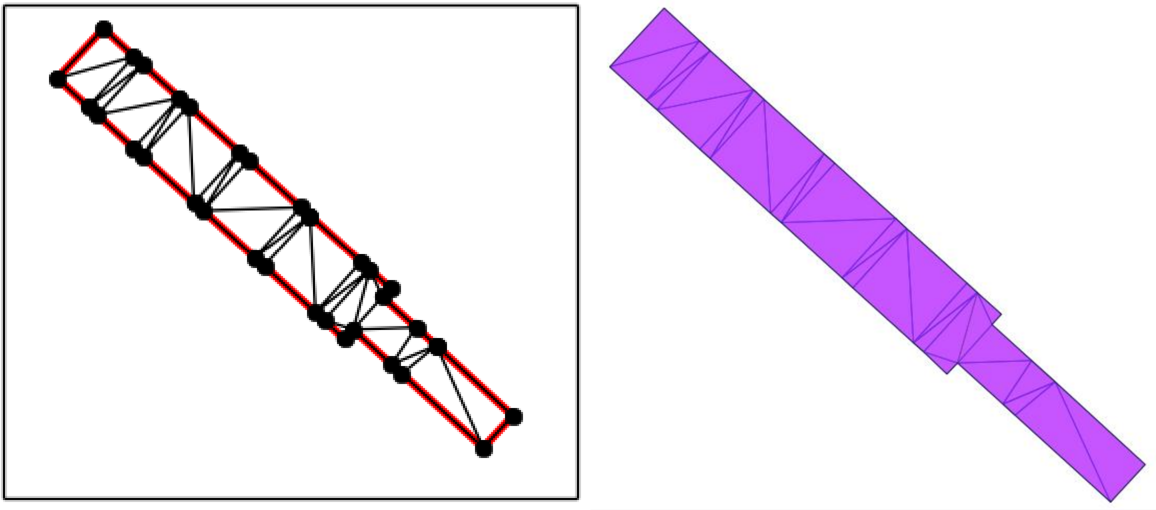

Figure 5.5: Constrained Delaunay Triangulation of connector polygon of GeoFort building

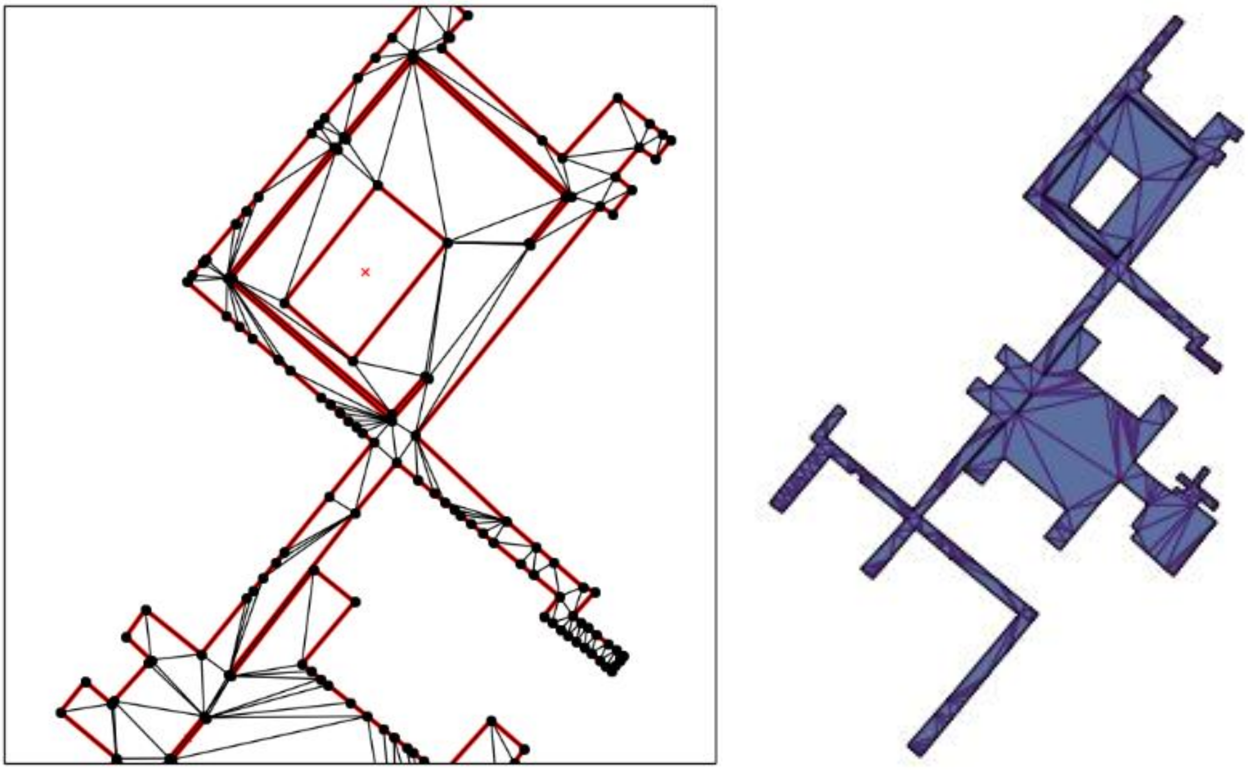

Figure 5.6: Constrained Delaunay Triangulation of connector polygon of Architecture building

In order to apply the CDT algorithm Python programming language was used. Python's extensive standard library covers many programming needs. However, there are cases for which some extra functionalities are needed and therefore some third-party modules are installed. For the purpose of this research Fiona, Shapely and Triangle libraries were installed. Fiona and Shapely are essential

Python tools for geospatial programming. Fiona does reading and writing geographic vector data formats. Thus, it is used in order to read the geometries and attributes of the objects stored in shape files. Fiona can read feature records as mappings from shape files or other GIS formats and write mappings as records to files using the same formats. There are no features or geometry classes. Records and their geometries are just data. Shapely is used in order to extract the geometry of the files as it contains spatial data types and functions. Shapely does manipulating and analyzing data, like buffers, intersections, unions, centroids, convex hulls. To perform the Constrained Delaunay Triangulation, Triangle library is used as it contains the required triangulation algorithm.

Triangle's input is a planar straight line graph (PSLG), defined to be a collection of vertices and segments, where the endpoints of every segment are also included in the vertices list. The set of vertices comprises the endpoints of the connector polygon boundary and the points which demarcate the occurrence of a transition space, e.g. doors or stairs. The set of segments consists of the segments that define the boundary of the connector polygon or any other obstacle represented as a hole that act as constraints for free movement. Using this input, Triangle module generates exact Constrained Delaunay Triangulations of the given PSLG. The number of generated triangles is governed by the geometry and the angle constraints specified by the user.

5.4 Decision Points Determination

As it has already been mentioned, the generated triangular subspaces after applying the CDT are of two types; these that contain constrained edges and these without constrained edges. The last type is the one that has to be classified in order to calculate the decision points for the two case studies. The classification of the triangle types is performed based on their topological relationships with the connector polygon.

Geospatial topology studies the rules concerning the relationships between points, lines and polygons representing a feature of a geographic region. In spatial analysis the topological spatial relations between features can be derived from the Dimensionally Extended Nine-Intersections Model (DE-9IM) (*Strobl, 2008*), as special predicates about relations between points, lines and polygons. Therefore, the topological spatial relations between the generated triangular subspaces and the originating polygon are examined by using the Dimensionally Extended Nine-Intersections Model (DE-9IM).

The DE-9IM is a topological model, which is based on a 3x3 intersection matrix with the dimensions of the intersection of the interior (I), boundary (B) and exterior (E) of two geometries (figure 5.7).

The boundary of a geometry object is a set of geometries of the next lower dimension. Consequently, the boundary of a polygon region consists of a set of curves which separates the region from the rest of the coordinate space. The interior of a geometry object consists of the points that are left when the boundary is removed and the exterior of a region consists of all the points that are not part of the boundary or the interior of it. For the extended model the values of the matrix can be -1, 0, 1 or 2 (-1 corresponds to no intersection).

$$DE-9IM(A,B)=\begin{bmatrix} \dim(I(A)\cap I(B)) & \dim(I(A)\cap B(B)) & \dim(I(A)\cap E(B)) \\ \dim(B(A)\cap I(B)) & \dim(B(A)\cap B(B)) & \dim(B(A)\cap E(B)) \\ \dim(E(A)\cap I(B)) & \dim(E(A)\cap B(B)) & \dim(E(A)\cap E(B)) \end{bmatrix}$$

Figure 5.7: DE-9IM or Clementini Matrix

This content of the matrix of the spatial relation between the input (originating) polygon and the generated triangular facets differs between triangles without constrained edges and triangles with at least one constrained edge. For the first case, the matrix is like the one illustrated below:

DE-9IM (Originating Polygon, Generated Triangular Subspaces without constrained edges) = $\begin{bmatrix} 2 & -1 & -1 \\ 1 & \mathbf{0} & -1 \\ 2 & 1 & 2 \end{bmatrix}$

while for the second case it looks like:

DE-9IM (Originating Polygon, Generated Triangular Subspaces with constrained edges) = $\begin{bmatrix} 2 & -1 & -1 \\ 1 & \mathbf{1} & -1 \\ 2 & 1 & 2 \end{bmatrix}$

Based on the previous matrices it is apparent that if the result of the intersection of the boundaries of the two geometries is a point set then the triangle contains zero constrained edges. Otherwise if it results in a line set the triangle has at least one constrained edge. In that way the triangles without constrained edges are selected, as it is depicted in figure 5.8. The non-constrained triangular subspaces generated based on this overlay operation correspond in reality to areas where two or more segments of the connecting spaces intersect. In most of these cases, more than two possible directions of moving occur, starting from the current location.

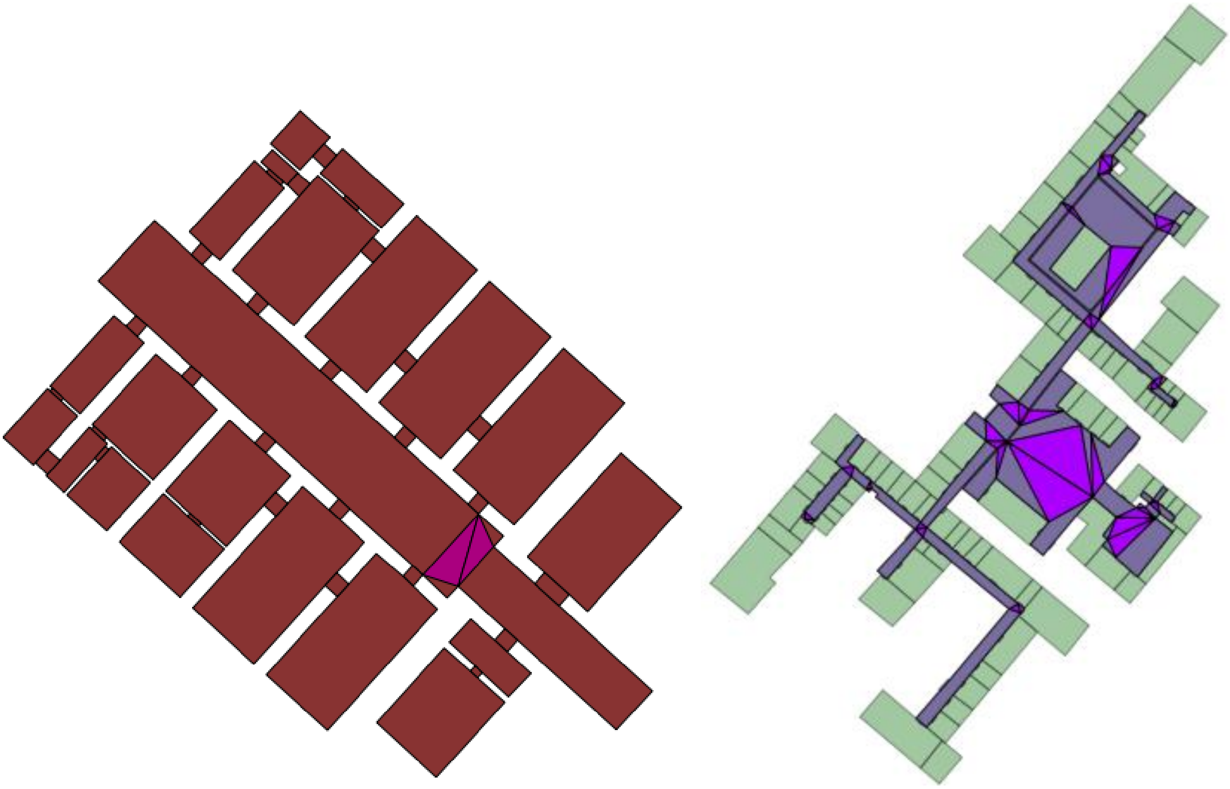

Figure 5.8: Triangular subspaces without constrained edges based on the overlap relationship

However, direction change may occur also in locations where entrance or exit from a connecting or destination space is possible. This case should be taken into consideration in the process of determining the subspaces where decision points are located. So far the CDT takes into account the positions of the openings of the connector polygon, i.e. the doors or stairs or elevator, as constraints. If both starting and ending points of a door are mapped, the generated output will entail a facet whose constrained edge is spanning over the whole length of the door frame. However, in reality this is not a real constraint. To solve this issue, the semantics of objects indicating openings should be considered in the process of discriminating between triangle types. Thus, a classification of the segments used as an input for the triangulation is performed and the set of triangles without constrained edges is extended by these triangular subspaces that are adjacent to transition spaces, i.e. openings. In figure 5.9 all the triangular subspaces without constrained edges for the two case studies as they derived after applying the previous operations are illustrated. The arrival at a destination space is signified through the landmark-signs located at these decision points.

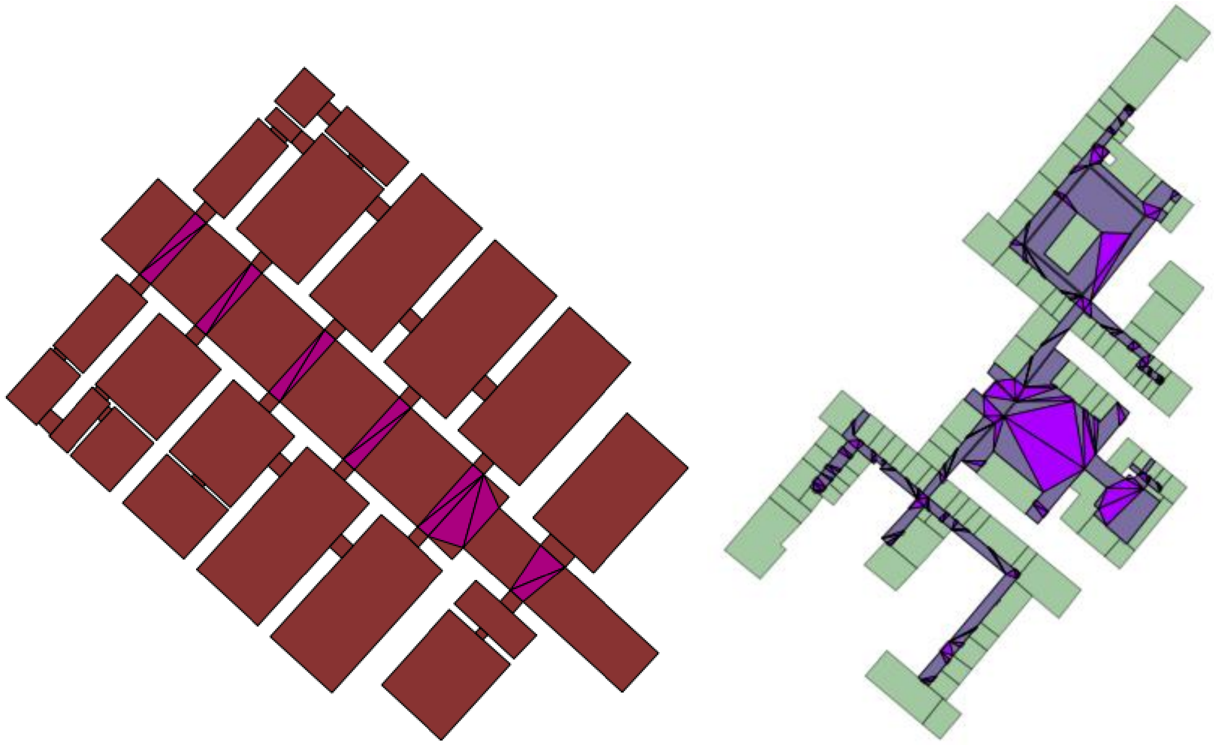

Figure 5.9: All triangular subspaces without constrained edges

The centroids of the triangles without constrained edges are calculated as they are the most representative points in order to act as the precise locations of decision points. However, in some cases some of these possible locations are very close to each other, as it is illustrated in figure 5.10. This creates a redundancy of landmark-sign locations. The problems arising from this situation is that firstly, two or more signs can be installed very close to each other or even partially overlap depending on the sizes of the selected signs and secondly, this entails the risk of creating confusion or misinterpretation of the assistance. Moreover, from a practical point of view, the presence of a higher number of landmark-signs requires more effort and maybe higher costs depending on the materials used for the fabrication of the landmark-signs.

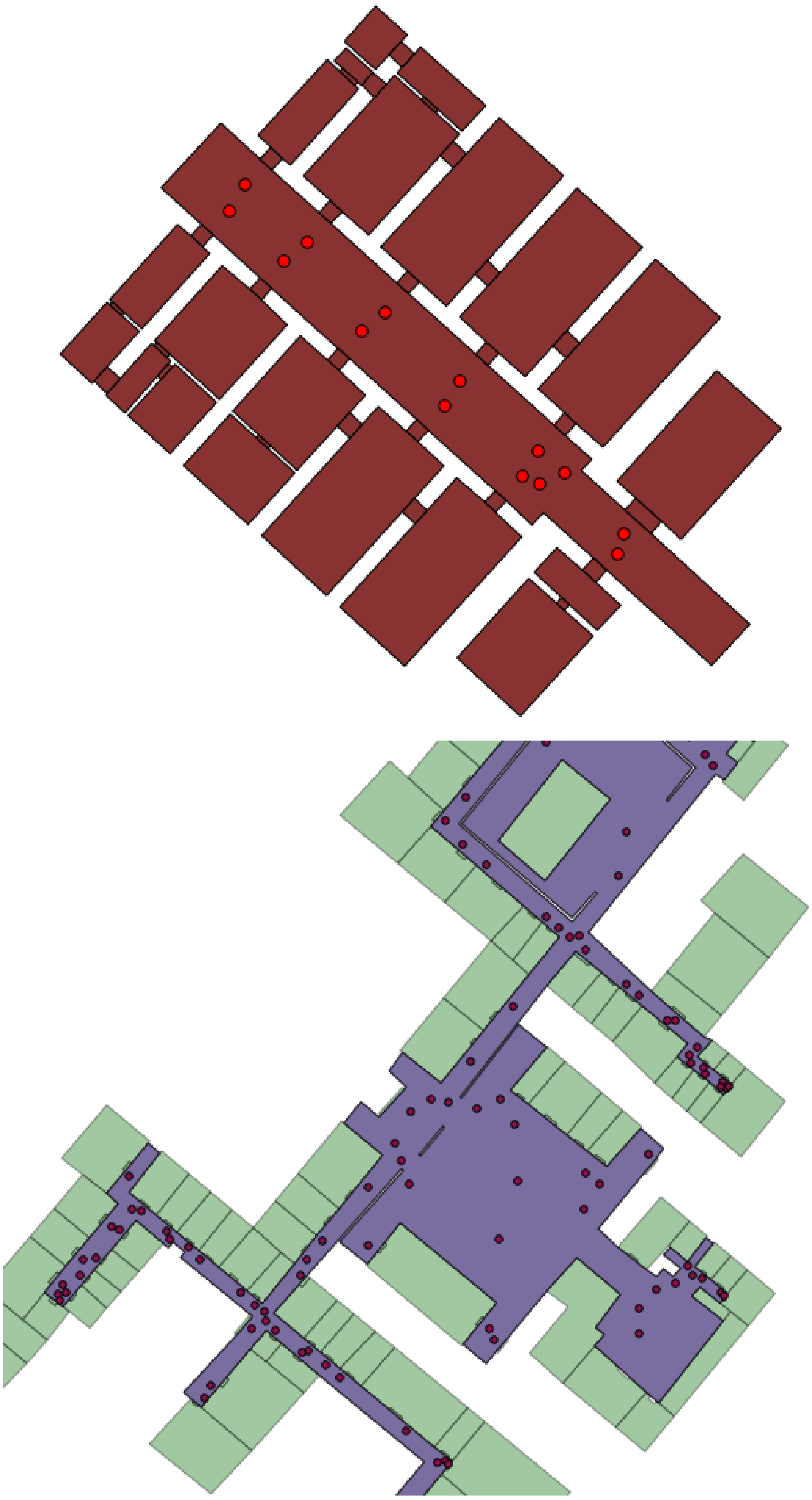

Figure 5.10: Cases in which decision points are in a very short distance to each other

Therefore, two adjacent triangular subspaces are merged into one larger polygon and its central point can represent the decision point by replacing the previous generated centroids. In that way the final decision points for the two case studies are calculated, as it is illustrated in figures 5.11 and 5.12.

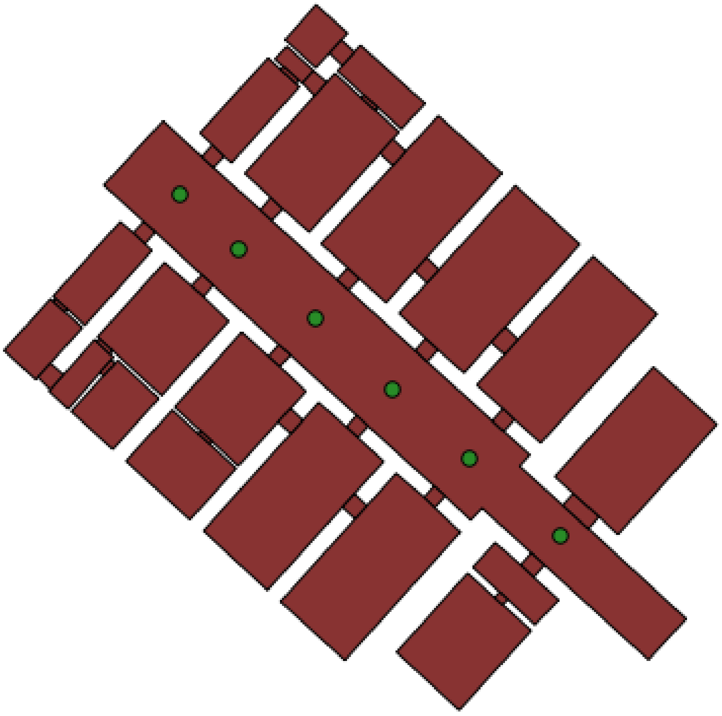

Figure 5.11: Decision Points of GeoFort building

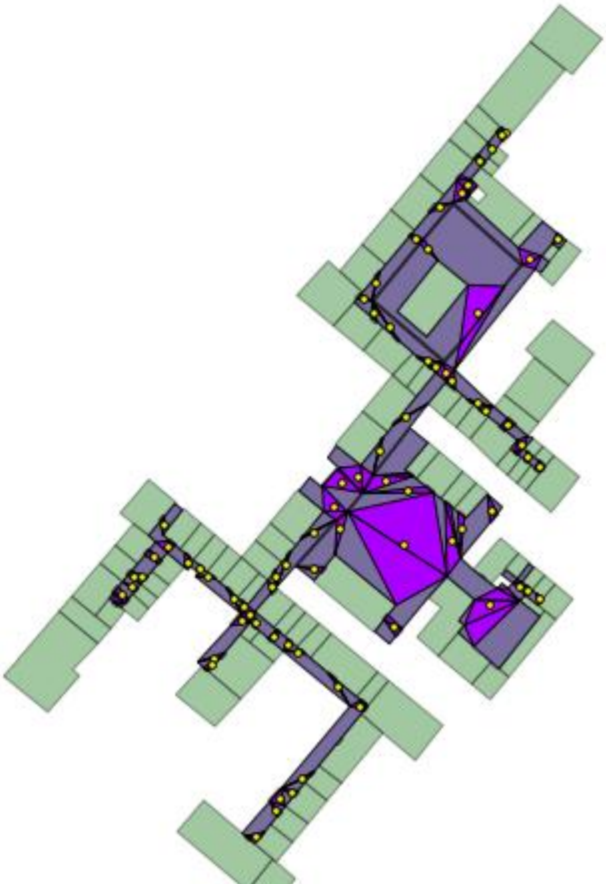

Figure 5.12: Decision Points of Architecture building after CDT

Another issue which is detected after calculating the decision points based on space partitioning according to the Constrained Delaunay Triangulation criterion is that their locations can sometimes be quite before or even after the real location where direction change is imposed. The cause of this circumstance is that the CDT generates large triangles with irregular shapes and small angles. In order to solve this problem, the insertion of Steiner points is imposed in order to split the constrained segments and create a more symmetrical and more regular space subdivision result. The Conforming Delaunay Triangulation is then used while further area and angle constraints can be imposed to generate an even better outcome containing triangles as equilateral as possible. The output of the conforming Delaunay triangulation is quite similar with the output of the CDT for the GeoFort building, as the connector polygon has a regular shape and the input PSLG is symmetrical at all sides of the polygon. However, this is not the case for the building of Architecture. By applying the conforming Delaunay triangulation, the connector polygon space is subdivided into smaller, more equal triangles with more regular shapes, as it is depicted in figure 5.13.

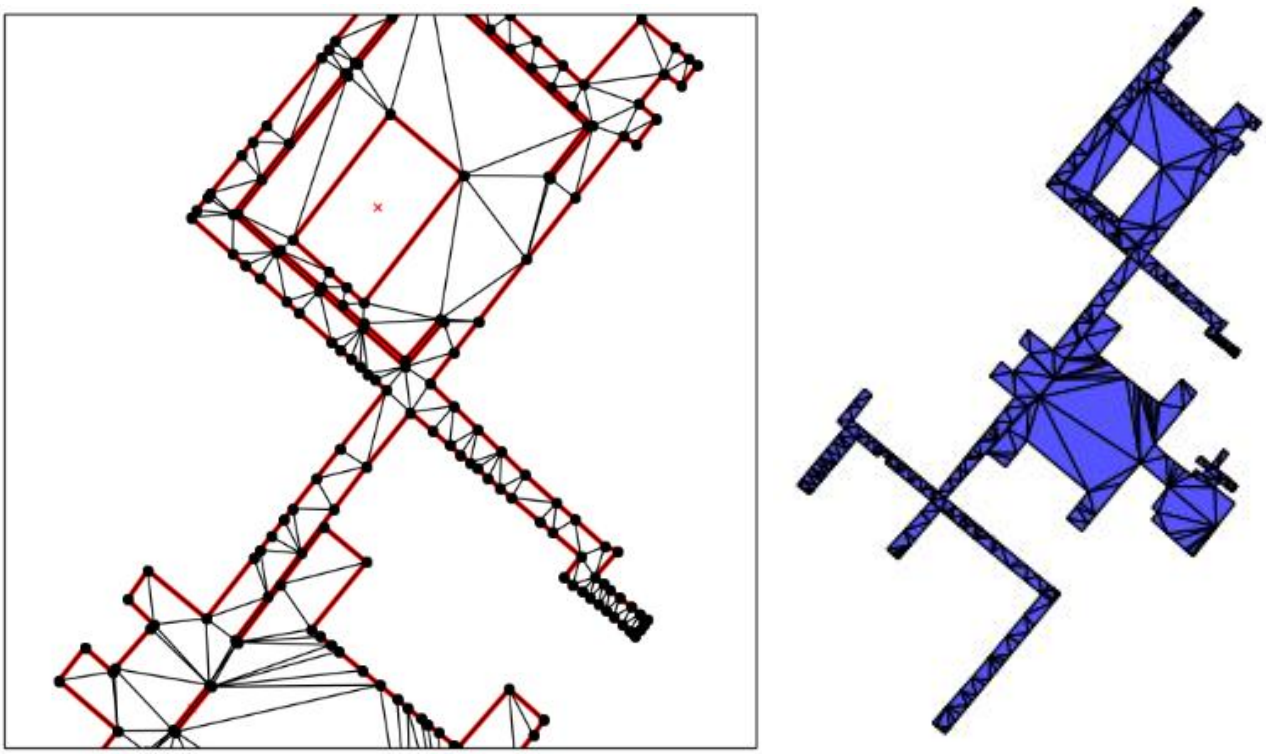

Figure 5.13: Conforming Delaunay Triangulation for Architecture building

Therefore the determination of the final decision points for environments like Architecture building, for which the input PSLG is not symmetrical, is performed based on this space subdivision approach while following the previous mentioned steps for the differentiation of the generated triangular subspaces. The result of determining the subspaces without constrained edges for Architecture is illustrated in figure 5.14.

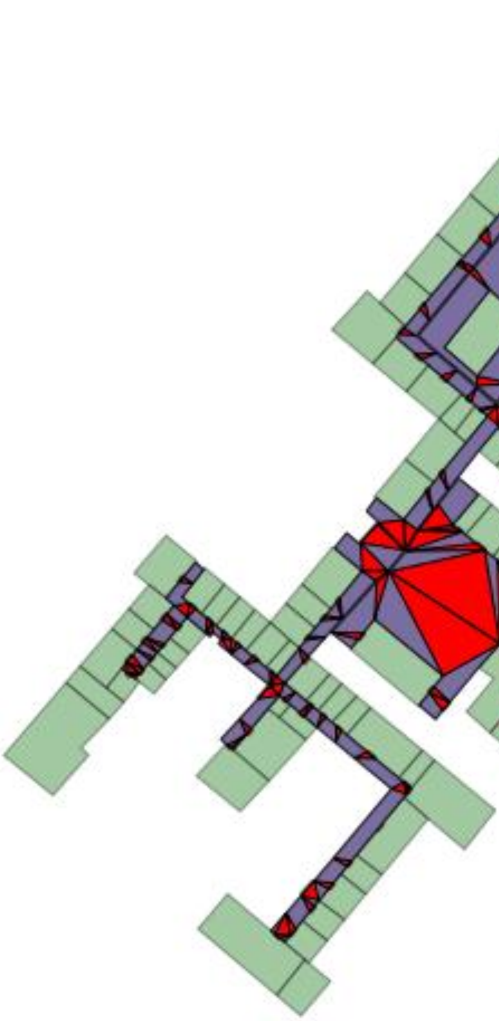

Figure 5.14: Triangular subspaces without constrained edges after applying Constrained Conforming Triangulation

Even after performing the conforming triangulation method some of the decision points locations are not accurate with respect to the locations of the transition spaces. The result of the triangulation is always influenced by the input list of vertices and in some cases the insertion of Steiner points is not possible. This is mainly observed in the open spaces where the boundary of the polygon is quite extensive. Figure 5.15 shows the final determined decision points for the ground floor of the Faculty of Architecture and the Built Environment. The deployment of the points in the largest part of the building is the expected one. In the large open space in the middle of the building it is not very accurate but for the purposes of providing wayfinding assistance to humans is satisfied as the routes that people can follow are clearly specified.

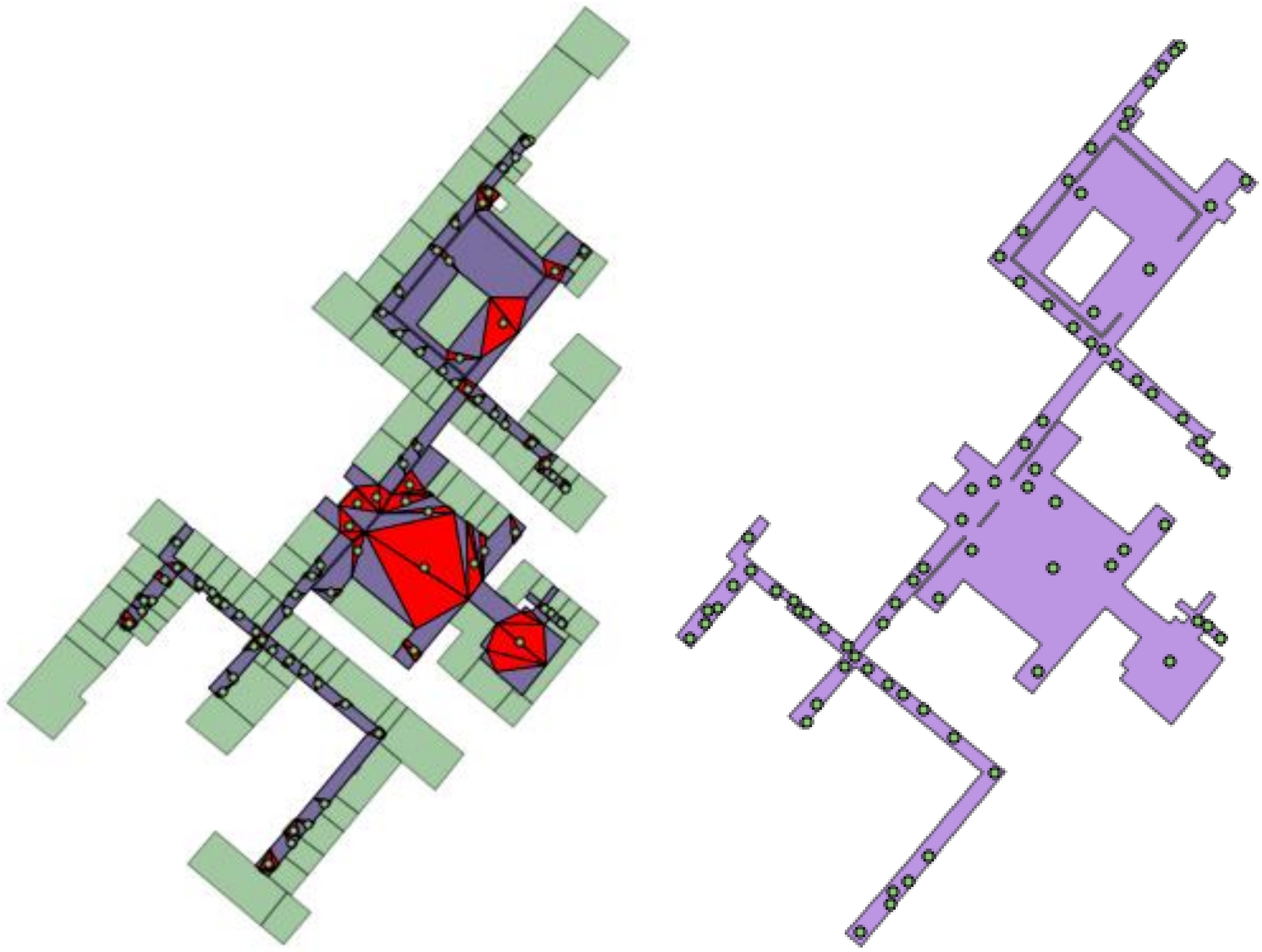

Figure 5.15: Decision Points of Architecture building

5.5 Network Generation

In order to extract the graph representation of the connecting spaces, the middle points of the edges of triangles with at least one constrained edge that are not part of the boundary of the originating polygon are calculated and all the nodes (decision points and middle points) are linked based on the adjacency relationship of their polygons. Finally, for the generation of a network of the entire building the central points of polygons representing destination spaces and transition spaces are calculated and linked to the closest decision point node. In that way all the possible routes of the building are represented and distances between the nodes can be estimated as the graph reflects not only the topological relationships between spaces but also the geometry of the building.

The fact that at least three possible directions of moving occur at the decision points is certified by the degree of the nodes. The decision points nodes have a degree of three or more as at least three edges are incident to these vertices. All other nodes of the graph representing connecting spaces have only two links. The same is for most of the nodes representing destination spaces. However, in the case of GeoFort network (Figure 5.16) it is observed that some of these nodes have a higher degree. This is due to the existence of transition spaces between rooms, which creates a second possible path. This can be treated by considering this path as connecting space and further subdivide it in order to determine new decision points. However, this is not necessary for a small building like the one of GeoFort as it does not generates further navigation problems.

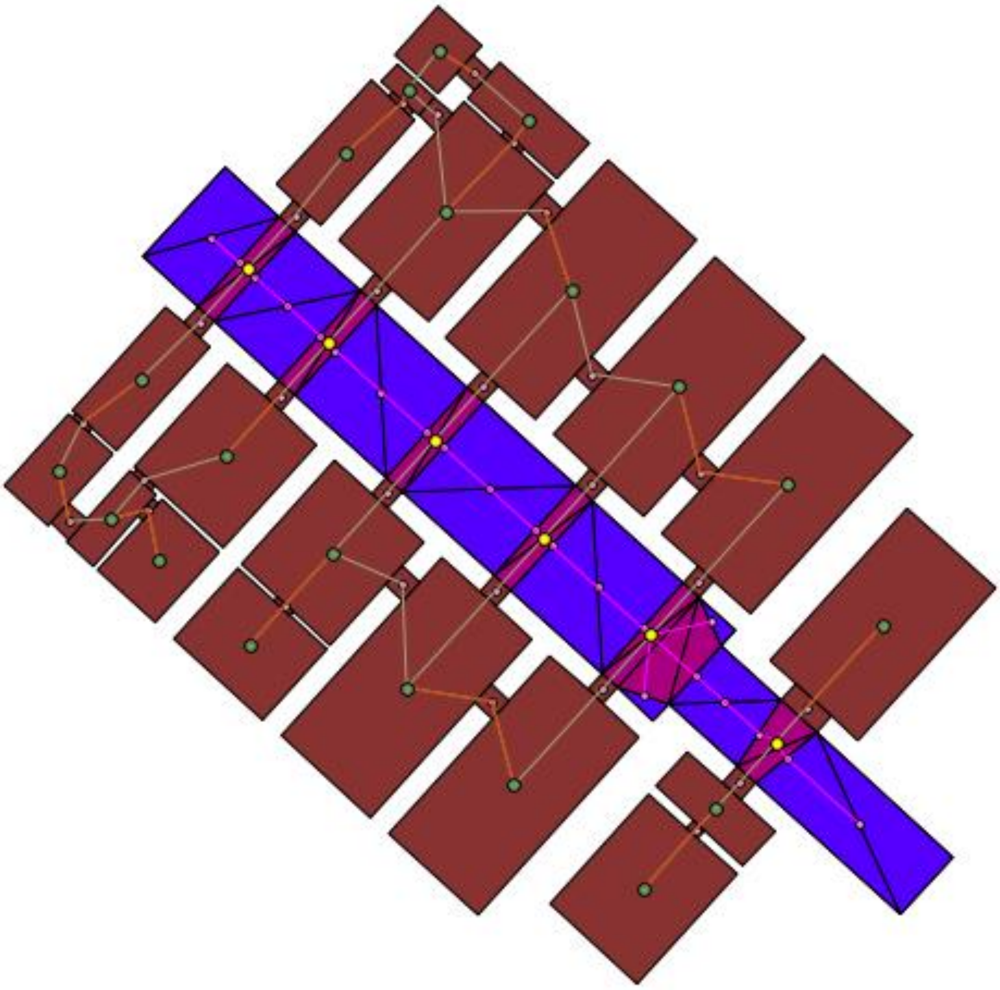

Figure 5.16: Network of routes for GeoFort building

The generated network for the case of Architecture building is illustrated in figure 5.17. Appendix A contains a smaller part of the network in order the details to be more clear. The network of routes represents quite well the way people move in the space especially in the corridors. In the open spaces it does not always provide a smooth line and it might create a strange path and backtracking in some cases. However, this is a problem that can be resolved by smoothing the edges between the decision points.

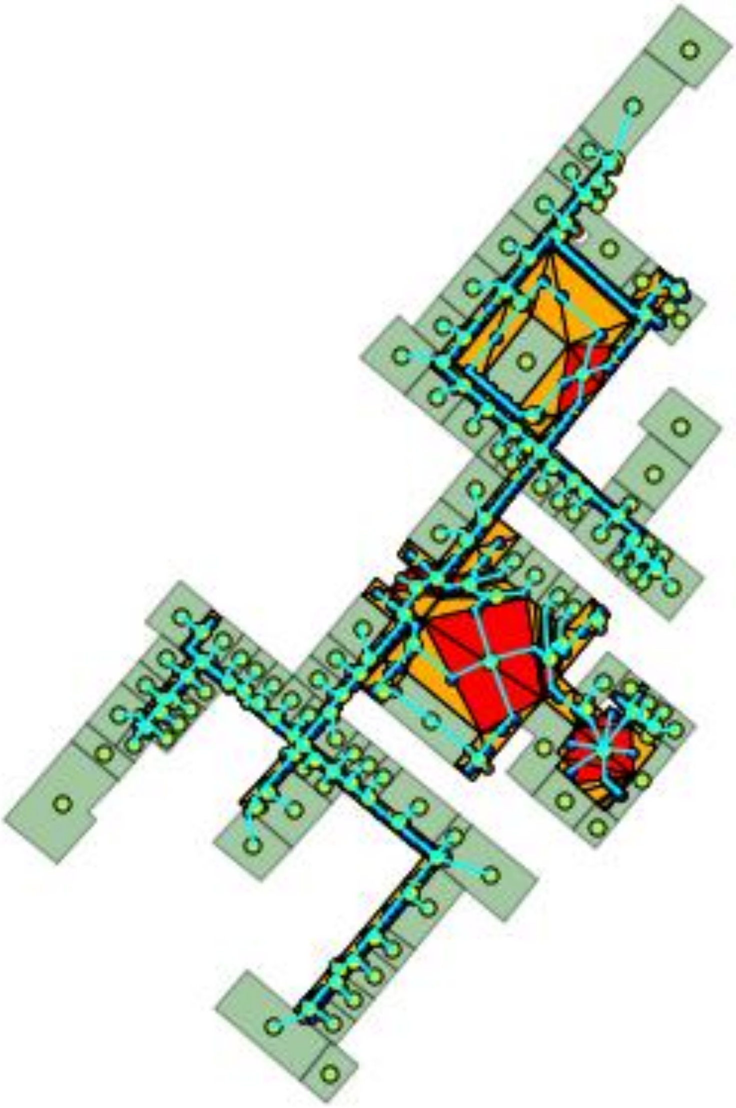

Figure 5.17: Network of routes for Architecture building

The whole process starting from the space subdivision and the determination of the deision points to the generation of network is performed by creating a Python script, which is cited in Appendix B. The two generated networks are stored in PostgreSQL database. The decision points are stored in a table with their IDs and geometries and the network is stored in two tables; one for the nodes and one for the edges. Additional information for the nodes and edges can be stored in the database.

Having determined all the decision points and their links in the network, numbering them and fabricating the landmark-signs according to the given numbers is the last step to be performed. The number of possible directions of moving and consequently, the amount of directional arrows in the landmark-sign is derived by the degree of each one of the decision points. For the examined building cases the maximum degree of node encountered is four. Therefore, only landmarks-signs with three and four indications of the next numbered node were used.

6. Validation

The validity of the applicability of the proposed wayfinding assistance system is verified based on a human-based survey. Mocked-up paper versions of the proposed numbered landmark-signs (Figure 6.1) are placed at the already determined decision points and people are asked to follow them in order to reach pre-specified destinations. Their movement is observed in order to deduce about the usability of the system. The time to reach the destination and the number of detours are the main measures to infer about the reliability of the approach as an indoor wayfinding aid, as well as the personal opinions and comments of the participants as they are revealed through a questionnaire-based survey. The main questions that this experiment seeks to investigate are firstly, the appropriateness of the generated by the model decision points and secondly, the ease with which people can follow the landmark-signs in order to reach a destination.

Figure 6.1: Landmark-signs used at the validation test

Validation of the reliability of the proposed approach to act as a wayfinding assistance system for indoor environments was performed only for the case of BK building. BK is a more appropriate environment as it is a more complex building with different types of spaces and different floor levels. Moreover, implementation in both environments was difficult due to time and distance limitations. The implementation of the proposed system was not an easy task as the landmark-signs interfere in the environment and conflict with the existing wayfinding system of the building. Moreover, the installation process is getting complicated due to the movement of people in the space. Thus, the installation of the landmark-signs was performed at a very specific time, when the faculty was not very crowded. For the test purposes the original room names were replaced by numbers, as it is also required by the rules of the system, so that the existing signage system of the building not to be able to be used, even by people familiar with the environment.

6.1 Human Observation

The ultimate aim of the experiment is to test whether people are able to follow the proposed system and whether they consider it more comprehensible and reliable compared to other indoor wayfinding systems. More specifically, the participants were asked to find their way from one location to another by following the landmark-signs that were placed at the ground and first floor of the Architecture building. During the test the participants were observed and their behavior was registered. People unfamiliar with the environment were asked to find the same rooms by following the existing signage system in order to have a measure of comparison between the proposed system and the existing one that relies on wall-signage.

Three routes from a starting point to a destination specified by the experimenter were executed. The three routes are indicated with red colour in figure 6.2; the first one is from the main entrance of the building (Nr.1 at the picture) to the Urbanism section (Nr.2), the second one is from Urbanism section to room R (Nr.3) and the third one is from the main entrance (Nr.1) to room T (Nr.4). The first two routes are entirely on the ground floor of the building while for the third one there is a floor change as the starting point is on the ground floor and the destination on the first floor. The routes were signified by the numbered landmark-signs, which were placed at the decision points. The sequence of numbers that corresponds to the landmark-signs composing the route was given to the participants for all three routes. Accordingly, their task was to reach the given destinations by following the sequence of numbers that represents the route.

The experiment was held on three different days, in the evening that the faculty was not crowded. The total number of participants for the first and second route is 25 people, while for the third route 15 people participated. The vast majority of these people are students of TU Delft. However, not all of them were students at the faculty of Architecture. Therefore, the sample is composed by people familiar with the building and people unfamiliar with it.

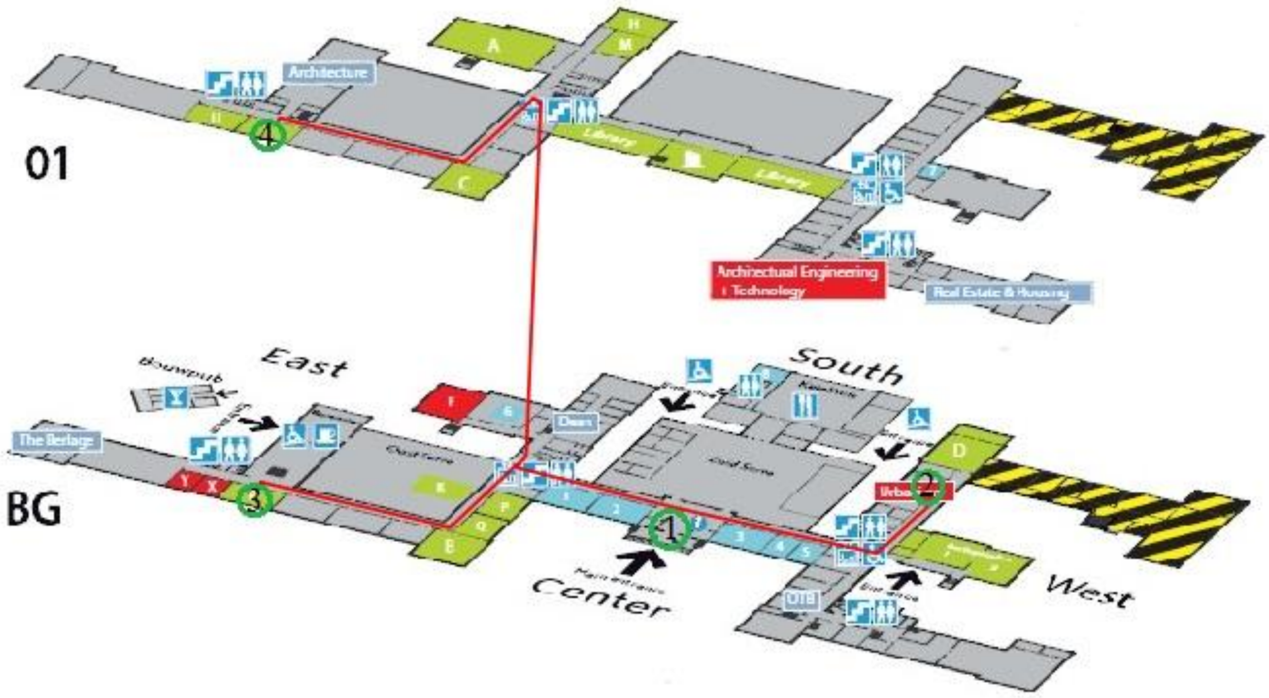

Figure 6.2: Validation test routes

The density of the landmarks-signs was differentiated along the three routes; the first one contains a small number of landmark-signs, as only the decision points at the intersections of the connector polygons (corridors) were used. The second and third routes are denser; all the decision points at these route segments were used. This different setup of the routes was employed in order to investigate the possibility of following the system with confidence using a small number of landmark-signs only at the most crucial decision points, where many possible directions of moving are presented to the user.

The first sparse route consists only of a sequence of three landmark-signs in order to reach the destination room, as it is illustrated in figure 6.3. All the participants were able to find their way to the destination in a relatively short time. The average time was about 1 minute. The range of the time values varies from 55 to 67 seconds (figure 6.4). There was also an outlier as one of the participants reached the destination in 38 seconds as he was running while executing the task. Therefore, it cannot be perceived as a representative indication. The outlier was excluded by the calculation of the average time. The short time to reach the destination can be attributed to the short distance of the route, as well as to the fact that there was line of sight between the landmark-signs. However, it was mentioned by some of the participants that the non-existence of landmark-sign at the stair before the landmark-sign number 2 was a bit confusing. Their preference to include this location at the decision points was expressed during the test and in the questionnaire.

Figure 6.3: First route of the experiment

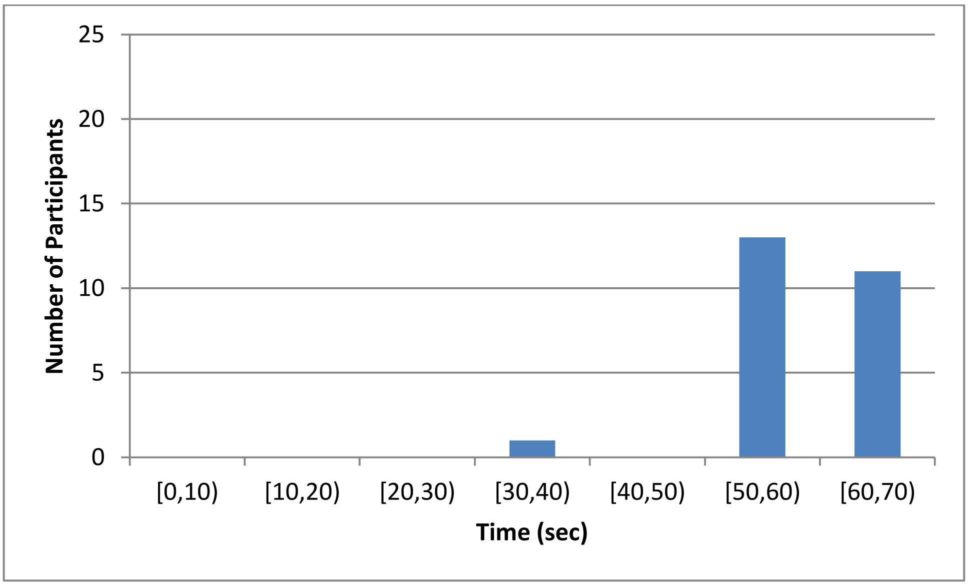

Figure 6.4: Time to complete the first route

The second dense route consists of all the automatically generated as it was described in the previous part decision points and it is illustrated in figure 6.5. The starting point of the route is the landmark-sign (Nr.5) closer to the destination of the previous route and the destination is room 33, which is located at the opposite side of the building. This is a quite longer route compared to the previous one. The participants had to cross a big part of the ground floor of the building in order to reach their destination. The time they needed for this route is longer as the travelled distance is also longer. The average time was about 2,4 minutes. The time values range from 2,14 to 3,38 minutes (figure 6.6). In this case the maximum value is quite higher compared to the average value. This is due to the fact that there was a backtracking from one of the participants, who misinterpreted the numbers on the landmark-signs. However, throughout this route there was an increased feeling of security that users are on the right track as a result of the density of landmark-signs.

Figure 6.5: Second route of the experiment

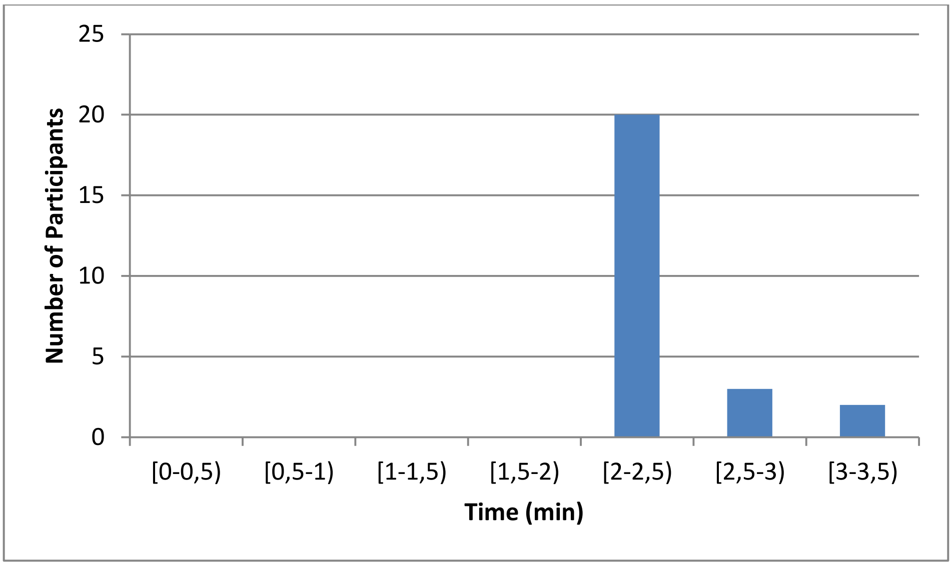

Figure 6.6: Time to complete the second route

The third route has the specialty of extending in two floor levels. It consists of all the automatically determined decision points and it is illustrated in figure 6.8 (Nr.112 is the destination). This is not a linear route as the previous two and it was selected in order to test the ability of people to follow the system in the case that a floor change is involved. The time to reach the destination ranges between 2,12 and 3,48 minutes (figure 6.7) and the average time is calculated to be about 2,4 minutes. The maximum value was observed for a participant that was confused at the point of floor change and lost time. A general conclusion that comes out after the completion of all three routes is that as people are becoming familiar with the system it is becoming easier to follow it without confusion. Another important conclusion is that the differentiation between the time values is mainly due to the different pace of moving of the participants rather than to the difficulty to follow the system.

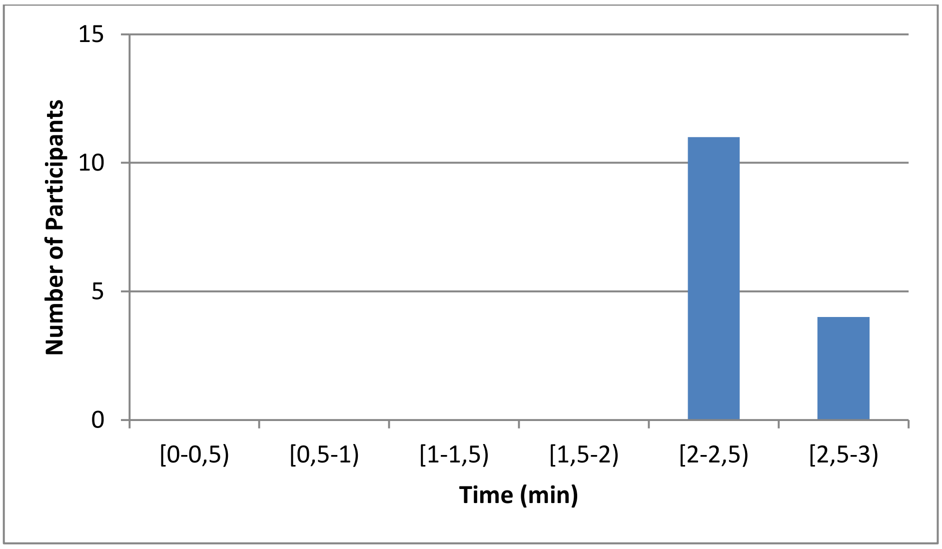

Figure 6.7: Time to complete the third route

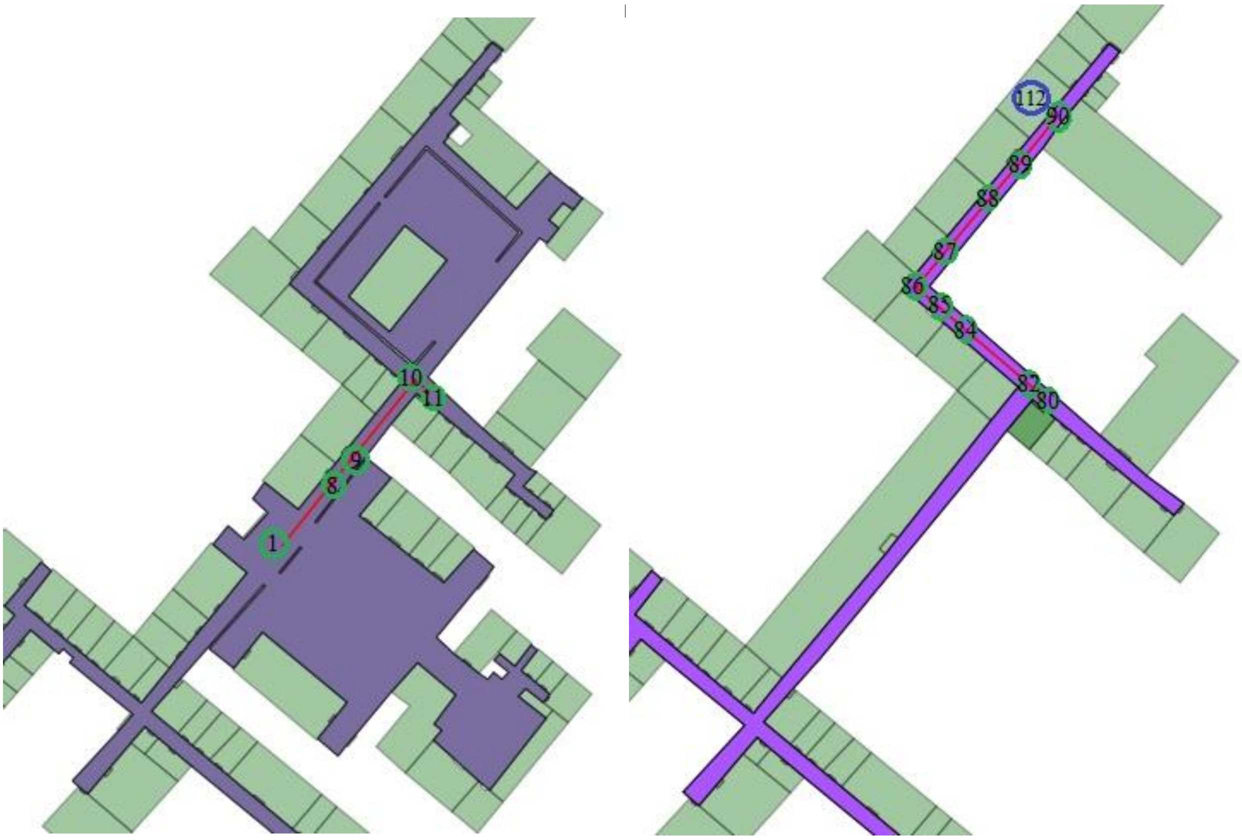

Figure 6.8: Third route of the experiment (left image: ground floor, right image: first floor)

Additionally, throughout the routes participants were asked to specify the times when they were lost or felt insecure about the direction they had to follow in order to examine the possibility of the system to develop a feeling of anxiety or stress or even to disorient people from their target. It was observed that most of them followed the routes with security and they were not lost. Only two detour behaviors were registered, while all the participants reached the destinations.

The participants visiting for the first time the building performed the first two routes using the existing signage system of the building in order to have a measure of comparison between the two wayfinding assistance approaches. The time to reach the destinations by following the existing system was quite longer. Participants needed approximately double time to complete the first route following the existing system, while for the second route they needed about one minute more than the time they needed following the proposed system. It was observed that especially for the first route they were particularly confused by the name of the room (BG.west.250); they couldn't understand the meaning of the name. Additionally, not adequate signage indicating the direction of the room was provided. Finally, all the participants spent time in front of the signs in order to find their destination and confirm the direction to move. For the second route the room name (room R) was easier to be remembered and more frequently referenced along the route, especially at central locations. Nevertheless, also during this route participants needed confirmation that they are moving to the right direction and finally they needed more time to reach the destination.

There are many wayfinding systems that provide instructions to people independent of the means they employ to do it. However, most of them lack the positioning component. The proposed system attempts to give an indication about the relative position of a person in the indoor setting, without the need of consulting a plan of the building. In order to test whether the participants were able to recognize their location in the building in conjunction with their starting point or previously encountered places, they were asked not only to find their way to a specified destination by following the landmark-signs but also to explain their location in comparison to the starting point at regular times during the experiment. Varying answers were received. People familiar with the environment were aware of their location in the setting but this cannot be perceived as a reliable measure. Among the other participants, two opinions were voiced. The first one is that the logical and symmetrical numbering with respect to the main entrance or the centre of the building can be helpful in order to provide an indication of how deep in the building is a person located. The second one is that the system is a nice wayfinding assistance tool but they are not able to orient themselves or infer their location. Through the experiment the reliability of the system as a kind of referencing system was not verified. However, there are positive indications that this issue can be further investigated. By using a numbering which follows a logical order, people can maybe infer how far away from the starting point or the entrance of the building are located at any time.

6.2 Questionnaire-based survey

After the completion of the experiment the participants were asked to fill in a short questionnaire. The aim of the questionnaire is to gain an insight on people's opinion about the effectiveness of the system. Besides the structured part of the questionnaire, participants were encouraged to express their comments regarding the applicability of the system and the limitations they observed either in a written or oral way.

The survey consists of questions regarding two types of information; firstly about the level of satisfaction regarding the user-friendliness of the system and secondly about the level of satisfaction regarding the performance of the system in the wayfinding assistance task. The questionnaire is cited in Appendix C.

The purpose of the first two questions was the investigation of participants opinion about the simplicity and comprehension of the proposed system. As it is a new system which is firstly introduced, it is quite important to be easily perceived by users. The results indicate that the vast majority of the participants consider the system quite simple to be learned and used, as it is shown in figure 6.9. A learning or information phase throughout which they are getting familiar with the working principles of the system and the concept hidden behind the numbers is definitely needed. However, it is not a long procedure. Moreover, participants are quite satisfied with the way the information is provided to them, as it is depicted in figure 6.10. However, some problems were highlighted regarding the comprehension of the landmark-signs. More specifically, in some cases the numbers on the landmark-signs are inversed as they are placed so that they are read correctly only in one way. Therefore, when the participants follow the route in the opposite way they might be confused and spend time trying to read the landmark-signs. Furthermore, two participants were confused with numbers 6 and 9 and referred to the need to better differentiate them.

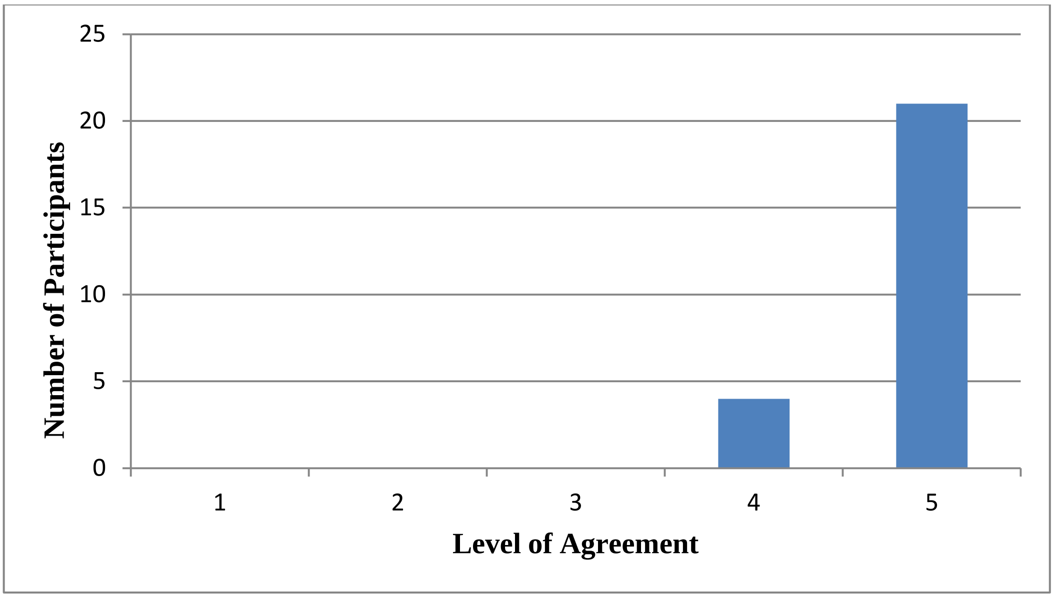

Figure 6.9: Level of satisfaction regarding the simplicity of the system

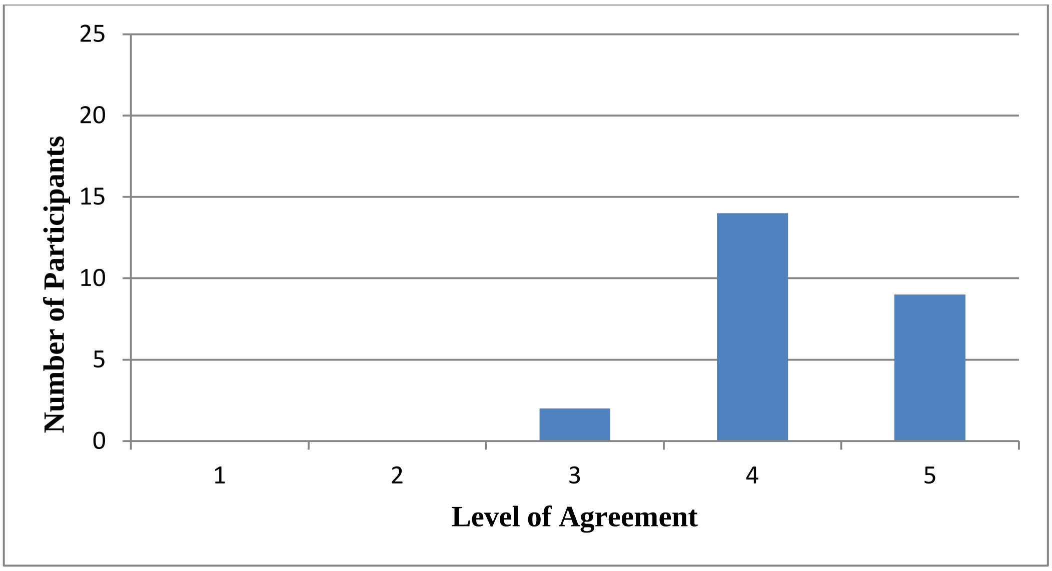

Figure 6.10: Level of satisfaction regarding the comprehension of the landmark-signs

The third question aimed at investigating the opinion of participants regarding the presentation of the information for the provision of assistance. More specifically, they were asked to declare their preference among numbered and textual signs. As it is depicted in figure 6.11, there is a slight preference of the numbered signs. They are more easily remembered. It was also reported by the participants a great benefit of numbered signs, which is the fact that they are read by all people regardless their language. However, as it was indicated by some of the participants, the way of presenting the information is not as important as the location and information itself.

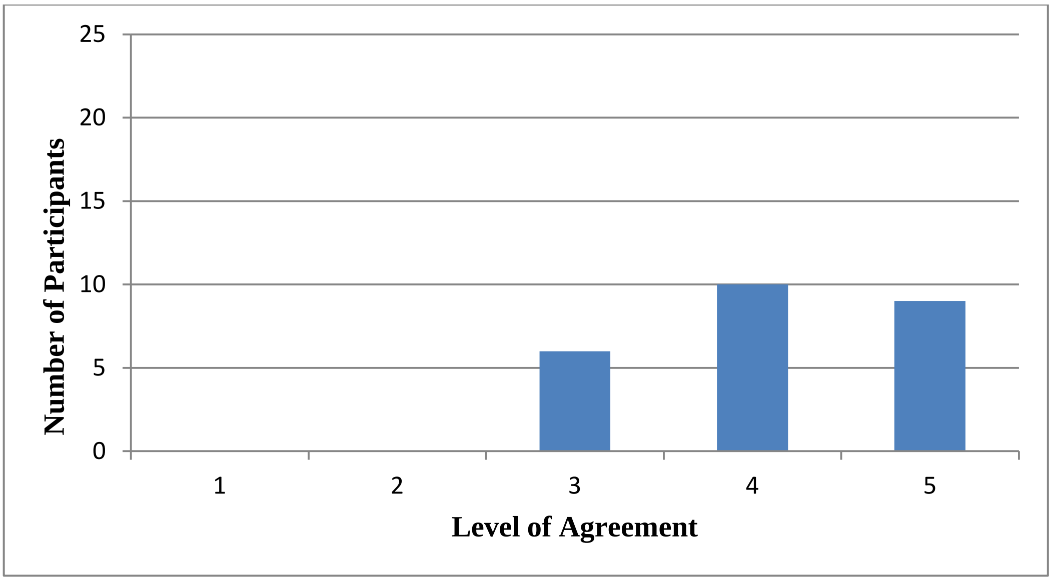

Figure 6.11: Level of preference of signs containing numbers instead of text for wayfinding assistance purposes

The next two questions aim at extracting the feelings of the participants regarding the effectiveness of the system. The two main measures that are used for concluding about the reliability of the system to act as a wayfinding assistance tool are the time people need to reach a destination and the security they feel that they are on route. The results (Figure 6.12) show that the participants consider the system efficient in terms of time of travelling. This is also demonstrated by the results of the time they needed to complete the two routes of the experiment. On the other hand, according to their answers people were not absolutely confident that they are following the right track as shown in picture 6.13, despite the fact that none of them got lost during the experiment. Their confidence is influenced by visibility and density factors.

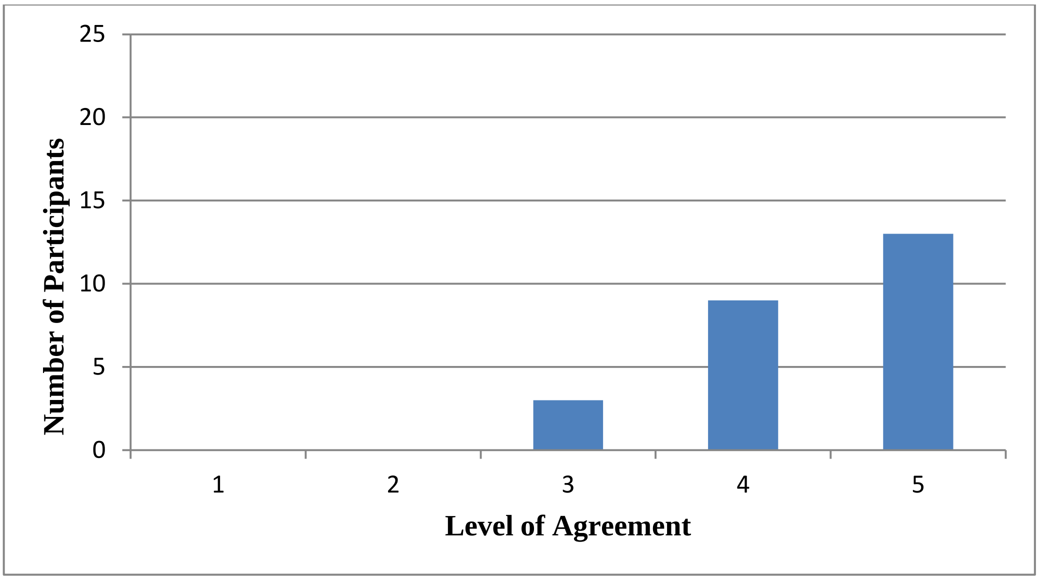

Figure 6.12: Level of satisfaction in terms of time to reach destination

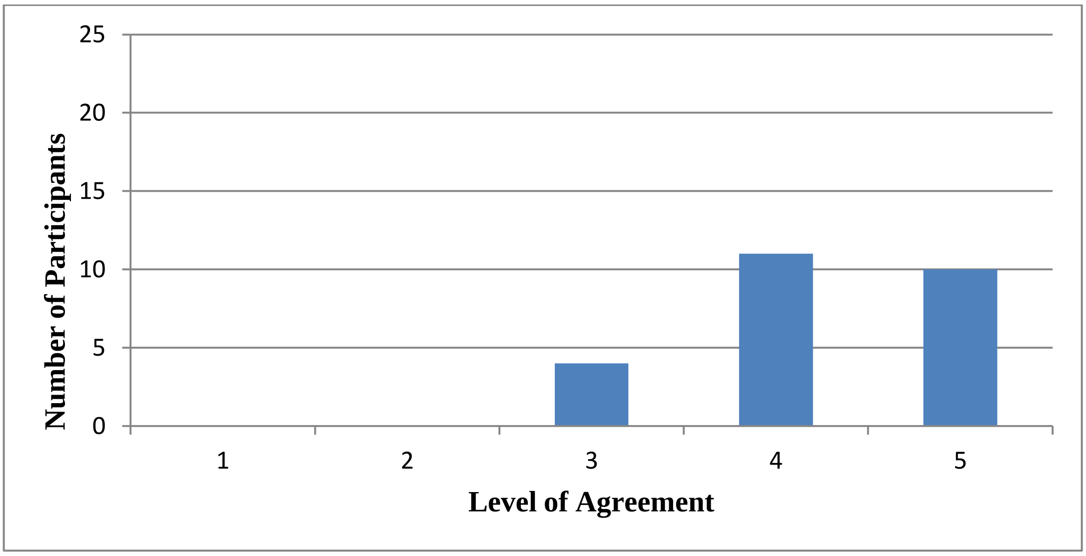

Figure 6.13: Level of satisfaction in terms of confidence being on the right track

Finally, the overall impression participants got from the system was positive, as it is illustrated in figure 6.14. They consider it an approach that can be quite useful in the way people are navigating in unfamiliar environments. Participants recognized not only the fact that following numbers is more convenient and does not create misunderstandings but also the fact that assistance was provided to the locations where it is needed. Many of them emphasized on this aspect during the experiment either by recognizing the fact or by detecting the locations where they expected assistance and it was not provided. There are though improvements that can be consider. Participants referred to the fact that the numbers on the landmark-signs are reversed in the return routes and they should read them upside-down. Moreover, some of them need a mobile application or another means of feeding the sequence of numbers in order to be aware of the meaning of them.

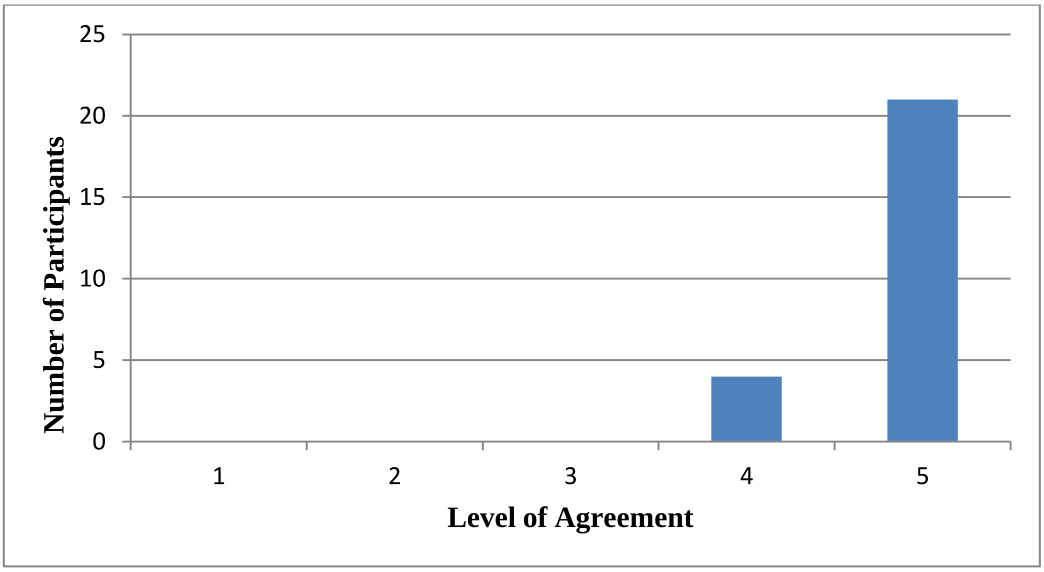

Figure 6.14: Overall impression of the system

7. Discussion

In this work the main target was to propose a new innovative wayfinding assistance system for indoor environments, which incorporates the concept of landmark through the presence of special physical objects at specially-determined locations. The output of the work is the theoretical framework of how the system can be applied in various types of indoor settings. At the beginning of the research, separate objectives were set that were expressed through the formulated research questions and sub-questions. The outcome was tested in order to verify that the objectives have been met. The findings of the research will be further discussed with respect to the research questions. Additionally, the limitations of the proposed system will be pointed out in order to facilitate future improvements and better functionality of the system.

How can the principles of the Junction Network System be applied in order to enhance wayfinding in the context of indoor navigation?

In order to achieve the main objective of the research, which was to develop a system to enhance wayfinding in indoor environment, an already existing and successful outdoor system was employed as foundation. Two steps are distinguished in the process of building the new system. The first one is the deep understanding of the original outdoor system and the second one is the generation of the conceptual model for the adapted indoor system. The Junction Network System as it applies for providing guidance to cyclists in the Netherlands was used as the starting point of this work. The "Junction Network System for Indoor Environments" emerges as the equivalent of the outdoor system as it derives from the translation of the principles of the original system to the case of indoor space. However, the principles of the original system are not blindly adopted for the formation of the indoor system but they are thoroughly reviewed and specifically adapted to the case of indoor space.

1. What are the principles of Junction Network System as it is applied for cyclists?

More specifically, one of the main points of the outdoor system is the creation of a network of nodes equipped with signs in order to provide guidance. The system makes use of the area where bikes move in the space, i.e. the cycling lanes, which have a very specific geometry and functionality. In this area assistance is provided to the users at the points where cyclists actually need it, i.e. at the junctions of two or more cycling lanes. However, not all the junctions are used. An arbitrary selection of the junctions to be populated with signs is made. The numbering of the signs is the technique used to reveal all the information to the cyclists. Thus, a sequence of numbers corresponds to a specific route. Furthermore, in the original system the numbered signs act as a kind of landmarks along the cycling paths as they are easily recognized by cyclists when they are becoming familiar with them.

Besides the use of the Junction Network System for cyclists as a starting point, the thorough review of relevant literature on several topics supplies this research with all the information needed in order to further develop the new concept. More specifically, findings of human wayfinding studies and current indoor wayfinding systems are used in order to get acquainted with the information requirements of wayfinders and the difficulties encountered while executing the task. Throughout the process of achieving the ultimate goal, the existing indoor wayfinding approaches were investigated and compared to the proposed approach. The overview of the limitations of the existing systems provides a knowledge on bad practices and examples that should be avoided. Additionally, the findings of several research approaches regarding the landmark theory and the concept of route directions in wayfinding are integrated into this research in order to reinforce the new concept.

More specifically, the current approach takes into consideration the fact that people usually employ a central strategy when looking for their way in unfamiliar environments and that they are heavily relied on prominent objects. Thus, a landmark-based system was developed that makes use of the main circulation routes of the indoor setting. The system is based on signposts as signage systems is the most popular wayfinding assistance method indoors and at the same time the same objects have a great potential to become proper landmarks. The recorded limitations of existing indoor wayfinding systems regarding illegible signs, overabundance or absence of signs, assistance provided in erroneous locations and incomprehensive text do not appear in this approach. Furthermore, several studies related to route directions in wayfinding task reveal the importance of decision points as re-orientation points where a change of direction is needed and support the conceptualization of a route as a pair of decision points and actions to be made at these points. However, there is no automatic and distinct solution for determining the decision points in an indoor or outdoor environment.

2. How can the decision points be determined in indoor environments and how they will be connected?

3. Where should the landmark-signs be located in order to become prominent objects?

Indoor space is more complicated compared to the outdoor space used in the Junction Network System. First of all, the geometry and shape of indoor space differs significantly from the ones of the cycling lanes. Large open spaces can occur indoors and possible change of direction is encountered more frequently. Therefore, a proper representation of indoor space is necessary; and more specifically, only the part of the navigable space where movement occurs when people are searching for a destination applies to the concept for the indoor space. Thus, only the connecting spaces are used.

In this research techniques from computational geometry which are applied for the robotics and mobile navigation systems are used in order to decompose planar layouts of indoor environments into network-based maps and determine automatically the decision points. The graph representation of the indoor space is employed in order to illustrate the structure of the environment and the links between decision points and destinations. This is in line with several works that utilize this method for structuring of indoor space. However, in this work the main interest lies in the generation of a denser network for the connecting spaces which is based on the decision points derived by the space decomposition according to a geometric criterion (Constrained Delaunay Triangulation) and the semantics of the environment.

The decision points are the locations where the landmark-signs are placed so that they enhance the understanding of the direction instructions and provide a better conceptualization of the route. The importance of the decision points for wayfinding is verified through the results of the human-based survey. The location where the assistance is provided is maybe the parameter that should be mostly considered when a wayfinding system is implemented in an indoor environment. This was inferred by the short times of executing the routes in the survey and was stated by most of the participants.

4. What kind of landmark-signs will be used and how many different types of them are needed in order to make the system applicable?

5. How many landmark-signs are needed in order to provide a full coverage of the indoor space without confusing the user?

An innovation of this system in the field of indoor wayfinding systems is that a new method of presenting the wayfinding assistance information is proposed. The Junction Network System for Indoor Environments is the first attempt to investigate the potential of numbers to act as a unique identifier providing all the information at every decision point. So far numbers are used in some cases, mainly to differentiate between floors or to indicate room numbers. However, a comprehensive system based entirely on numbers does not exist yet. In this work, the directions are given as paths between numbered nodes and not as semantically given instructions, e.g. turn left or right at the second intersection. The arrival at a destination is signalled by a sign of different colour, while the numbering of the destinations follows a different order. The vertical movement is incorporated in the concept through the semantics of the indoor setting, by mapping the stairs, escalators and elevators as transition spaces. A special designed graphic is used to illustrate the floor change. The use of numbers instead of text on the signs is verified through the test as an effective means of providing assistance indoors.

6. What are the principles of the Junction Network System for Indoor Environments?

The proposed indoor system is - similarly to the outdoor one - based on the presence of physical objects at the nodes of a network of landmark locations. Assistance is provided to people where they need to make a decision on how to go on. However, in this case the decision points are automatically determined and provide a full coverage of the indoor space. Consequently, the possibilities of getting lost when following a route are minimized. Moreover, the proposed approach incorporates the landmark concept by integrating in one physical object all the attributes that make an object salient, such as the visual characteristics which bring it in contrast to the surroundings, the importance of the location for the wayfinding task and their content as a tool to provide assistance and for which wayfinders are in search. Finally, an important aspect of the indoor system which comes directly from the outdoor approach is the enumeration of the landmark-signs and the conceptualization of routes as sequences of numbers.

7. What is the reliability of the proposed approach?

The reliability of the new system was tested based on site observations. The promising result of the human-based survey shows the potential of the system to act as a solution for the wayfinding problem indoors. It was observed that people are able to follow it and that it is simple in its perception and usability. Further testing of the system in several building cases is definitely necessary in order to accept the system as an overall solution but the first indications about its reliability are quite positive. The feedback received after the test of the system at the Faculty of Architecture and the Built Environment reveals peoples acceptance.

Limitations

Overall, the potential of the proposed system to be successfully applied for facilitating indoor wayfinding is validated based on the results of the experiment. However, there are some aspects that have still to be considered. Firstly, in some cases the decision points are not coincident with the actual location where the choice of direction is imposed, so that the human should modify the automatically generated points according to the common sense during the installation phase. The main source of this error is identified at the manual work phase, where the boundaries of the polygons were digitized. Secondly, the way of numbering the landmark-signs should be carefully decided. The numbers should follow a logical sequence, so that people to be able to remember and follow them easier and to estimate their relative location at the building and the travelled distance. A uniform numbering system that reflects the structure of all indoor environments cannot be easily determined due to the diversity of indoor space configurations.

Moreover, the problem of not detecting the landmark-signs from a distance might arise when the environment is very crowded. This case was not examined as the validation test took place when the building was not full. However, this problem can be overcome by the fact that the density of existing landmark-signs creates a security that wayfinders follow the right route until they come to the next in the order landmark-sign. Nevertheless, the investigation of the potential of free-standing or ceiling-hung landmark-signs can be investigated. Finally, one of the important conclusions that came out of the experiment is that some people need to be aware of the meaning of the numbers and to have an overview of the numbering system for the whole environment. This was not investigated in the context of this experiment, which was focused on testing people's ability to perceive the principles of the system, but this is something to be further considered.

8. Conclusions and Future Work

The present research has contributed to the existing literature on indoor wayfinding systems by proposing a new system which is based on the significance of the location of providing assistance as the most important parameter for a successful system. In this approach, techniques from computational geometry and computer navigation systems are combined with the physical indoor space in order to realize the generation of a comprehensive system. The automatically determined decision points are populated with a unique physical object, which incorporates all the attributes of a salient object and therefore, acts as landmark. In that way, the landmark concept is naturally integrated into the wayfinding system and facilitates the assistance task.

Findings from literature in indoor wayfinding and landmark theory are used to build the new system filling the deficiencies of current systems, while new concepts are also introduced. In this work a model for the determination of the decision points is proposed. The location of providing assistance is the attribute that adds value to the system. The model employs geometric, topologic and semantic information for accurate determination of their locations. The indication of decision points within indoor space can improve the functionality of indoor wayfinding systems. This model is designed for different space configurations in order to be able to be implemented in various building cases. Furthermore, it can be incorporated in navigation models and enhance the conceptualization of turning instructions.

The locations and the high density of decision points and thereby, the full coverage of the indoor space with landmark-signs, minimizes the possibilities of getting lost when following a route. This is an important contribution as still there is no indoor wayfinding system relied on physical objects that can achieve that people are always on route. The technique of enumerating the landmark-signs and representing a route with sequence of numbers provides a better conceptualization of direction instructions. Moreover, it eliminates the requirement to explicitly state the semantics of the indoor space in order to reach a destination. The use of numbers as the only source of information providing is a new concept for indoor wayfinding systems and it is proved by the findings of the human based survey conducted at the last phase of the research to be quite promising. Additionally, the system can act as a referencing system and reveal the relative location of the user in the network space by applying a logical numbering system that reflects the structure of the building.

The evidence of this research suggests that the proposed system can be applied without any changes or with slight modifications to different cases of indoor space. The proposed model is initially designed for complex buildings with elongated shapes, such as office or university buildings.

However, the conceptualization of navigable space as it is introduced for the purposes of this research supports also the application of the concept in buildings with open spaces.

Since there is no uniform solution for indoor wayfinding problem, this work can be considered a good contribution to this direction. It encompasses concepts that can be successfully integrated in the existing systems or autonomously applied in new environments. Finally, the proposed system can be easily combined with digital navigation systems as the underlying network for route generation is already in place or with a mobile application with an inventory of the room names corresponding to the numbers and other details for people familiarize with technology.

Recommendations

As it has already been mentioned, the proposed system involves aspects that can be more carefully considered in order to provide an improved result. First of all, further investigation of the decision points determination can be performed in order to obtain more precise locations of changing direction. Different parameters of triangulating the navigable space can be tested, as well as a more detailed initial space partitioning.

Additionally, open space can be decomposed into smaller functional subspaces in order to be more suitable for applying the proposed concept. The presence of objects, like furniture, can be considered in order to provide a more reliable conceptualization of the navigable indoor space. In the case studies used in this work the open spaces were not further decomposed as the result of applying the concept in the whole space was satisfied. However, the paths that people employ to move in these spaces can be extracted for better precision in the results. The use of space syntax techniques can be examined in order to support the choice of connecting spaces by identifying the locations in a building that are mutually visible and have high accessibility values. Additionally, space syntax techniques can be applied to support the selection of the locations of placing maps throughout the building.

In the conducted test, the proposed system was treated as a stand-alone system, which provides all the information through the presence of the landmark-signs throughout the indoor environment. No additional tool, such as maps, inventory of room names or other details or mobile application, was used to support it. A better estimation of the performance of the system can be achieved by including the special maps with all the numbers and routes in the building and the inventory containing the meaning of the numbers and the destinations closer to each one of the decision points, so that people will create on their own the sequence of numbers to follow.

Finally, the system should be tested in a larger area in order to gain an insight on people's response when the environment is getting more complex. Several building cases should be used in order to certify the effectiveness of the system in different environments where users have different needs in terms of wayfinding efficiency. A first step to start with is to implement the system at GeoFort park as the technical work has already been performed and this specific place has several advantages regarding the testing of the reliability of the approach.

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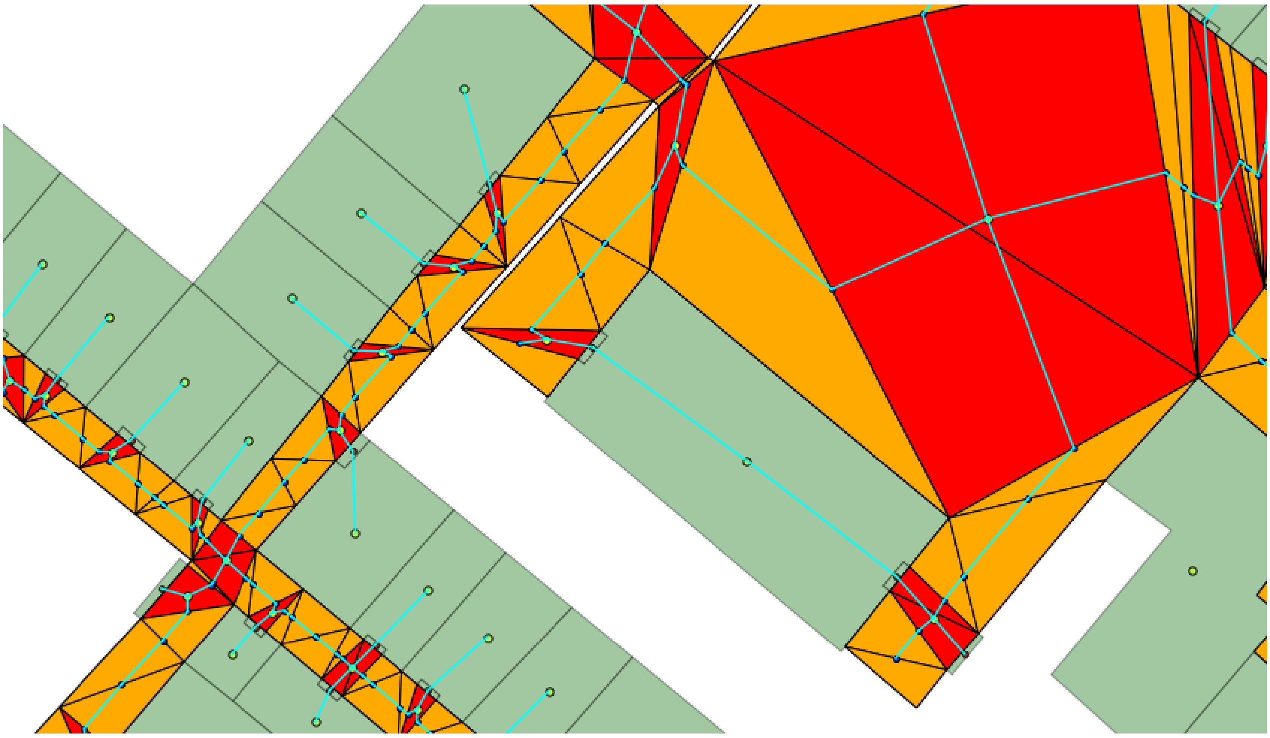
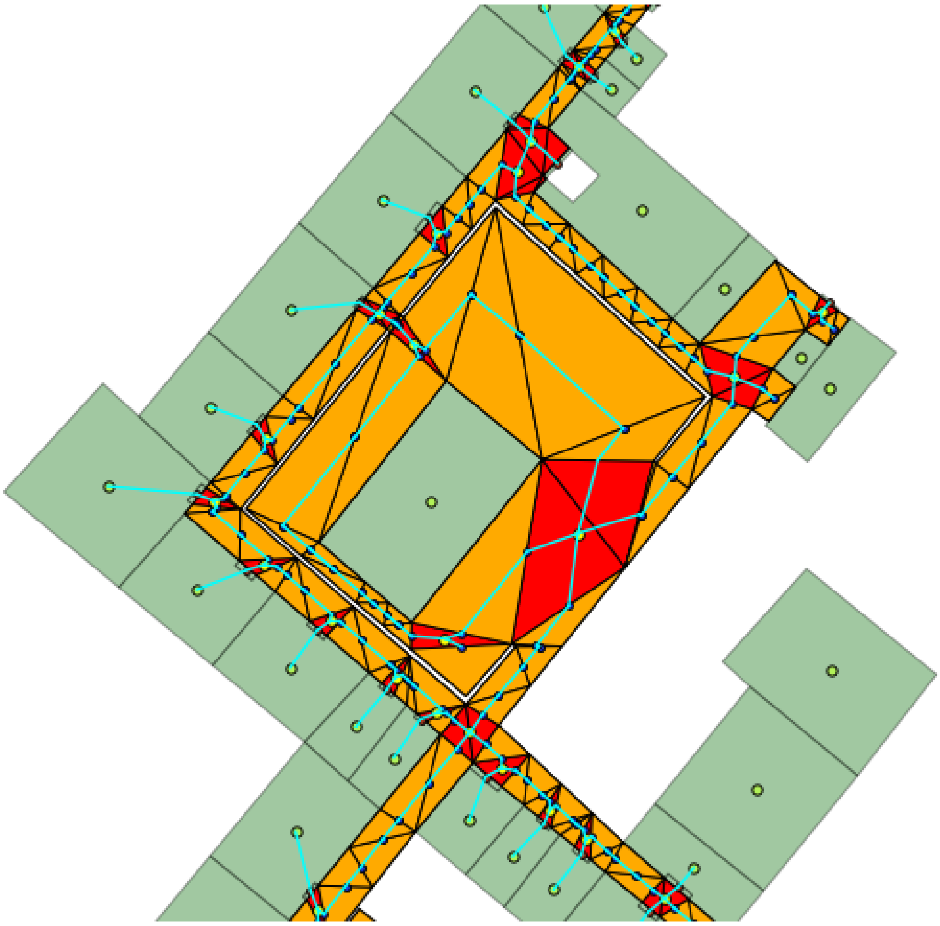
Appendices

Appendix A. Architecture Network

Smaller area of Architecture network for better illustration of details





Appendix B. Python Script

Constrained Delaunay Triangulation and Selection of Triangles with Constrained Edges

```
import fiona
from fiona import collection
from collections import OrderedDict
import numpy as np
from numpy import array

from shapely.geometry import Polygon, Point, LineString
from shapely.geometry.linestring import LineString, geos_linestring_from_py
from shapely.geometry import asPoint, import MultiPolygon
from shapely.geometry import mapping, shape

# read shapefiles as a collection of objects
data = fiona.open('C:/Users/antigoni/Desktop/Data/Architecture_polygons.shp', 'r')

import itertools, triangle, triangle.plot, matplotlib.pyplot as plt
import psycopg2

nodes = [], geom = [], polygonList = [], doors = []

# traversing all items in the collection in order to extract from the polygon geometry, the vertices, edges and holes that are necessary for the CDT
for feat in data:
    properties = feat['properties']
    geometry = feat['geometry']
    coord = geometry['coordinates']

# only for corridors (connecting spaces)
    if (properties['Type'] == 'Corridor'):
# extract segments for the triangulation
        edges = []
        boundary_line = []
        holePoints = []
        holes = []
        start = 0
        for i, ring in enumerate(coord):
            if start > 0:
                pg = Polygon(ring)
                hole = pg.representative_point().coords[:]
                holePoints.append(hole)
                holes.append(pg)
```

```
            elif start == 0:
                polygonList.append(Polygon(ring))
            coord[i] = ring[0:-1]
            length = len(coord[i])
            for i in range(0, length):
                edges.append([start+i, start + ((i+1)%length)])
            start = start + length

# extract vertices for CDT
# chain function treats consecutive sequences as a single sequence
# create the boundary line of the originating polygon
        points = list(itertools.chain(*coord))
        polygon_line = LineString(points)
        boundary_line.append(polygon_line)
# create dictionary of vertices, segments and holes
        if holePoints:
            geom.append(dict(vertices=array(points), segments=array(edges), holes=array(holePoints)))
        else:
            geom.append(dict(vertices=array(points), segments=array(edges)))
    elif properties['Type'] == 'Door':
        doors.append(Polygon(coord[0]))

# Constrained Delaunay Triangulation of a PSLG
trianglesList = []
for i, d in enumerate(geom):
    tri = triangle.triangulate(d, 'p')
    trianglesList.append(tri)

# visualization of the result
    ax1 = plt.subplot(121, aspect = 'equal')
    triangle.plot.plot(ax1, **tri)
    plt.show()

triangle_edges = [], triangle_polygons = []
# Edges of triangles in a shp
for t in trianglesList:
    points = []
    lineList = []
    lineList2 = []
    trianglePolygon = []
    vert = t['vertices']
    seg = t['segments']
    trian = t['triangles']
```

```
    for tri in trian:
        points = vert[tri].tolist()
        points.append(points[0])
        polygon = Polygon(points)
        trianglePolygon.append(polygon)
        lines = LineString(points)
        lineList2.append(lines)
        lines_coord = lines.coords[:]
        lineList.append(lines_coord)
    triangle_edges.append(lineList)
    triangle_polygons.append(trianglePolygon)
ilgis = len(triangle_edges)

# Select the triangles without constrained edges based on the overlap relation between the boundary of the originating polygon (outer and inner rings) and the triangle edges
originating_polygon = []
boundar = []
hole_edges = []
for elem in holes:
    bound = elem.boundary
    hole_edges.append(bound)
    originating_polygon.append(elem)
for elem2 in polygonList:
    originating_polygon.append(elem2)

for elem in originating_polygon:
    bound = elem.boundary
    boundar.append(bound)

not_constrained_triangles = []
edges_of_constrained_triangles = []
edges_of_non_constrained_triangles1 = []

for elem in lineList2:
    for elem2 in boundary_line:
        if not elem.overlaps(elem2):
            edges_of_non_constrained_triangles1.append(elem)

for elem in lineList2:
    for elem2 in boundary_line:
        if elem.overlaps(elem2):
            edges_of_constrained_triangles.append(elem)
```

```
# Calculate the neighbouring triangles of the door polygons as they are also triangles without constrained edges
# Find the segments of the connector polygon that are neighbouring to door polygons
doorsegments = []
for elem in doors:
    ds = elem.boundary
    doorsegments.append(ds)
tri_edg_adj_todoors = []
for elem in doorsegments:
    for tri in lineList2:
        if elem.overlaps(tri):
            tri_edg_adj_todoors.append(tri)
for elem in edges_of_constrained_triangles:
    while elem in lineList2:
        lineList2.remove(elem)

# All the triangles without constrained edges in one list
for elem in edges_of_non_constrained_triangles1:
    t = Polygon(elem)
    not_constrained_triangles.append(t)
for elem in tri_edg_adj_todoors:
    t = Polygon(elem)
    not_constrained_triangles.append(t)

# Calculate the centroids of the non-constrained triangles, which are the possible (candidate) decision points of system
all_decision_points = []
for triangle in not_constrained_triangles:
    centroid = triangle.centroid
    centr_coord = centroid.coords[:]
    all_decision_points.append(centr_coord[0])

# Merge the adjacent triangles
not_used_triangles = []
length = len(not_constrained_triangles)
checked_triangles = []
poly = []
poly_bound = []
for i in range(0, length):
    tri = not_constrained_triangles[i]
    bound = tri.boundary
    checked_triangles.append(tri)
    for ind, elem in enumerate(not_constrained_triangles):
        bound2 = elem.boundary
        if not (tri == elem):
```

```
            if not elem in checked_triangles:
                if bound.overlaps(bound2):
                    p = tri.union(elem)
                    poly.append(p)
                    bound_p = p.boundary
                    poly_bound.append(bound_p)
                    not_used_triangles.append(elem)

for elem in not_used_triangles:
    while elem in not_constrained_triangles:
        not_constrained_triangles.remove(elem)

# Calculate the centroids of the non constrained triangles,
final_decision_points = []
for triangle in not_constrained_triangles:
    centroid = triangle.centroid
    centr_coord = centroid.coords[:]
    final_decision_points.append(centr_coord[0])
# and add to them the central point of the polygons created by merging adjacent non-constrained triangles, to have all the final decision points of the system in one list
for elem in poly:
#    print elem
    centr = elem.centroid
    centr_coord = centr.coords[:]
    final_decision_points.append(centr_coord)

with fiona.open('C:/Users/antigoni/Desktop/ Data/Architecture_polygons.shp') as source:
    source_driver = source.driver
    source_crs = source.crs
    source_schema = {'geometry':'Point', 'properties': OrderedDict([(u'id', 'int'), (u'Type', 'str')])}
    print source_schema

with fiona.collection('C:/Users/antigoni/Desktop/Data/decision_points.shp', 'w', driver = source_driver, crs=source_crs, schema=source_schema) as c:
    output = fiona.open('C:/Users/antigoni/Desktop/Data/Architecture_polygons.shp')
    for elem in final_decision_points:
        record = {'geometry' : mapping(shape(Point(elem))),'properties': OrderedDict([(u'id', '1'), (u'Type', 'Room')])}
        c.write(record)

# Select the triangles that have at least one constrained edge and calculate the middle point of the edges that are not part of the boundary of the originating poygon (non-constrained edges)
other_triangles = []
for elem in edges_of_constrained_triangles:
    t = Polygon(elem)
```

```
    other_triangles.append(t)
#print other_triangles

lines_of_triangles = []
for i, elem in enumerate(edges_of_constrained_triangles):
    p = list(elem.coords)
    for i in range(0,3):
        if i < 2:
            line = LineString([p[i], p[(i+1)]])
        else:
            line = LineString([p[i], p[0]])
        lines_of_triangles.append(line)
#print lines_of_triangles
l = len(lines_of_triangles)
print l

non_constrained_edges = []
for elem in lines_of_triangles:
    for elem2 in boundary_line:
        if not elem.within(elem2):
            non_constrained_edges.append(elem)
#print non_constrained_edges

middlePoints = []
for elem in non_constrained_edges:
    midpoint = elem.centroid
    midpoint_coord = midpoint.coords[:]
    middlePoints.append(midpoint_coord)
#print middlePoints

# Calculate the centroids of transition spaces (doors, stairs, elevators)
d_centroid= []
for d in doors:
    door_centroid = d.centroid
    door_centr_coord = door_centroid.coords[:]
    d_centroid.append(door_centr_coord)
#print d_centroid

# create room polygons (destination spaces) and find their centroids
rooms = []
r_centroids = []
for feat in data:
    properties = feat['properties']
    geometry = feat['geometry']
```

```
    coord = geometry['coordinates']
    if (properties['Type'] == 'Room'):
        rooms.append(Polygon(coord[0]))

for r in rooms:
    room_centroid = r.centroid
    room_centr_coord = room_centroid.coords[:]
    r_centroids.append(room_centr_coord)
#print r_centroids
```

Network Generation

```
network_edges = [], lines = []
lengthNetwork = len(r_centroids)
for i, elem in enumerate(r_centroids):
    shortestDistance = float("inf")
    winner = 0
    for otherI, otherElem in enumerate(d_centroid):
        distance = Point(elem).distance(Point(otherElem))
        if distance < shortestDistance:
            winner = otherI
            l = LineString([Point(elem), Point(otherElem)])
            shortestDistance = distance
    i = i + lengthNetwork
    network_edges.append([i, winner])
    lines.append(l)

lengthNetwork2 = len(final_decision_points)
for i, elem in enumerate(d_centroid):
    shortestDistance = float("inf")
    winner = 0
    for otherI, otherElem in enumerate(final_decision_points):
        distance = Point(elem).distance(Point(otherElem))
        if distance < shortestDistance:
            winner = otherI
            l = LineString([Point(elem), Point(otherElem)])
            shortestDistance = distance
    i = i + lengthNetwork2
    network_edges.append([i, winner])
    lines.append(l)
```

```
networkPolygons = [], networkPoints = []
for elem in not_constrained_triangles:
    networkPolygons.append(elem)
for elem in poly:
    networkPolygons.append(elem)
neighbors = []
for i, elem in enumerate(networkPolygons):
    dec_point = elem.centroid
    for otherI, otherElem in enumerate(constrained_triangles):
        if not i == otherI:
            mPolygon = MultiPolygon([elem, otherElem])
            if mPolygon.is_valid:
                neighbors.append([i, otherI])

ConnPoints = []
for elem in final_decision_points:
    ConnPoints.append(elem)
for elem in middlePoints:
    ConnPoints.append(elem)

for ind, each in enumerate(ConnPoints):
    lengthNetwork = len(networkPoints)
    vertices = each['vertices'].tolist()
    edges = neighbors[ind]
    for e in edges:
        e[0] = e[0] + lengthNetwork
        e[1] = e[1] + lengthNetwork
        network_edges.append(e)
    networkPoints.extend(vertices)

for i, elem in enumerate(networkPoints):
    shortestDistance = float("inf")
    winner = 0
    for ind, elem2 in enumerate(networkPoints):
        if not i==ind:
            distance = Point(elem).distance(Point(elem2))
            if (distance < shortestDistance):
                winner = ind
                shortestDistance = distance
                l = LineString([Point(elem), Point(elem2)])
    network_edges.append([i, winner])
    lines.append(l)
```

```
with fiona.open('C:/Users/antigoni/Desktop/Data/ Architecture_polygons.shp') as source:
    source_driver = source.driver
    source_crs = source.crs
    source_schema = {'geometry':'LineString', 'properties': OrderedDict([(u'id', 'int'), (u'Type', 'str')])}
    print source_schema

with fiona.collection('C:/Users/antigoni/Desktop/Data/network_connector2.shp', 'w', driver = source_driver, crs=source_crs, schema=source_schema) as c:
    output = fiona.open('C:/Users/antigoni/Desktop/ Data/ Architecture_polygons.shp')
    for elem in lines:
        record = {'geometry' : mapping(shape(LineString(elem))),'properties': OrderedDict([(u'id', '1'), (u'Type', 'Corridor')])}
        c.write(record)
```

Appendix C. Questionnaire

Questionnaire for inferring participants opinion about the usability and performance of the system - used during validation experiments:

Please indicate your personal perception on certain characteristics of the system, by selecting a level of agreement with the following statements, using the given scale:

1 - "strongly disagree"; 2 - "disagree"; 3 - "not agree, neither disagree"; 4 - "agree"; 5 - "strongly agree"

1. The system is simple to use.

1 2 3 4 5

2. The information provided by the system is easy to be read and understood.

1 2 3 4 5

3. It is easier to follow signs with numbers instead of textual signs.

1 2 3 4 5

4. It is efficient in terms of time required to find my destination.

1 2 3 4 5

5. It is efficient in terms of feeling confident that I am on the right track.

1 2 3 4 5

6. Overall, I liked the system.

1 2 3 4 5