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User-Oriented Campus Routing

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Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

"User-Oriented Campus Routing"

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Munich, 14.09.2018 Armand KAPAJ

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Abstract

University campuses constitute highly complex architectural buildings with many entrance points, connection routes, confusing numbering and naming systems, lack of adequate signage, etc. These campuses deal with a high fluctuation of first time user groups such as new students and visitors that end up getting lost due to the lack of appropriate interactive campus routing systems. For effective and efficient indoor navigation systems cartographic principles related to map design and visualization should be utilized. However, indoor cartography is still a "territory to be discovered".

This thesis illustrates how a cartographically appealing campus routing system that facilitates the navigation process of various user groups in complex university campuses can be designed and developed. The main criteria for an interactive 3D web application that combines the visualization of indoor spaces for an effective and user-friendly route planning and route communication are outlined. As a case study for this thesis, the main building of the Technical University of Munich main campus is used. An exemplary workflow from the raw data, to the campus basemap and finally to a fully interactive 3D routing published as a web application is described.

To investigate the cartographic design and visualization methods applied to the developed campus routing system, two user evaluations were designed and conducted. The first user evaluation focused on campus map design and the visualization of interior spaces. This evaluation used an expert-based method to gather feedback from experienced user in the field of map design and visualization techniques. The second user study was conducted to evaluate the usability and utility of the developed campus routing system, by measuring its effectiveness, efficiency and users' satisfaction. A user-based method was applied for this evaluation and first time visitors were chosen as the target group for this evaluation.

According to the results gathered from these two user studies, it can be concluded that a campus routing system makes use of structural indoor features to plan and convey the route in an effective and efficient way. Users stated that they were satisfied with the developed 3D web application and would like to use it for other university campuses.

Keywords: campus routing system, 3D web application, indoor navigation, indoor wayfinding, indoor cartography, map design, usability and utility, user study

Table of contents

List of figures

List of tables

Abbreviations

2D	2 Dimensional
3D	3 Dimensional
API	Application Programming Interface
CAD	Computer Aided Design
CRS	Campus Routing System
CSS	Cascading Style Sheets
EG	Erdgeschoss (German) – ground floor
ETA	Estimated Time of Arrival
FHWS	University of Applied Sciences Würzburg-Schweinfurt
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HTML	Hypertext Markup Language
IIS	Internet Information Services
IR	Infrared
ISO	International Organization for Standardization
OG	Obergeschoss (German) – upper floor
POI	Point of Interest
RFID	Radio Frequency Identification
TUB	Technical University of Berlin
TUD	Technical University of Dresden
TUM	Technical University of Munich
TUW	Vienna University of Technology
UI	User Interface
USID	Ultrasound Identification
WLAN	Wireless Local Area Network
WTL	Web Tile Layer

1 Introduction

In this chapter, the motivation and the problem statement are presented. In addition, the research goal and the related objectives, the hypotheses and research questions are stated.

1.1 Background

The proportion of time that humans spend in indoor spaces is significant. A series of studies carried out in different continents at different times indicates that the average person spends approximately 90% of their time in indoor environments (home, work, and other indoor spaces) (Jenkins et al. 1992, Brasche and Bischof 2005, Schweizer et al. 2006). Hence, Fallah et al. (2013), Cho and Choi (2015), and Dudas, Ghafourian and Karimi (2009) state that approximately 10 years ago an era of increasing research and development in the field of indoor navigation systems began. Moreover, Cho and Choi (2015) state that there are at least 170 companies today working on indoor location, indoor maps, building tracking and indoor navigation. Maps represent important presentation forms for routes and topographic features and, therefore, usually are considered as central parts of all kinds of navigation systems (Gartner and Hiller 2009). Moreover, maps for wayfinding and navigation are of a particular social relevance since they can be used to shape human behaviour, such as to influence where, when, and in what order the individual person will visit places (Kueh 2007).

Outdoor navigation systems have a long tradition due to the high amount of research conducted in this field. Therefore, the map design, data visualization, positioning techniques for the classical use case outside of a building has known great achievements. For the ease of use, in this thesis the term "*outdoor cartography*" is used to refer to the wayfinding and navigation process in an outdoor space.

In contrast to outdoor cartography, indoor cartography is still a "*territory to be discovered*". Existing indoor navigation systems make use of building floor plans and overlap them with route representation, which do not fulfil cartographic requirements for data visualization (Lorenz et al. 2013).

According to (Kueh 2007) the lack of studying indoor map design and the understanding of the people-map-space interaction as a whole negatively affects the effectiveness of indoor wayfinding. Even though maps play an important role in representing the environment to facilitate navigation (outdoor and indoor navigation), the effectiveness of current indoor map design is being challenged by the following facts:

- The body of knowledge that relates to users' responses towards the map design of actual indoor environments is underdeveloped and this contrasts with the

increasing opportunities provided by new technology in designing and presenting wayfinding maps.
- There is lacking research directed at indoor map design.
- Research and findings from cognitive science and cartography are not being adequately applied in current indoor map design.
- There is a lack of unified theory that could underpin the design of more effective maps

Despite the latest development in the field of indoor navigation, only a few design guidelines exist for indoor navigation maps, which emphasize the design features that should be taken into consideration. Based on a user study carried out by Lorenz et al. (2013) map perspective and landmarks constitute 30% of users satisfaction with indoor maps. This percentage represents the biggest share in the success of the navigation model used for the Lorenz et al. (2013) study.

Based on the results of the user study conducted by Lorenz et al. (2013), 3D maps have a considerable advantage for an indoor navigation system where a realistic perspective, smooth transition between floor levels, representation of vertical and horizontal structures, and recognition of surrounding objects like doors and passages, is of crucial importance. Whereas the benefits coming from landmark presence are significantly related to the map perspective, route complexity, and the number of elements on a map, but not with the number of landmarks or their type.

Even though the existence of several studies about the map design for indoor navigation systems (Puikkonen et al. 2009, Worboys 2011, Zlatanova et al. 2013), the results are mostly products of various user studies. While they represent valuable information and insights about indoor map design, they are not enough to be considered as stand-alone guidelines of design recommendations for indoor navigation maps.

It remains a challenge for cartographers to design indoor navigation systems, which will facilitate users' navigation in indoor premises. These indoor navigation systems should resolve the present challenges by making use of cartographic design principles, indoor localization and orientation techniques, route planning and representation, users' needs and the knowledge, gained from cognitive sciences regarding users' behaviour in indoor environments.

1.2 Motivation and problem statement

Human's navigation process takes place between outdoor and indoor environments. Therefore, indoor maps emerged in 2009 as startups such as Point Inside[1], Micello (now part of HERE Technologies)[2] and Nokia[3], which released their indoor mapping data to be used for indoor navigation applications (Cho and Choi 2015). However, navigation within building premises and especially in the case of complex and unfamiliar ones is not an easy task to complete. Therefore, users often end up getting lost. According to

(Carlson et al. 2010) this happens due to three main factors: (1) the spatial structure of the building, (2) the cognitive maps that users construct as they navigate, and (3) the strategies and spatial abilities of the building users.

Finding the way around and inside university campuses is being more and more of a challenge due to the spatial structures. University campuses consist of several buildings, with various connection routes, entrance points, floor levels, dimensions, confusing numbering and naming system, limited line of sight, lack of local cues, missing signage etc. These are the main factors, which contribute to increasing the level of confusion for the indoor navigation process of various user groups on and between campuses. University campuses deal with a high fluctuation of various user groups such as students (existing and new students), staff members, and visitors. The process of indoor navigation in university buildings is particularly difficult for first time students and visitors. The struggle comes due to their lack of familiarity with architectural structure of the building, large campuses and many entrance points and connection routes, confusing numbering and naming system, lack of adequate signage, etc. and finally missing well-designed and user-friendly campus maps.

Technische Universität München (TUM) represents one of these examples where the indoor navigation process is not an easy task to handle. This happens due to several reasons: presence of several buildings, many entrance points, numbering and naming system for each individual building, lack of signage, continuous construction sites, several connection routes in several floor levels, connections between the buildings, mezzanine floor levels, restricted access to several points, etc. This affects various user groups starting with students, staff members and especially visitors that are not familiar with the TUM premises. For these reasons, the TUM is offering several reasons to facilitate the process of indoor navigation: (1) floorplans at the entrance of each building, and (2) a web application service "Roomfinder". However, both these options does not solve the indoor navigation problem for several reasons, such as missing room information, lack of interactivity, lack of route planning and communication. Lorenz et al. (2013) state that existing indoor navigation systems make use of building blueprints to represent interior spaces, but they do not fulfill cartographic requirements for map design and visualization techniques. Additionally, Winter et al. (2017) state that floorplan maps are notorious for their difficult reading, required advanced mental rotation and orientation skills. These factors impair efficient route finding also within the TUM campus to many users. Therefore, developing something better that will facilitate the indoor navigation process within the TUM main campus is a necessity.

1.3 Research goals and objectives

Based on the motivation and problem statement, this thesis concentrates on conceptualizing a theoretical and practical framework that is beneficial to the indoor navigation process. The TUM main campus serves as a sample case study and the Campus Routing System (CRS) will be beneficial to three different user groups: (1)

students, especially new students, (2) staff members, and (3) visitors. Hence, the main goal of this thesis is to *design and develop a web campus routing application that facilitates orientation and navigation of various user groups (students, staff members, and visitors) on the TUM main campus.*

In order to meet the goal of this thesis, the main objective is *to determine the main factors that affect the effectiveness and efficiency of a CRS in facilitating the indoor navigation of various user groups on TUM campus, and its usability.* Based on the literature review, indoor map design principles should be developed, which will serve as a theoretical framework for building a CRS as a web map application.

- Make use of building blueprints Computer Aided Design (CAD) files. These raw data should meet certain requirements, have specific indoor elements, and if not, data pre-processing steps should be carried out.
- Find a proper way to visualize indoor spaces and indoor elements, in order that the visualization can be interactive and comprehensible to the user groups.
- Take into consideration the users' needs and experts' opinions to choose a suitable visualization technique for the indoor navigation system.

For testing the design of the web map application, usability and utility of the applied methods, and users' preferences, the following objectives should be met:

- Find methods to test the web map application design of indoor navigation system.
- Find methods to test the usability and utility of indoor navigation system.
- Obtain users' preferences when operating the application, and based on their performance, evaluate the effectiveness, efficiency, and users' satisfaction with the application and if the goals of applied techniques are achieved.

Concerning the results of the usability tests, the following objectives should be taken into account:

- Take both theoretical background and experts' opinion test result into consideration to adapt the design principles for visualizing the interior space data.
- Propose and implement additional functionalities for a more interactive web application of an indoor navigation system.
- Discover additional functionalities and services that can be added to the application as part of future improvements.

1.4 Research questions and hypothesis

The main challenges that the field of indoor navigation is facing are complex, and mostly related to indoor positioning techniques, map design, route planning and communication. Additionally, the various user groups with different requirements and user needs play an important role. Hence, this thesis is based on several hypotheses:

- Users can navigate in indoor campus environments with only a few or no landmarks, as long as the map design is intuitive and the route planning as well as the route representation avoid confusions among the users.
- It is possible for the users to reach their destination in indoor campus navigation systems without the aid of indoor positioning and orientation techniques.

Based on these hypotheses, the research questions addressed to meet the thesis main objective are:

- *What map design principles and visualization techniques are appropriate for a campus routing system?*
- *What map elements, navigation network elements, and user interactions are needed for an effective and efficient campus routing system?*

1.5 Scope and limitations

The scope of this master thesis is to design and develop a campus routing system that will facilitate the navigation of various user groups in indoor environments. This thesis focuses on the main building of the TUM man campus that is used as a case study.

The limitation of this thesis is that it focuses only on the main building of the TUM main campus in Munich, even though the initial plan was to take into consideration two campuses. This change of plan was due to the high amount of data pre-processing steps and the time limitation. However, a detailed description of the necessary steps how to connect several buildings of a university campus and campuses far located from each other, will be provided as part of the theoretical framework. A detailed workflow for developing the CRS of the TUM main building will be presented. Additionally, this workflow can be adapted and applied to other buildings and to other university campuses.

Another limitation is that one of the user studies conducted for this thesis is focusing only in one user group, first time visitors. The first time visitors are chosen to test the developed CRS due to their lack of familiarity with the TUM building. Their prior knowledge of the building spatial structure, naming and numbering system, presence of landmarks, etc. will not interfere during the interaction with the TUM CRS. Additionally, they are chosen, as they are the most "*complicated*" user group. Therefore, if a visitor is able to use the TUM CRS, everyday users of the TUM premises (students and staff members) can also use it.

1.6 Overview of contents

In the *first chapter*, the motivation and the problem statement are presented. In addition, the research goal and the related objectives, the hypotheses and research questions are stated.

In the *second chapter*, state of the art, an introduction to the main developments in the field of indoor navigation so far is provided and also the main challenges that it is facing are described. The chapter is divided in four main parts: (1) indoor navigation systems, (2) indoor data visualization, (3) evaluation of interactive web applications, and (4) campus routing systems. In the first subchapter, the components that are needed to create an operational CRS are explained. The second subchapter deals with map design principles and visualization techniques applied to indoor spaces, as well as the presence of landmarks and user interface design. The third subchapters explains the medium to evaluate the usability and utility of interactive web applications. In addition, the methods for an effective evaluation are presented. The last part of this chapter describes and evaluates some of the existing CRSs regarding their interactivity and functionalities.

The *third chapter* is explaining the adopted methodologies to create a routing system for university campuses, while the *fourth chapter* is focusing on the data pre-processing, data processing and data visualization for the case study area. Based on the literature review and possible users' needs identified by different scenarios, the appropriate design principles and visualization techniques applied to the study area are described. In addition, a description of the user studies conducted, the methods applied, participants and materials is provided.

Chapter five is based on the results of usability and utility tests. Based on user studies carried out, the chapter consists of three main parts: (1) map design evaluation, (2) evaluation of effectiveness and efficiency, and (3) a summary and conclusion of results. In the *sixth chapter*, a critical discussion of the work performed for this thesis is provided. The research findings and future work recommendations are presented in *chapter seven*.

2 State of the art and theoretical background

This chapter covers research background and developments of four major aspects of this thesis. The first part contains information about the current state of the art in campus mapping regarding the indoor navigation systems and their related elements. The second focusses on data visualization and design principles used for indoor spaces as well as developed applications for indoor navigation and their interfaces. In the third part, the evaluation methods applicable for indoor navigation systems and campus routing based on users' needs and requirements are described. Finally, some existing CRS are described based on their interactivity and functionalities.

2.1 Indoor navigation systems

In order to develop methodologies to build up a successful indoor navigation system, this thesis focuses on the key elements that constitute a navigation system. According to Montello (2005) navigation is considered as a coordinated and goal-directed movement through the environment by organisms or intelligent machines. He proposed that the navigation is composed of two main components: *locomotion* and *wayfinding*.

Locomotion is the movement process around an environment based on local or proximal surroundings – the environment that is directly accessible to our sight at a given moment. Opposite to locomotion, *wayfinding* is a goal-directed and planned movement around an environment in an efficient way. This process requires a destination as a goal we want to reach, which in most cases is not in the local surroundings. Therefore, the memory stored internally in our cognitive system and externally in visual representations, such as maps, plays a crucial role in the wayfinding process. (Montello 2005)

An indoor navigation system can be considered as effective and efficient if it facilitates the process of wayfinding in indoor spaces. Due to their long tradition, outdoor navigation systems are used as a reference to dictate the components that an indoor navigation system should have. According to Huang and Gartner (2009), these elements consist of *indoor positioning*, *route planning*, and *route communication*. There has been a lot of research and technological achievements concerning these elements and they will be further discussed in the following three sections.

2.1.1 Indoor positioning

Indoor positioning is defined as any system, which attempts to provide an accurate positioning of people or objects in large buildings and in closed areas (Retscher 2016). Fallah et al. (2013) state that all navigation systems must include a basic form of localization, in order to determine the users' position and/or orientation. While outdoor navigation systems achieve localization in high accuracy and low cost with the help of

Global Navigation Satellite Systems (GNSS), indoor navigation systems have to rely on other methods, as per fact that GNSS signals cannot be perceived indoors.

The lack of GNSS signal in indoor spaces is resulting in an emerging number of techniques that can be used to substitute it. Fallah et al. (2013) summarize the localization techniques that are used for indoor positioning into four categories: (1) *dead-reckoning*, (2) *direct-sensing*, (3) *pattern recognition*, and (4) *triangulation*. A summary of the working principle of these four categories including their advantages and drawbacks as described by Fallah et al. (2013) are further explained in the following paragraphs

Dead reckoning is a technique, which estimates users location, based on a previously known or estimated position. The initial position of the user is determined with the help of GPS signals, Radio frequency identification (RFID) tags, or cellular phone positioning. To estimate the user's location as they move along the route, various sensors such as accelerometers, magnetometers, compasses, and gyroscopes are used. The main benefit of this technique is a lower installation cost due to the fact that a small number of identifiers have to be installed. The drawbacks of this technique consist of low accuracy and the need to be combined with other localization techniques.

Direct sensing technique determines the position of users' by sensing identifiers or tags (*RFID*, *infrared (IR)*, *ultrasound identification (USID)*, *Bluetooth beacons*, and *barcodes*), which are installed in the indoor space. The location information can be stored directly on the tag or it can also be retrieved from a database by using the tags' unique identifier. On one hand, using multiple localization techniques in the form of tags can improve the accuracy; on the other hand, it increases the drawbacks of the technique. These drawbacks include, but are not limited to installation costs, signal strength, finding the tags, additional equipment required, etc.

Pattern recognition technique determines user's location by using data collected by various sensors (*computer vision* or *image matching*, and *signal distribution* or *fingerprinting*) that the user has to wear. These systems compare the acquired data with a database of prior acquired data that have been coupled with an indoor map. The drawbacks of this technique are the high storage capacity required, computational efforts, and the users are required to carry additional equipment.

Triangulation technique uses the location of at least three known points to determine the users' position. This method utilizes the geometric properties of a triangle to compute an object's position based on the position of two or three vertices of a triangle. This technique makes use of cell towers and/or wireless local area network (WLAN) base stations. The main drawback is the accuracy of the position.

Despite the latest developments and technological achievements, localization and orientation remain one of the biggest challenges that indoor navigation systems are facing. In addition, the existence of various indoor localization techniques with their benefits and drawbacks poses further obstacles to their implementation. Furthermore, currently none of these techniques have achieved large-scale deployment due to issues with cost, accuracy, and usability.

2.1.2 Route planning

In addition to localizing users in indoor environments, an indoor navigation system should provide movement information to the users via the route planning process. Route planning process should maximize the efficiency of the route and minimize users' confusion while navigating. This is a key step to facilitate users' navigation from a start point to the intended destination in complex indoor spaces.

The route planning process can be computed based on a variety of criteria, which vary from user to user, based on their needs, requirements, environment, etc. The criterion in route planning process changes drastically between outdoor and indoor navigation systems. Routes for outdoor navigation can be computed by taking into consideration criteria such as travel time, distance, traffic, scenery, etc. Within an experiment conducted by Golledge (1995), users were asked to perform a route selection from maps and to rank the importance of each criterion. The results of this experiment are shown in the below table 2-1.

Criteria	Rank	Criteria	Rank
Shortest Distance	1	Longest Leg First	6
Least Time	2	Many Curves	7
Fewest Turns	3	Many Turns	8
Most Scenic/Aesthetic	4	Different from Previous	9
First Noticed	5	Shortest Leg First	10

Table 2-1. Ranking of criteria most often used in outdoor route selection (Golledge 1995)

In outdoor navigation systems, people might choose also criteria that are related with environmental street characteristics such as the presence of shops, crossings, crowds, shelter, air pollution, traffic noise, safety and street attractiveness (Borst et al. 2009). When it comes to indoor navigation systems, the main criteria for the route planning process are the shortest distance or the fastest travel time (Dudas et al. 2009).

Similar to outdoor navigation systems, the route planning process in indoor navigation systems should be built by taking users' needs and requirements into consideration. Route planning algorithms use graph-based methods to represent the indoor premises. In order to plan the route using graph-based methods, the indoor spaces are divided into sets of nodes and edges connecting these nodes. Nodes represent the indoor spaces, while the edges connect these indoor spaces together.

Liu and Zlatanova (2013) provide a classification of indoor route planning based on typical graph-based methods:

- *Shortest (shortest-distance)*, which minimizes the required distance between the start point and destination.
- *Least-effort*, which minimizes the total required time to reach the destination.
- *Central point strategy*, which finds a route by trying to transit well-known locations (e.g. landmarks) of buildings.
- *Direction strategy* heads to the horizontal position of a destination as directly as possible and regardless of the level changes.
- *Floor strategy* firstly finds a route to the floor of a destination, and then horizontally finds the destination on the floor.

Liu and Zlatanova (2013) propose two additional methods that should be considered while planning a route with the use of an indoor navigation system. These methods are (1) *least spaces visited* and (2) *least obstructions*. The *least-space-visited* finds a path by visiting the least number of indoor spaces between a start point and a destination. *Least-obstruction* finds a path guaranteeing the least degree of obstruction between a start point and a destination. Table 2-2 below summarizes all merits and drawbacks of the described indoor route planning approaches.

Path type	Merit	Drawback
Shortest-distance	It is a route providing the minimum distance between a start point and a destination	Full building metrics is required to get an accurate shortest path. Sometimes, the shortest path isn't the one that is passable or easy to be followed
Least-effort	It is a route considering the minimum travel time as the 'optimal' criterion	It needs users' type and speed as parameters for computation. Yet usually these parameters are just rough estimations
Central point strategy	It's an easy and practical way for users to find a route by themselves	It may cause considerable detours
Direction strategy	Finding a route by sticking to the direction between the start and the destination	It may result in a winding path which can get unfamiliar users lost
Floor strategy	It is an easy-followed pattern to arrive the floor of destination	It may not be the minimum distance route
Least space visited	It is a route presenting the least number of visited rooms between assigned start and destination	To follow it may result in more traveling time and distance
Least obstruction	It is a route considering the least degree of blockage between a start and a destination. It has no request for building metrics	Gaining an accurate path of such type needs accurate dynamic information. The information is difficult to be exactly collected in practice

Table 2-2. Comparison of different route types (Liu and Zlatanova 2013)

According to Fallah et al. (2013) and Zlatanova et al. (2013), shortest route or shortest travel time is desirable for the majority of users and most of the current navigation system use these algorithms to compute indoor routes. Using the shortest route or shortest travel time might result in higher uncertainty in localizing the user. However, it represents a walkable pattern more close to the one that users will tend to follow in order to reach the destination and if combined with structural features such as doors, stairs, etc. will decrease users' uncertainty.

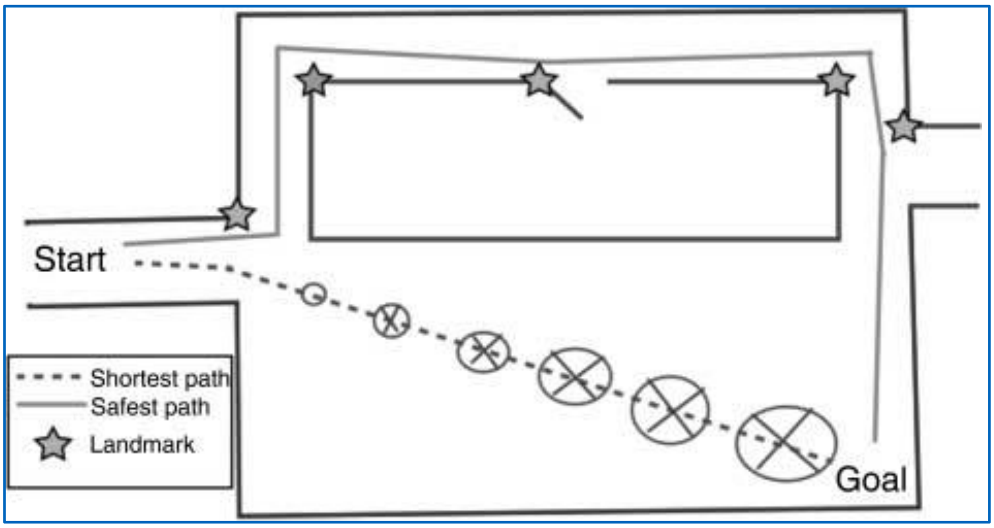


Figure 2-1. A short route may result in higher uncertainty (Fallah et al. 2013)

2.1.3 Route communication

According to Fellner, Huang and Gartner (2017), various techniques can be used to communicate navigational information in indoor navigation systems. These techniques consist of visual instructions (maps), verbal instructions (voice-based) augmented reality, and haptic to communicate the planned route in indoor navigation systems. Gartner and Hiller (2009) state that visual instructions represented by maps are important representations to convey route and topographic features. They are therefore usually central parts of all navigation systems.

The design of wayfinding maps has an emergent dimension going beyond simply providing information to map users. They can be used to shape social behaviour, such as to influence where, when and in what order individuals will visit places (Kueh 2007). Moreover, the adequacy of route communication highly influences the usefulness of the indoor navigation application and the comfort of its use. However, the cartographical methodology is still very limited in the process of designing indoor navigation systems and detailed research is required (Gotlib and Marciniak 2012).

As per the fact that route communication is the last step in the indoor navigation process it should be designed to convey the information effectively and efficiently to the users. Indoor spaces can be visualized in two (2D) or three-dimensional (3D) maps to communicate the information to intended users. Based on a user study carried out by Lorenz et al. (2013), the map perspective and landmark representation make up to 30% of user satisfaction with map design for indoor spaces. This percentage represents the biggest share of users' satisfaction.

Based on this study of Lorenz et al. (2013), 3D maps have a considerable advantage compared to 2D maps when it comes to indoor navigation, where a realistic perspective, a smooth transition between building parts, the representation of horizontal and vertical structures, and the recognition of surrounding objects (doors, passages) is of utmost importance.

In this subchapter the components that are applied in indoor navigation systems, inherited from the long history in the field of outdoor navigation systems were described. The importance of this subchapter stands in the fact whether any indoor positioning techniques can be identified as ubiquitous, and if indoor navigation system can function without providing indoor positioning and orientation. The criteria of route planning for indoor navigation systems are identified and explained as well as the route communication process for an effective indoor navigation. Therefore, the following subchapter describes the medium for indoor data visualization for a more efficient route planning and communication.

2.2 Indoor data visualization

To develop methodologies for visualizing indoor spaces, this thesis needs to focus on the characteristics of the data in hand, as well as the existing principles to visualize these data. A lot of research has been conducted about visualizing indoor spaces, and how to apply cartographical design principles and methodologies. All this research findings will be discussed in the first part of this chapter. In order to link the visualization of indoor spaces with the reality, users' will need a certain level of context information. This information is presented with the help of landmark representation in indoor navigation systems. Hence, the second part of this chapter focusses on the existing research about the presence of landmarks in indoor navigation systems. As the final version of the TUM CRS developed within this thesis will be a web map application, hence, the interface design of web maps will be discussed in the third part. Moreover, in order to maximize the usability and users' experience with the campus routing application, user interface principles will be explained.

2.2.1 Visualization of indoor spaces

From the first multi-level building of the Roman Empire to the world's highest building with 163 floors, most public indoor spaces have been built based on increasingly complex indoor environments incorporating many underground levels and above ground floors. Therefore, the growing size of indoor spaces makes these structures seem like an 'indoor city', meaning that they are large and cognitively complex environments with many possible destinations and heavy pedestrian traffic. Multi-level buildings have the advantage of the more efficient use of land space, especially where space is limited or expensive. However, these complex multi-level buildings often cause navigators to become frustrated, disoriented, or lost during navigation, especially when traversing between floors levels. (Li and Giudice 2012)

Buildings are getting bigger and more complex, including university campuses. Therefore, finding the way around university campuses is being more and more of a challenge due to the spatial structures. University campuses consist of several buildings, with various connection routes, entrance points, floor levels, dimensions, confusing numbering and naming system, limited line of sight, lack of local cues etc. As a result, there exist more than 170 companies today working on indoor location, indoor maps, building tracking and indoor navigation systems (Cho and Choi 2015).

Zlatanova et al. (2013) state that research in support of mapping and modelling indoor spaces has been active for more than thirty years. This research has been in the form of as-built surveys, data structuring, visualization techniques, indoor navigational systems, etc. Nowadays, individuals and commercial enterprises to facilitate their business processes are applying indoor models and indoor navigation systems on a large scale. The increasing presence of indoor navigation system is affected by three main reasons: (1) greater use of spatial data, (2) technological advancements, and (3) visualization of indoor spaces. The visualization process has seen geometrically and semantically advancements, by developing user-oriented and context-aware indoor navigation applications.

Hence, indoor navigation systems are becoming more and more useful in reality, especially to guide users to reach their planned destinations. An indoor navigation system requires an appropriate visualization of indoor spaces. Additionally, it should support the planning and communicating of indoor routes. Therefore, according to Boysen et al. (2014) constructing indoor navigation systems faces two major technical challenges: (1) indoor distance computation, as discussed in the above route planning and communication subchapters, and (2) indoor space model creation from raw building formats.

Gotlib and Marciniak (2012) state that depending on the indoor space models the following objects may be distinguished:

- Reference data, which presents the arrangement of rooms, installations and fixed equipment in a building (walls, doors, rooms, windows, stairs, etc.).
- Communication routes (typical trajectories of users' movement).
- Movable equipment (such as stands or booth in a commercial centre).
- Address data (identifiers of rooms, corridors).
- Points of Interest (such as locations of automated teller machines, exhibitions).

Indoor maps play an important role in indoor navigation systems. Gärling, Lindberg and Mäntylä (1983) presented evidence, gathered from a user study, regarding the familiarity of participants with the building. When a floor plan was shown to participants, before they were asked to complete the wayfinding task, resulted in reducing the effects of familiarity with the building and improved they wayfinding performance. Moreover, Wang et al. (2007) state that map design and information plays an important role in facilitating all the indoor navigation processes (figure 2-2).

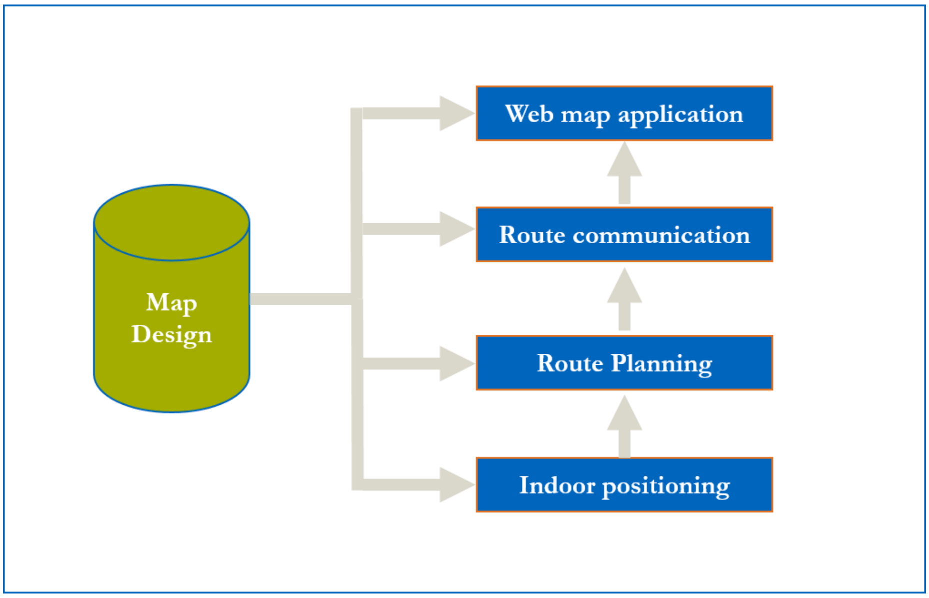


Figure 2-2. Importance of map design in Indoor Navigation System (Wang et al. 2007). Designed by A. Kapaj

Map design and information is integrated in all aspects of a CRS. In the indoor positioning layer, we are able to estimate not only the user's geometrical location but also semantic location by using the map, e.g., the located floor and room. In the route planning and route communication layer, map design is used to plan the route according to present indoor features (rooms, walls, doors, etc.) and to convey accurately this route to the users by specifying walkable and non-walkable areas. Finally, map design and information is used in the web application layer to support intelligent room detection, routing or other location/context aware services.

According to Lorenz et al. (2013) and Gotlib and Marciniak (2012), the visualization of indoor spaces should be based on utilizing building floor plans and applying cartographic design principles. In addition, as a result of the already mentioned user study, Lorenz et al. (2013) emphasize that "*good map design is essential for indoor wayfinding process*". Moreover, Zlatanova et al. (2013) states that the raw data have to be edited, fused, reformed and attributed and therefore being subject to cartographic methods. The editing process involves the selection of relevant architectural structure and removing unwanted data from the building floor plans. The selected data are fused to develop an amalgamated scene of indoor spaces.

Visual techniques make use of depicted indoor premises in a map to provide direction for an indoor navigation system. Visualizing these indoor spaces can be realized in 2D or 3D map perspective. Atila, Karas and Rahman (2014) state that most of the current navigation systems are represented in a 2D map perspective. However, several studies have shown that this does not constitute a satisfactory solution to visualize 3D objects (Atila et al. 2014, Lorenz et al. 2013).

Lorenz et al. (2013) state that in 3D maps the difference between the map perspective and the realistic perspective is much smaller. Therefore, according to Aretz and Wickens (1992) the mental rotation between the map and reality, which forms the central operation of cognitive alignment, is easier to be performed in a 3D map perspective. As mentioned on the background subchapter of this thesis (subchapter 1.1), Lorenz et al. (2013) summed up that 3D maps have considerable advantages. Lorenz reached this conclusion after a user study conducted at the Technical University of Berlin (TUB) main building. The campus map of the TUB main building was represented in a 3D map perspective, and was used as the basemap for indoor navigation process. The advantages of 3D campus maps are noted especially for an indoor navigation system where a realistic perspective, smooth transition between floor levels, representation of vertical and horizontal structures, and recognition of surrounding objects like doors and passages, is of crucial importance. As a result, this thesis is focused on applying cartographic methods and design principles to depict indoor spaces and visualize them in a 3D map perspective.

2.2.2 Landmarks in indoor navigation systems

Sorrows and Hirtle (1999) defines landmarks in physical space as objects that have key characteristics that make them recognizable and memorable in the environment. Sorrows and Hirtle state that landmarks serve as a navigation tool by identifying choice points where navigational decisions are made, identifying the origin and destination points. At the same time, landmarks provide verification of route progress and influence expectations, provide orientation cues for homing vectors and suggest regional differentiating features.

Navigation within building premises and especially in the case of complex and unfamiliar ones like campus buildings is not an easy task to complete. Consequently, users often end up getting lost. Therefore, Fellner et al. (2017) state that to improve navigation performance and provide good user experiences, landmarks should be included in route communication, mainly due to their essential roles in human orientation and wayfinding.

Landmarks can be classified into *global* and *local* landmarks. Lorenz et al. (2013) describes global landmarks as highly visible and remote objects used for orientation in a global context, while local landmarks are situated along the route and are used to verify local position. In indoor navigation systems, the role of global landmarks is futile due to the line of sight limitations. Therefore, these systems should focus on local landmarks to provide context information to users.

As stated by Giudice, Walton and Worboys (2010) the availability and type of navigational landmarks in indoor spaces lack in comparison to outdoor spaces. To eliminate this disadvantage and improve the efficiency of indoor navigation systems Li and Giudice (2012) propose two types of indoor landmarks. These landmark types are *transition landmarks* and *contiguous landmarks*. Users' access to these landmarks will facilitate their ability to visualize the vertical structures during the indoor navigation, which as a result will yield more accurate multi-level cognitive map development.

Transition landmarks are the highlighted information content composed of the transition points and direction of transition points as well as the lines connecting them, while the *contiguous landmarks* consist of vertically aligned landmarks and the lines that connect them. Contiguous landmarks contain *contiguous structural landmarks* and *contiguous object landmarks*. If two floors have the same kind of structural landmarks (i.e., both floors have a cross intersection that is vertically aligned), it is classified as a *contiguous structural landmark*. Similarly, if two floors have vertically aligned object landmarks (i.e., both of the floors have one unique blue wall at the same horizontal coordinates), it is classified as a *contiguous object landmark*. (Li and Giudice 2012)

This landmark classification method proposed for indoor spaces, is illustrated in figure 2-3. Based on this illustration, A1 and B1 are *object landmarks* on each floor; A2 and B2 are the *transition landmarks* (*stairway*); A3 and B3 are both *transition landmarks* (*elevator*) and *contiguous landmarks*, as the transition points are vertically aligned; and A4 and B4 are contiguous landmarks, as the horizontal transition line is vertically aligned.

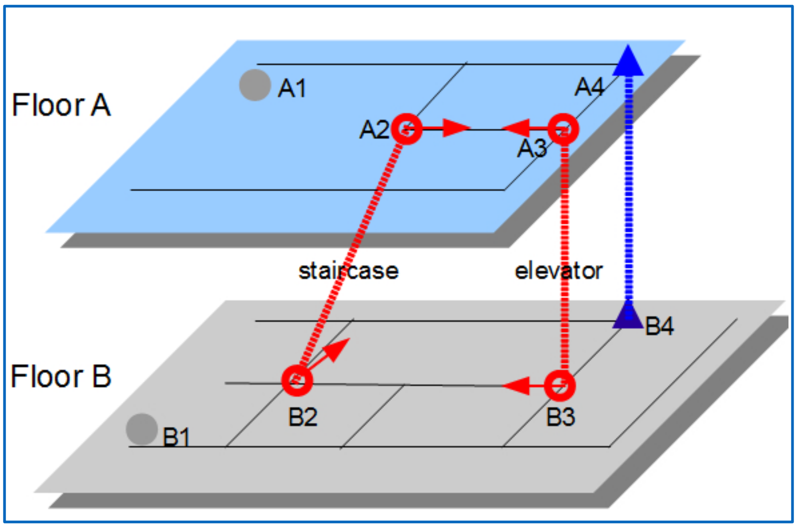


Figure 2-3. Multi-level indoor landmarks (Li and Giudice 2012)

The results of the user study carried out by Lorenz et al. (2013) revealed that benefits deriving from landmarks were significantly correlated with the map perspective and route complexity, but not with the number of landmarks and their types. Moreover, landmarks may not be regarded as helpful when added to an already complex or overwhelmed map design. Therefore, the right balance between an indoor spaces map and its relevant context information, represented by landmarks is very important.

2.2.3 User interface design

As mentioned in subchapter 1.3, the final product of the TUM CRS will be a web-based application, where the users will interact with the campus map and the stored information regarding indoor spaces. Therefore, Frank (1993) suggests that compared to Geographic Information Systems (GIS) mapping applications the *user interface* (UI) is the system. This means that the UI is often the only part of a system that users' have direct contact with and therefore its design is a crucial factor in the success of a web map application, including indoor navigation systems. Fairbairn et al. (2001) point out that graphical presentation of information has a long history, and some of the earliest extant graphical presentations are maps. Cartography has had and continues to have, an important role to play in the graphical presentation of geospatial information. Additionally, Kraak (2004) emphasizes that maps can function as an interface to the wealth of available geo-data. Therefore, Fairbairn et al. (2001) point out that representing geospatial data is intimately connected with interaction, visualization, and the human-computer interface.

Roth (2017) points out that advances in personal computing and information technologies have fundamentally transformed how maps are produced and consumed, as many maps today are highly interactive and delivered online or through mobile devices. Accordingly, Roth (2017) proposes that interaction needs to be considered as a fundamental complement to representation in cartography and visualization. Therefore, UI describes a set of concepts, guidelines, and workflows for critically thinking about the design and use of an interactive product, map-based or otherwise.

Due to the important role of design Howard and MacEachren (1996) suggested three principles for the interface design of visualizing georeferenced data. These principles of UI design are summarized in a hierarchical approach, consisting of (1) *conceptual*, (2) *operational* and (3) *implementation* levels.

Conceptual level is defined as a set of question that should be addressed: what needs are met by the system, how is this goal reached, what should be the result of working with the system, and for what target group is the system designed? These questions are addressed by the *operational* level, by performing a particular operation or function on the available information. The *implementation* level includes anything that the user will have to see and decipher in order to interact with the system.

Even though the representations of cartographic products are based on rigorous steps to fulfil UI design principles, not all the interactive maps can be used efficiently. Fairbairn et al. (2001) and Roth, Ross and MacEachren (2015) note that at a human interface level, the capacity to respond to different types of changes in differing representations may be limited. This might be the result various reasons: conceptual problems involved in accessing the depth of the human understanding the system, understanding complex data processing operations, difficult to learn and use, the presence of non-necessary functionalities and commands, etc. In order to address these problems, Roth et al. (2015) suggest the topic of *interface success* (i.e., does the interactive map work?) form the perspective of cartography, GIScience, and visual analytics. It involves a deep study of the target users and supported use case scenarios during design, with multiple evaluation-and-revision stages planned into the development process to address these users and use cases fully.

Roth (2017) describes three dimensions of UI design. These dimensions are (1) the fundamental *interaction operators* that form the basic building blocks of an interface, (2) *interface styles* (widget, menu or form that triggers an event) that implement these operator primitives, and (3) recommendations for the *visual design* of an interface. Furthermore, Roth points out that UI design primarily focuses upon *interaction operator primitives* (panning, zooming, search, overlay, etc.), or the generic functions implemented in the interactive application that enable the user to manipulate the display. According to Roth (2017), the visual look and feel of the UI design are "*more than just icing on the cake*": it sets the tone for the entire user experience, from setting the mood and evoking an appropriate emotional response through improving usability and subjective satisfaction. UI design is a highly creative process, and creation of a coherent and unique visual brand relies on iterative refinement of *global design decisions* (e.g., interface layout and responsiveness, application navigation, visual affordances and feedback, colour scheme, typefaces) and *local design decisions* (e.g., visual metaphors for direct manipulation interface widgets, specific text phrasing for icons, tooltips, and information windows).

To achieve an effective human-computer interaction for CRS several rules need to be applied regarding the interface design. Shneiderman (2010) proposes eight golden rules to interface design that are acceptable in most interactive systems, including even the ones visualizing geospatial data in the form of interactive campus maps. These golden rules are:

1. *Strive for consistency*: consistent sequences of actions should be required in similar situations.
2. *Cater to universal usability*: recognize the needs of diverse users and design for plasticity, facilitating the transformation of content.
3. *Offer informative feedback*: for every user action, there should be system feedback, where the intensity of response should be dependable by the frequency of the action.

4. *Design dialogs to yield closure*: sequences of actions should be organized into groups with a beginning, middle, and end.
5. *Prevent errors*: as much as possible, design the system that users cannot make serious errors.
6. *Permit easy reversal of actions*: as much as possible, actions should reversible.
7. *Support internal locus of control*: experienced operators strongly desire the sense that they are in charge of the interface and that the interface responds to their actions.
8. *Reduce short-term memory load*: the limitation of human information processing in short-term memory requires that displays should be kept simple.

In this subchapter the medium of visualizing indoor spaces were described as well as what is considered a landmark in indoor premises and what their connection with the map design is. In addition, the importance of the interface design for the web map applications was explained. The importance of this subchapter stands in the fact whether the map design principles and the minimal presence of landmarks in indoor navigation systems can create effective and efficient CRSs. Therefore, the following subchapter describes the process of evaluating interactive web map application, which will be the medium of visualizing an interactive CRS.

2.3 Evaluation of interactive web map applications

Due to all kinds of societal and technological developments, and the developments in other fields such as industrial design has affected the evaluation of map products. In order to see if these products are effective, efficient and appreciated, cartographers also develop and applied methods and techniques to evaluate the usability of their products. The aspects that are mainly evaluated are the map effectiveness (does it answer the questions asked?), efficiency (does the task takes a reasonable amount of time?), and satisfaction (is the map pleasant to interact with?). Considering an interactive mapping environment, this is not an easy task. For one thing, what do you test the interface or the map, or both?[4]

Roth et al. (2015) state that interactive maps are becoming essential in our everyday life, and professionals in a variety of fields are embracing interactive maps as the front-end of their information systems. However, not all interactive maps "work" as they could or should; as the general public relies more on interactive maps, they are becoming increasingly aware of the shortcomings and failures of these interactive maps. Therefore, to measure the *interface success* or to answer the question if an interactive map works, Roth et al. (2015) proposed two categories of evaluation: *usability* and *utility*.

According to Grinstein et al. (2003) *usability* describes the ease of using an interface to complete the user's desired set of objectives, while *utility* describes the usefulness of an interface for completing the user's desired set of objectives. Therefore, *usability* and *utility* are both attainable goals that complement each other in developing successful user interface design. Moreover, Grinstein et al. (2003) explain the order of these concepts, which one comes first from the perspective of which user group. If utility comes first for an expert tool (i.e., for discovery tasks requires days of data examination and manipulation), usability has to come first in public access information systems that require "immediate usability" (i.e., interactive displays of geospatial data), otherwise, users will feel frustrated. Grinstein et al. (2003) defines utility as the usefulness of an interface for completing the user's desired set of objectives.

In order to evaluate the map usability and utility, and measure its effectiveness, efficiency and users' satisfaction, quantitative and qualitative methods are being used on a large scale. However, Roth et al. (2017) emphasizes that geographers, cognitive scientists, and usability engineers alike recognize that quantitative methods will not explain everything we need to know about how maps work. Therefore, the *mixed methods* of the quantitative and qualitative technique are being used more often. Roth et al. (2015) propose three broad categories of evaluation methods, discriminated by evaluators:

- *Expert-based methods* solicit input and feedback about an interactive map from consultants with training and experience in interface design and evaluation. It is important that an expert is a person from outside the project team, as it is necessary that he or she has little or no prior knowledge about the interface under evaluation.
- *Theory-based methods* require the designers and developers to evaluate the interface themselves, using theoretical frameworks established through scientific research.
- *User-based methods* solicit input and feedback about an interface from a representative set of target users.

Usability

Usability evaluation was introduced in the late 1980s, and since then many research and development is done in this field (Viitanen 2007). Consequently, this has led to different definitions and approaches by various authors. For example, Grinstein et al. (2003) define usability as the ease of using an interface to complete users' desired set of objectives.

The International Organization for Standardization (ISO)[5] defines usability as *the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use*. Additionally, ISO defines what effectiveness, efficiency and satisfaction mean.

- *Effectiveness*: accuracy and completeness with which users achieve specified goals.
- *Efficiency*: resources expanded in relation to the accuracy and completeness with which users achieve goals.

- *Satisfaction*: freedom from discomfort, and positive attitude towards the use of products.

In order to measure usability, it is necessary to identify the goals and to decompose effectiveness, efficiency, and satisfaction and the components of the context of use with measurable and verifiable attributes. These components and the relations among them are illustrated in figure 2-4.

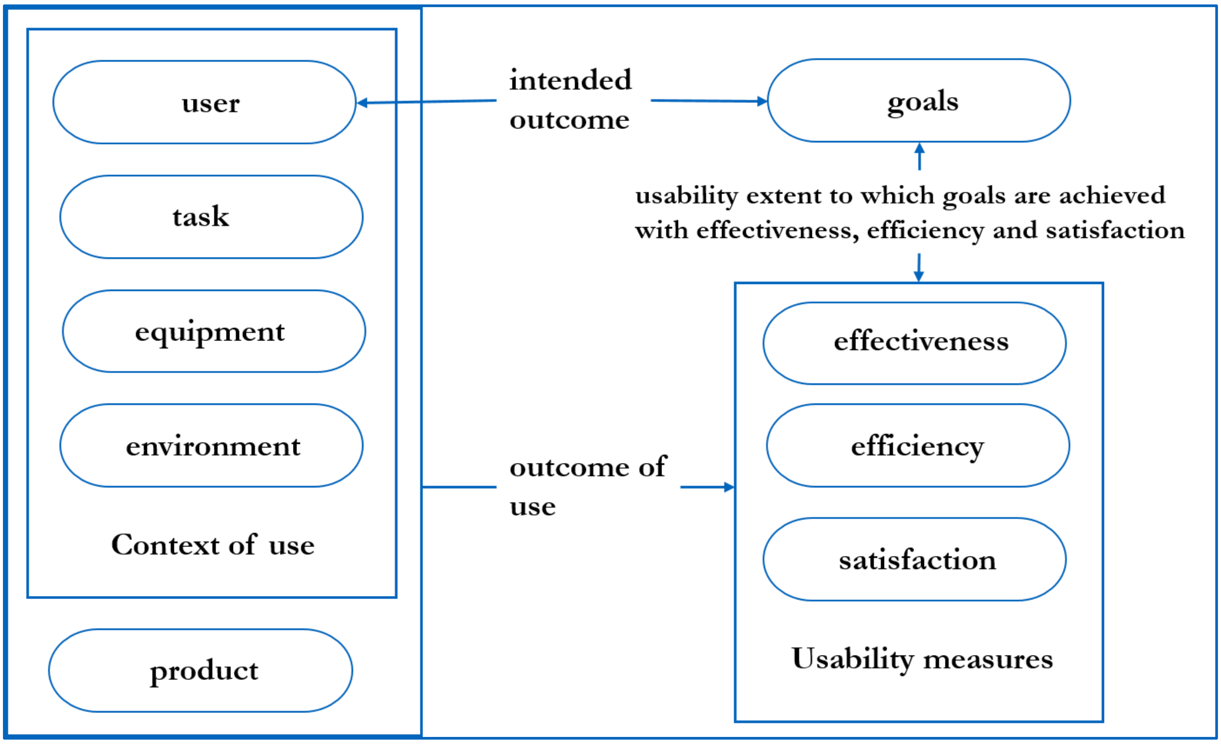


Figure 2-4. Usability components and framework (ISO 9241-11: 2018). Designed by A. Kapaj

Despite the large volume of studies in this field, all the researchers put the user as the central point of usability studies. Therefore, to measure users' interaction with a product or a service Nielsen (1992) lists five measurable parameters:

1. *Learnability*, how quickly users understand the interface without prior use.
2. *Efficiency*, how quickly users can interact with the interface once learned to complete the desired tasks.
3. *Memorability*, how well users can return to an interface and pick up where they left off.
4. *Error frequency and severity*, how often users make mistakes and how fatal they are, respectively.
5. *Subjective satisfaction*, how well the interface is liked by the users.

Regarding these parameters, Roth et al. (2015) point out that while the first four measures of usability primarily evaluate work productivity, the latter describes the user's engagement with the interface and general impression of it, an aspect of usability essential for promoting buy-in and improving uptake of an interactive map. Many researchers (Kraak 2004, Fairbairn et al. 2001, Howard and MacEachren 1996, Roth et al. 2015) have noted that same as the graphical user interface in software engineering, maps can also be considered as user interfaces. Therefore, this enables the possibility to apply the usability concepts and approaches in the field of cartography and GIScience. Peterson (1995) points out that maps can be considered as an interface for two reasons: first, they constitute interface of the location and data they represent, and second, they are composed of UI elements. These UI elements include the legend, visual variables, and colours, furthermore, Kraak and Brown (2001) state that interactive web maps are considered as UI based on the multimedia characteristics they have.

Utility

Roth et al. (2015) provide two strategies under which the process of evaluating utility falls. The first strategy assesses user performance according to a set of benchmark tasks, or representative combinations of user objectives and information content. The second strategy for evaluating utility instead assesses the quality of analytical products derived by the user when employing the interactive map. Such analytical products vary according to the user's overall goals and may include the hypotheses generated by the interface, knowledge constructed while using the interface, or decisions made with the support of the interface.

In this subchapter, the map usability and utility evaluations for interactive web map applications as well as the components that are evaluated were explained. In addition, the methods to measure the effectiveness, efficiency and users' satisfaction of an interactive web map application were described. Based on these evaluations focused on interactive web map applications, the following subchapter evaluates the interactivity of some existing CRS.

2.4 Campus routing systems

As stated in the subchapter 1.1, the importance of the visualizing indoor spaces and building indoor navigation systems has gained significant research and developments in the recent years. This has led to many applications being used for the indoor wayfinding process, including university campuses. Therefore, to analyse the current development of CRSs and campus maps, the campus maps of different universities are described here.

Weisman (1981) identified four major variables that influence wayfinding in indoor spaces: (1) visual access, (2) architectural differentiation, (3) floor plan complexity, and (4) signage and room numbers. University buildings fall as well under this category where the indoor navigation takes extra efforts, due to the presence of the above-mentioned categories. This leads to an increasing confusion to the users, especially the first time users due to their lack of spatial knowledge and naming and numbering system. This confusion will lead further on to delays in lectures, seminars, or even more important business meetings and appointment with first time visitors.

While finding the way to the university campus is relatively an easy task, and various navigation systems can be used for such a purpose. Once you go to the building, there is when the struggle starts, navigating the indoor premises with limited help by making use of signage and floorplan maps. Holscher et al. (2007) states that when it comes to real life wayfinding performance, it is not unequivocally clear that access to floorplan maps does have a positive impact. Additionally, it is well documented that interacting with such maps that misleads one's current orientation can be detrimental (Holscher et al. 2007). This is a feature of many standard floorplan maps in university buildings. Therefore, building a CRS for university campuses is becoming a necessity nowadays for many universities.

Nowadays, most of universities have published "campus plans" and "campus maps" on their website, and most of these maps are static representations of building floorplans. Despite the developments in the field of indoor navigations systems, there is no clear definition of what a CRS is. This is also reflected on the implementation, functionalities and the content that a CRS depicts. (Mittlboeck, Knoth and Vockner 2017)

Roth et al. (2009) state that universities across the world have fully embrace the digital revolution in many aspects of their work such as online information and registration, online subjects and materials, etc. The same way students, staff members and visitors expect to acquire spatial information about a university campus in a digital format. As a result, the campus map should be an interactive, online tool that facilitates spatial information acquisition in a manner familiar to the students and staff members brought up in a digital environment.

In a study carried out for the University of Wisconsin-Madision campus, Roth et al. (2009) identify two types of interactive, online campus maps: (1) *wayfinding-based model*, and (2) *atlas-based model*. In the *wayfinding-based model* the focus is in searching for and locating specific university features (departments, buildings, athletic areas, etc.), and navigating the campus efficiently to reach them. *In the atlas-based model*, the focus is upon providing numerous geographic discourses about an important place on campus.

For the *wayfinding-based model* Roth et al. (2009) identify two primary audiences: (1) potential and new students unfamiliar with the university Campus, requiring general information about the spatial configuration of campus features, and (2) existing students and faculty familiar with the spatial layout of campus, but requiring specific details about one or more of its features. With this in mind, the design of CRSs and campus maps should encourage interactive exploration of the full campus extent while also providing an immediate means to query specific locations on campus or information about campus. Such site navigation follows Shneiderman (1996) mantra "*overview first, zoom and filter, then details-on-demand*."

Mittlboeck et al. (2017) have defined three interactivity levels of campus maps based on their implementation: (1) floorplans/static maps, (2) semi-interactive (i.e., clickable and partially zoom-able) maps, and (3) full interactive maps. The characteristics of these categories of campus maps are represented on figure 2-5 below.

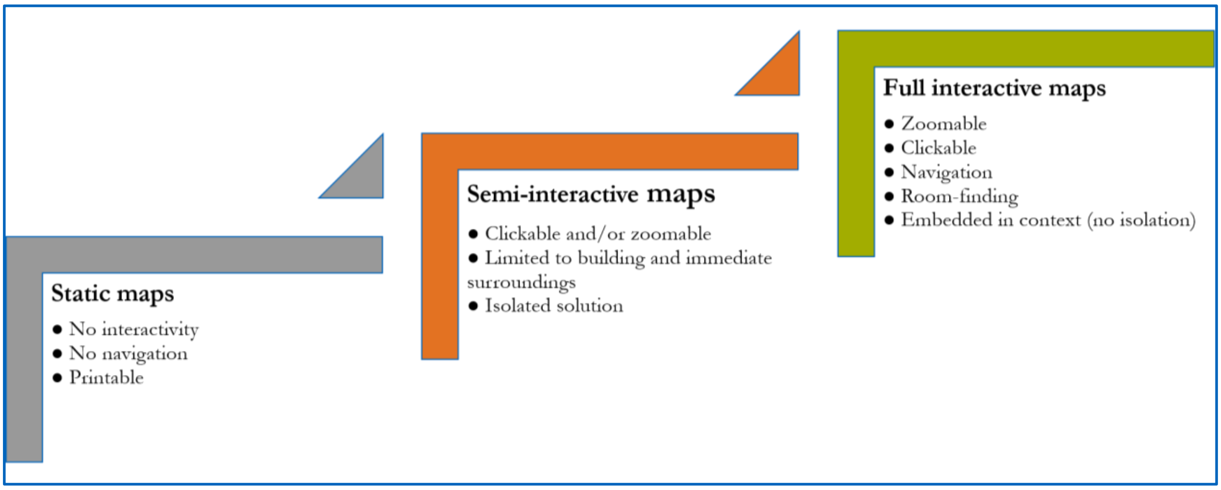


Figure 2-5. Categories of campus maps and their characteristics. (Mittlboeck et al. 2017). Designed by A. Kapaj

Andrienko, Andrienko and Gatalsky (2003) state that in comparison to paper maps, computer-based visualization tools have two principally new properties: interactive and dynamics. These features enable, among others, two fundamental exploratory techniques that can be applied to all types of data visualized: (1) querying, and (2) focusing and linking.

1. *Querying*. Andrienko et al. (2003) define querying as a software capability to answer users' questions concerning data under analysis. The queries include two major parts: the target and constraints. These two major parts are easily adapted to querying attributes of indoor spaces. For example, the user may ask the program to retrieve the space information which has a specific identification attribute. In this example, indoor space is the target whereas constraint is the indoor space attribute value (room number). Additionally, Andrienko et al. (2003) mentions two principal ways in which a software tool can answer questions about data: (1) to provide the requested information in addition to what is already present on the screen; (2) to remove from the user's view the data that do not satisfy the query constraints. The former type of querying may be called ''lookup'' and the latter ''filtering''. However, query tools differ from one software to the other, in how the questions are stated and how the information is retrieved.

2. *Focusing and linking*. Buja, Cook and Swayne (1996) classify visualization techniques into three categories: focusing, linking and arranging views. Andrienko et al. (2003) point out that f*ocusing* techniques include the selection of subsets and variables

(projections) for viewing and various manipulations of the layout of information on the screen: choosing an aspect ratio, zooming and panning, 3-D rotations, etc. Focusing results in conveying partial information, therefore, must be compensated by showing different aspects of data. The data need to be linked so that the information contained in partial extensions can be integrated into a coherent image of the data as a whole. In the first case, linking is provided by smooth animation. The most popular method for linking parallel views is via identical marking of corresponding parts of multiple displays, e.g. with the same colour or some other form of highlighting.

To analyse the current development of CRSs and campus maps, the campus maps of different universities are taken into consideration concerning their interactivity. The university campus maps taken for comparison are: (1) the Technical University of Munich, (2) the Technical University of Vienna (TUW), (3) the Technical University of Dresden (TUD), and (4) the University of Applied Sciences Würzburg-Schweinfurt (FHWS). The results of this comparison are shown in table 2-3.

University	2D	3D	Indoor features	Indoor space categorization	Room finder	Search for information	Indoor navigation	Outdoor navigation	Static	Semi-interactive	Full interactive
TUM[6]	●				●	●			●		
TUW[7]	●	●					●		●		
TUD[8]	●		●	●	●	●		●			●
FHWS[9]	●	●	●	●	●	●	●	●			●

Table 2-3. Characteristics and level of interactivity of four university campus maps

The TUM campus map "Roomfinder" allows the users to search for a room name, alias name or room number. The displayed information is a static map based on building floorplans (figure 2-6 (a)), which shows an overview of the location of the room. The "roomfinder" lacks the interactivity and does not convey any route information to the users. While the TUW campus map is a collection of static maps stored online for the most of the TUW interior spaces. These interior spaces are represented in either 2D or 3D, and a route is drawn on top (figure 2-6 (b)).

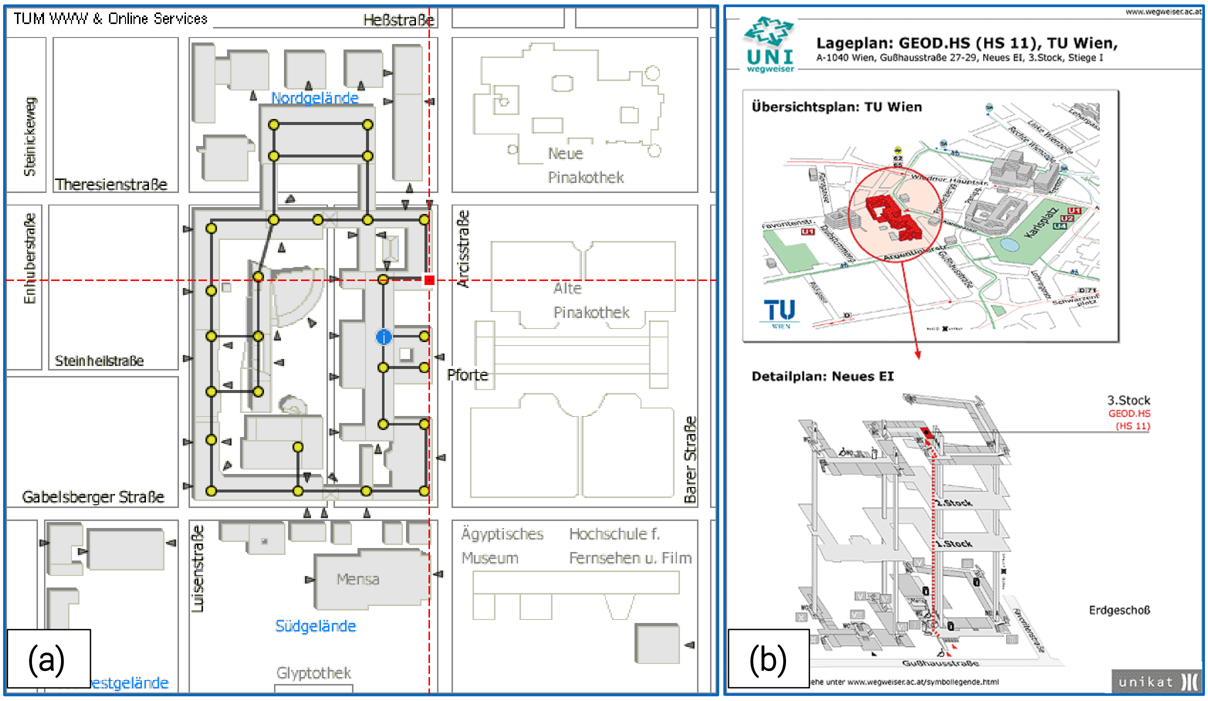


Figure 2-6. (a) The TUM "Roomfinder" representation after searching for a room (room 1779), (b) the TUW representation of an indoor space

In contrast to the TUM and TUW campus maps, the TUD and FHWS campus maps are fully interactive campus maps. They offer the possibility to search for room numbers and information, provide a detailed overview of interior features and spaces. The TUD campus navigator is built in a 2D map perspective by making use of building floorplans (figure 2-7) and does not offer indoor navigation options, only building-to-building navigation. While the FHWS campus map is built in a fully interactive 3D map perspective, and contains information regarding building footprints, a color-coded classification of indoor areas (i.e., lecture halls, offices, laboratories, etc.), building entrance points and points of interest (POI) (i.e., toilets, printers, cafeteria, etc.). The FHWS campus map forms the basis for an indoor 3D route planning and communication (figure 2-8). According to Wilkening, Schäffner and Staub (2018) the FHWS campus information system should allow the users to specify their start and end point of the intended route in the form of a room number or any other information related to the interior space. In addition, the user should be able to choose the parameters of the route by specifying whether to use the stars or elevators.

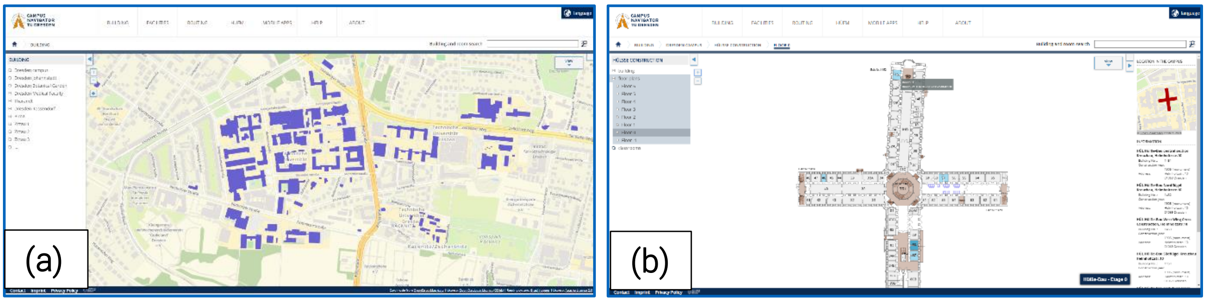


Figure 2-7. Illustration of the TUD Campus Navigator main view (a) and detailed building floorplans (b)

Figure 2-8. FHWS campus information system and route representation

Wilkening et al. (2018) state that the implementation of a web-based information system for the FHWS campus has positively affected the indoor navigation of students, visitors and staff members. The FHWS web based information system is built on a 3D route planner, which marks an important step in the overall concept of campus routing systems. However, the authors state that an evaluation should be carried on in order to measure the effectiveness and efficiency of a campus routing system.

In this subchapter, the general medium of visualizing university campus routing system and their level of interactivity was presented. Further on based on these medium four university campus maps were taken into consideration, and compared based on their level of interaction and what they offer to their user groups. This comparison method provides valuable feedback to plan a workflow for creating an interactive campus routing application. The steps of this workflow are presented in the methodology chapter (chapter 3).

3 Methodology

This chapter goes into details of the methodology adopted for this thesis, based on the approaches described in the state of the art in chapter two. This chapter describes the software, tools, and methods chosen for data pre-processing, processing, visualization, and evaluation of a CRS. Further on, the medium of publishing the CRSs in the form of interactive web maps is presented. In addition, the functionalities that an effective and efficient CRS should include are mentioned.

3.1 Research design

A campus routing system can be defined as a system designed and build to help various user groups to navigate in complex indoor spaces, such as university campuses, airports, shopping malls, etc. The focus of this thesis are university campuses, but the methodology adopted is suitable for all campuses including shopping malls, airports, etc. Building university CRS requires different steps to transform the raw data (CAD files) into an effective and efficient campus routing application with the help of different software, tools, and methods. These steps can be categorized in four main groups: (1) *data pre-processing*, (2) *data processing*, (3) *web application*, and (4) *campus routing evaluation*, as shown in Figure 3-1 below. These four steps will be described further on in this chapter, along with the software, tools and methods necessary to complete these steps.

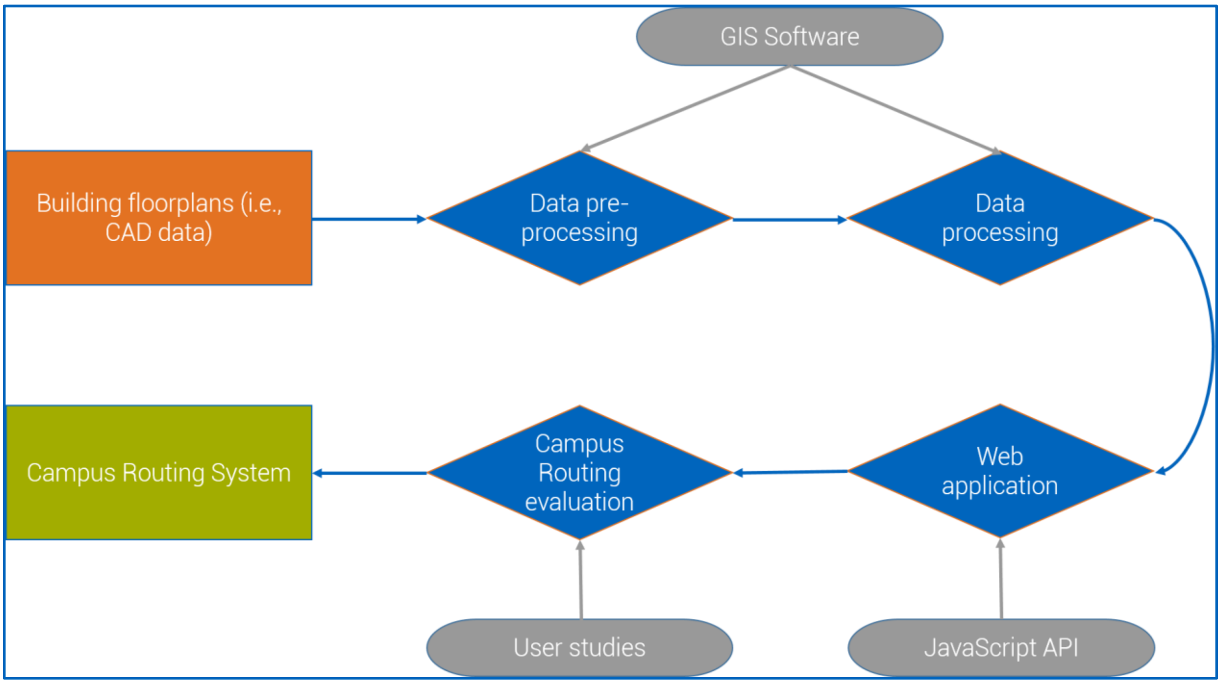


Figure 3-1. A workflow showing all the steps to generate a CRS

3.2 Data pre-processing

Campuses in general as well as university campuses consist of several buildings, with various connection routes, entrance points, floor levels, dimensions, confusing numbering and naming systems, limited lines of sight, lack of local cues, missing signage etc. Additionally, the presence of many entrance points, linked passages, various connection routes, floor levels, restricted areas, etc., make university campuses hard to navigate for different users. These are the main factors, which contribute to increasing the level of confusion for the indoor navigation process of various user groups on and between campuses.

Zlatanova et al. (2013) state that the software tools used for indoor modelling are largely generic CAD or computer graphics tools. The indoor navigation maps for university campuses are based on existing floor plans. Gotlib and Marciniak (2012) state that the conventional way of representing indoor spaces (figure 3-2) cannot be used in indoor navigation systems due to the high details, which will result in a cognitive load to the users.

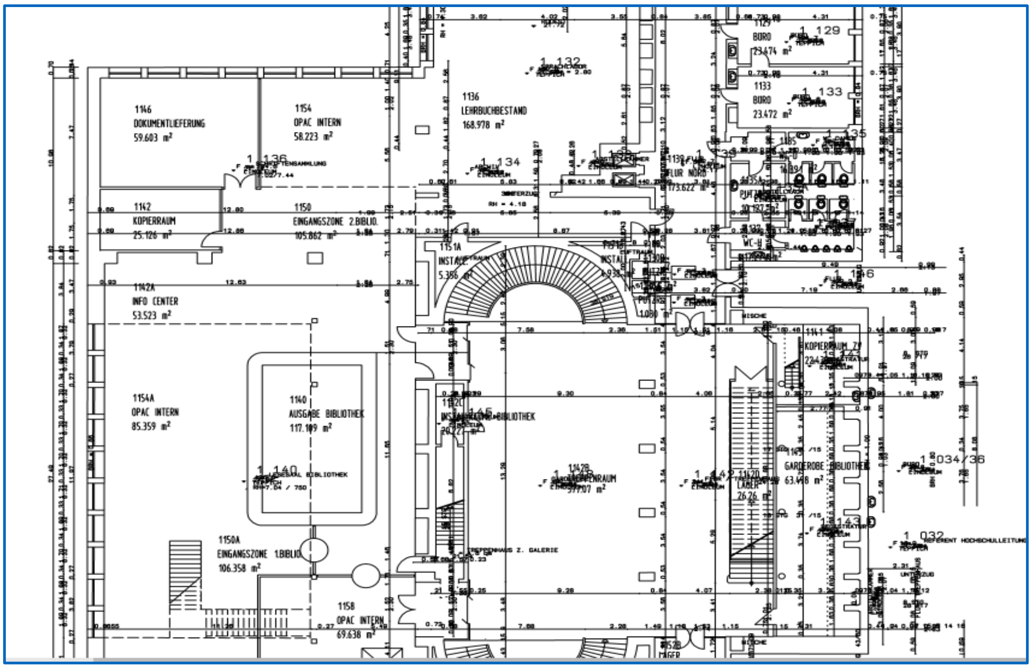


Figure 3-2. Example of a CAD file (floorplan of the 1OG of the TUM main campus building)

To avoid confusion coming from the highly detailed CAD files, a pre-processing step is highly required. To complete this step a GIS software should be chosen from the vast amount of either commercial or open source GIS software. In the following chapter (chapter 4), a description of GIS software used for the case study of this thesis will be provided. The floorplans should be generalized to the extent of indoor information that can be relevant for the navigation purposes (see figure 4-4, chapter 4).

Despite the generalization process, the CAD files need to be further analysed if they fulfil the necessary requirements for creating a CRS. These requirements include:

- *Categorization of floorplan lines* based on their type (wall, door, window, stair, etc.), and applying the same naming consistency across the building (i.e., if the interior wall is labelled as "*interior_wall*" in one floor, it should have the same name in all the floors)
- *Categorization of interior spaces* based on their type (lecture hall, seminar rooms, office, hallway, etc.) with the help of *annotations*. Annotations complete the CAD files with textual information related to the space function and identification number.
- *Projection* of CAD files to a real world coordinate system to align to the right position in the map

The data pre-processing constitutes a very important step, as it will create the data in which all the following steps will be based on. In order to create an effective and efficient CRS a lot of manual work might be needed, whose benefits will be evident in the later steps. The data processing step, described below will make use of the data generated after the data pre-processing step.

3.3 Data processing

After completing the data pre-processing step, this data has to be further processed to create a tailored campus routing navigation. To complete this step a complete mapping system for assembling, managing and sharing building and campus information can be used. In addition, the selected mapping application should be able to complete the following steps, in order to generate a CRS:

1. *CAD to GIS*. Zlatanova et al. (2013) state that the software tools used for indoor modeling are largely generic CAD or computer graphics tools. Therefore, Krisp et al. (2014) point out that the functions of an indoor navigation system based on CAD file format are very limited due to the lack of deeper indoor knowledge of such data format. The indoor knowledge includes topological relationships between indoor objects. Krisp et al. (2014) state further that converting CAD files to a GIS file format seems as a way to overcome this shortage. Therefore, this step constitutes the starting point in creating an Indoor GIS, which will transform the raw CAD data into a CRS. The output of this step includes building, floor, indoor spaces, and floorplan lines (walls, stairs, windows, etc.) features.
2. *Style and share campus layers*. The map layers can be easily styled, and designed following cartographic design principles and allow a 3D visualization for a more realistic perspective due to their enabled Z-values. As a result, this thesis is focused on applying cartographic methods and design principles to depict indoor spaces and visualize them in a 3D map perspective (see chapter 4).

3. *Indoor network creation*. A step that should allow the generation of an indoor transportation network, using the foundational indoor layers output by the CAD to GIS tool. This indoor network can then be used later on in web and mobile apps for indoor wayfinding and therefore for creating a CRS.
4. *Campus routing system web app*. This step will make use of the above-generated indoor data and network data set to create an interactive web campus application with the help of an application programming interface (API). Steiniger and Hunter (2013) state that an API offers methods that are frequently used in customized programming, such as data retrieval and display methods. The API will make use of the data created and shared as services in the above steps to generate the app.

3.4 Interactive web map applications

As mentioned in subchapter 2.4, Roth et al. (2009) state that universities across the world have fully embrace the digital revolution in many aspects of their work such as online information and registration, online subjects and materials, etc. Students, staff members and visitors expect to acquire spatial information about a university campus in a digital format, too. As a result, a campus map should be an interactive, online tool that facilitates spatial information acquisition in a manner familiar to the students and staff members brought up in a digital environment.

In order to build an effective and efficient user-oriented and interactive CRS, the specific users' needs and requirements need to be identified. Based on these requirements and needs a set of functionalities should be applied to an indoor navigation web application. The target groups of a CRS can be categorized into *students*, *staff members*, and *visitors*. Students are the largest group on university campuses and can be considered as "*permanent inhabitants*" of these premises. In order to reach different lecture and seminar halls, computer labs, information center, library, etc. they will have to navigate inside the complex campus buildings. The second largest group navigating within these indoor spaces are university staff members. Regardless of their position, employment type, etc. all these staff members will have to reach different parts of the university campuses as part of their everyday job. Additionally to students and staff members, another important user group of university campuses are visitors. Based on their lack of familiarity with the building, its complex architectural structure, naming and numbering systems, visitors may be the user group that will benefit the most from a CRS. Therefore, based on these user groups, different sample scenarios are proposed to identify their needs and requirements.

- *Scenario 1 – student*: "I will finish the first class at 10:30. The second class starts in *10 minutes*. Can I go *from the lecture hall* on the *northern side* of the *first floor*, *to the lecture hall* on *southern side* of the *fourth floor*, in this *time frame*? Do I have *time* in between to *find* and use a toilet?"

- *Scenario 2 – staff member*: "My next class is in *lecture hall number 3107*. What *time* should I leave my office to *reach* the lecture hall *on time*, and what is the *fastest route* to *reach* the *destination*?"
- *Scenario 3 – visitor*: "I have an interview at the room number V52-M-89 at the department of Geography of the University of Zurich. How can I *reach* this room from the *entrance* point of the building? Before the meeting, I want to reach the destination as *fast* as possible and with *less distraction* possible to avoid the risk of getting lost. On the way back I want to *take a look* around of the university building."

After identifying the needs, the functionalities that are needed for effective and efficient indoor navigation are planned accordingly. Table 3-1 summarizes users' needs and requirements with an indoor navigation as well as the functionalities needed to address these needs and requirements.

Users' needs and requirements	Needed functionalities
Interior space features	Walls, doors, stairs, etc.
Space categorization	Lecture halls, offices, toilets, etc.
Space identification	Numbering identification, employee info
Indoor navigation	Campus routing system
Floor connectivity	Floor transition elements (stairs, elevators)
Navigation time	Estimated time of arrival (ETA)
Special needs	Choose elevators
Fast and with less distraction or explore	Use elevators or stairs

Table 3-1. Needed functionalities to meet users' needs and requirements

Based on the above scenarios, it can be summed up that the users' needs and requirements in an indoor environment are related with the presence of architectural features and the classification of indoor spaces based on their use. Therefore, the functionalities resulting from these needs should convey the architectural features such as walls, doors, stairs, stair handlers, etc. to the user and classify the spaces based on their intended use and floor level. The spaces can also store additional elements, such as the identification number and name of the employees. These functionalities will help users' to identify what is a walkable and non-walkable area, what is the intended usage of an interior space and its identification number. The main need and requirement coming from an indoor navigation system is to compute and convey routing information to the users. Therefore, the functionality resulting from these needs is a CRS that connects every indoor space of a university campus by making use of every walkable area. The generated route should provide the users with the estimated time of arrival and the distance to the destination. Additionally, based on various requirements a CRS should offer the possibility to switch between stairs or elevators to reach the destination.

By following the above methodology steps a user-oriented university CRS can be generated. In order to measure the effectiveness, efficiency and users' satisfaction with this web application one or more user test should finally be designed and conducted. These user tests should evaluate all the aspects of the web app, starting from design to interface.

3.5 Campus routing evaluation – user studies

To examine the usability and utility of a CRS several user tests might be required. The evaluation method to evaluate these CRS can be based on the evaluation methods proposed by Roth et al. (2015):

- *Expert-based methods* solicit input and feedback about an interactive map from consultants with training and experience in interface design and evaluation. It is important that an expert is a person from outside the project team, as it is necessary that he or she has little or no prior knowledge about the interface under evaluation.
- *Theory-based methods* require the designers and developers to evaluate the interface themselves, using theoretical frameworks established through scientific research.
- *User-based methods* solicit input and feedback about an interface from a representative set of target users.

To evaluate the effectiveness and efficiency of a 3D indoor navigation model, the expert-based and user-based methods should be used. According to Roth et al. (2017) three aspects of existing mixed methods should be taken into consideration: (1) *the participants*, (2) *the materials*, and (3) *the procedure*.

The *expert-based method* can be used to evaluate whether the applied design principles and visualization techniques for a CRS are appropriate and what can be further improved on this matter. This method should be used as per the fact that it gathers opinions from users with a background in the field of geosciences, urban planning, architecture, etc. The experts are persons with little or no prior knowledge about the campus model that will be tested.

After gathering feedback from experts regarding map design and map usage of a CRS, and additional feedbacks, a second user study should be conducted. The purpose of this study is to evaluate the *effectiveness* and *efficiency* of the developed CRS based on users' interaction and experience with the developed model. The method adopted should be a *user-based method. Firs time visitors* can serve as the target group, due to their lack of familiarity with the campus building. Therefore, their prior knowledge of the building spatial structure, naming and numbering system, presence of landmarks, etc. will not interfere during the interaction with the CRS. Based on this user study it is possible to identify if the users can reach the destination with the help of the developed model by evaluating the CRS map, route design, and web-application interface design.

4 Case study

This chapter focuses in applying in practice the steps described in the methodology chapter (chapter three). As a case study for this thesis is taken the TUM main campus building. This building will be used as an example to create a CRS by following the data pre-processing, data processing and setting up the web applications as well as evaluating the developed CRS. Before starting with the steps to develop the indoor GIS model an introduction of the case study area and software used will be provided.

4.1 The TUM Campus

The TUM spans in three large sites in Bavaria: *Munich*, *Garching*, and *Weihenstephan*. These are home to the 14 departments and the university's most important research facilities. The TUM presence within the city is divided among three important sites: the downtown campus at Arcisstrasse, Olympic Park, and the university hospitals. In addition to the TUM Board of Management, the following departments are based on the historic main campus at 21 Arcisstrasse: Architecture, Civil, Geo and Environmental Engineering, Electrical and Computer Engineering and the TUM School of Management. The TUM School of Education, as well as the new TUM School of Governance and the Bavarian School of Public Policy.[10]

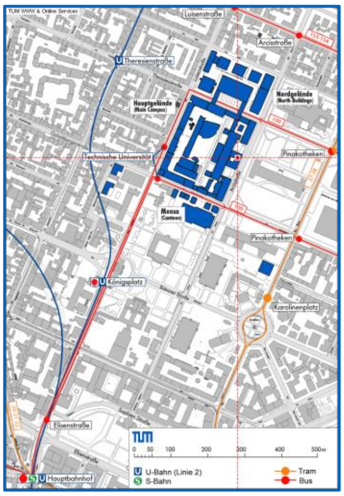


Figure 4-1. The overview and location of the TUM main campus within the city of Munich

The TUM represents a university campus where the indoor navigation process is not an easy task to handle. This happens due to several reasons: presence of several buildings, many entrance points, numbering and naming system for each individual building, lack of signage, continuous construction sites, several connection routes in several floor levels, connections between the buildings, mezzanine floor levels, restricted access to several points, etc.

Each room on the TUM campus is assigned a so-called SAP room code, such as 0103.01.302 (building, floor, room). In this case, the room number is 302. In addition, each room has a so-called architect number, such as 1302. This number is automatically augmented with the building number - 1302@0103 - making it a unique room number as well.[11]

4.2 Software used

Presently there are many commercial and open source GIS software available. Some of these products include ArcGIS, QGIS, GRASS, ILWIS, IDRISI, PostGIS, SAGA GIS, and many more. Each of this GIS software offers various capabilities to their users, starting with data analysing and visualizing in various aspect of business analysis, environmental applications, planning, utility, facility management, etc. The ArcGIS platform solves the tasks of data pre-processing, processing and publishing most efficiently, because it consists of several components (ArcMap, ArcGIS Pro, JavaScript API) that are integrated with each other. Table 4-1 below represents the workflow steps, each process taken for these steps and the software used.

Workflow	Process	Software
Data pre-processing	Generalization and inspection of CAD files	ArcGIS Desktop 10.6
	Generating new CAD files	
	Projection	ArcGIS Pro
Data processing	Create and publish campus basemap	ArcGIS Pro and ArcGIS Online
	Create building interiors	ArcGIS Pro: ArcGIS Indoors and ArcGIS Server
	Create campus scene	
	Create and publish campus network	
	Publish campus scene and locator layers	ArcGIS Online
Web application	Setting up and configuring the 3D campus application	ArcGIS API for JavaScript 4.4
User studies	First evaluation: design and visualization	Survey123 for ArcGIS
	Second evaluation: usability and utility	

Table 4-1. Workflow, processes and software components necessary to create the TUM CRS

Most of the steps for creating the TUM CRS will be conducted in the *ArcGIS Indoors*[12], which is an indoor mapping platform provided by Esri. ArcGIS Indoors is a complete mapping system for assembling, managing and sharing building and campus information. It is used for location discovery and wayfinding, asset management, operational data analysis, and crowdsource reporting to keep the indoor environment functional. ArcGIS Indoors download[13] folder contains two main part: (1) ArcGIS Indoors built in as an ArcGIS Pro[14] project, including all the necessary steps to complete the data processing steps, and (2) web application folder, which contains a set of folders used to create a web application template.

ArcGIS Indoors uses built-in tasks to complete the process of adding floorplan information to the ArcGIS platform. Task is a concept central to ArcGIS Pro, used to assist users in completing a specific process. Once the indoor data are part of the ArcGIS system, they can be styled into 2D and 3D maps and scenes, published as services, and consumed in a wide range of applications. The web application folder is based on the ArcGIS API for JavaScript 4.4, which is applied for the map and interface visualization process. The 4.x series of the ArcGIS API for JavaScript integrates 2D and 3D maps into a single, easy-to-use, powerful mapping API.[15] In addition to the JavaScript code, the web application folder contains Hypertext Markup Language (HTML) and Cascading Style Sheets (CSS) codes, used to design and to configure the web based application template. The online questionnaires for the two user studies were designed and distributed by using Survey123 for ArcGIS[16], which allows information gathering and analysing.

4.3 Development of the TUM Campus Routing System

The CAD files for the TUM main campus were provided by the Chair of Cartography at TUM. These files are in the DWG file format. Before converting these files to a GIS file format a prior inspection should be performed to check the validity of CAD data. Therefore, a pre-processing step is required before processing the CAD data and developing a CRS for the TUM main campus. As a result, the development of the TUM CRS consists of three main parts: (1) indoor data pre-processing, (2) indoor data processing, and (3) web application. The related steps to create a campus routing application for the TUM are illustrated in figure 4-2 below and further explained in the following subchapter.

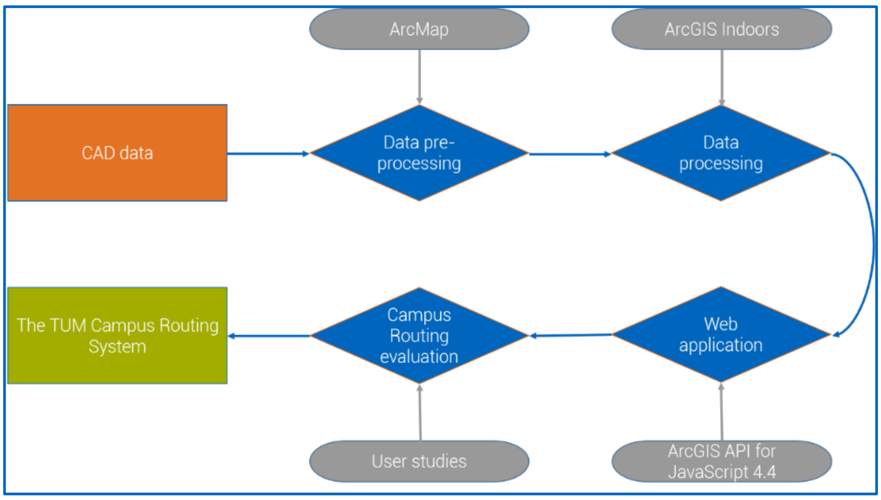


Figure 4-2. A workflow showing all the steps to generate the TUM CRS

4.3.1 Indoor data pre-processing

As stated in the methodology chapter of this thesis (chapter 3) the CAD files provided for the TUM campus are analysed if they fulfil the necessary requirements for creating a campus routing application. Table 4-2 illustrates the requirements that the CAD files should fulfil, in what they consist and if these requirements are fulfilled for the provided CAD files.

Requirement	Description	Fulfilled
Generalization	Identify if the CAD files depict information relevant to facilitate users' indoor navigation process	No
Categorization of floorplan lines and naming consistency	Identify if the floorplan lines are categorized based on their type (wall, door, stair, etc.) and the same naming convention is applied across the building	No
Categorization of interior spaces	Identify whether the interior spaces are categorized based on their intended usage (office, lecture halls, hallway, etc.)	No
Projection	Identify if the CAD files are in real world coordinate system	No

Table 4-2. Requirements that the CAD files for the TUM should fulfil

After an inspection of the TUM CAD files, it results that they do not fulfil the above requirements. Therefore, these requirements will be used as steps for the preparation of CAD files that can be used later on for the data processing. The software used to view, analyse and edit these files is ArcMap part of ArcGIS Desktop by Esri. ArcMap is chosen over ArcGIS Pro due to the familiarity of use. However, ArcGIS Pro can also be used to complete the pre-processing steps.

Generalization and inspection of CAD files

The provided CAD drawings consists of MultiPatch, point, polyline, and polygon features, as well as textual information in the form of annotations. These features are used to represent the indoor spaces of the TUM. Once the data is added to ArcMap, it is clear that the level of details presented is too high and it becomes hard to interpret and understand the data (figure 4-3).

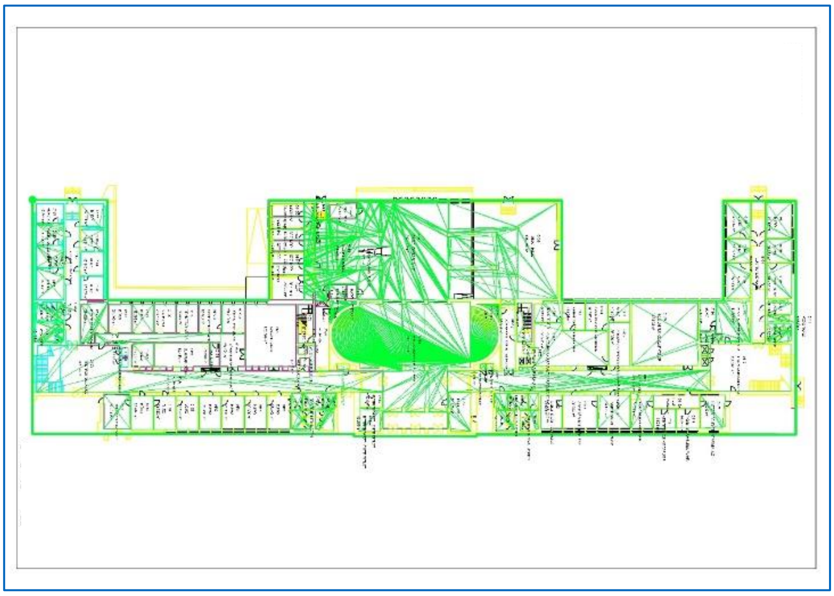


Figure 4-3. CAD file of the EG floor of the TUM main campus building

The generalization process involves selection of relevant architectural structures, geometric simplification of indoor spaces, exaggeration of important details in indoor spaces, and removing non-necessary indoor data. Hence, presenting to the users the right amount of information needed to interact with an indoor navigation CRS. The CRS should facilitate their cognitive load in carrying out an indoor wayfinding task.

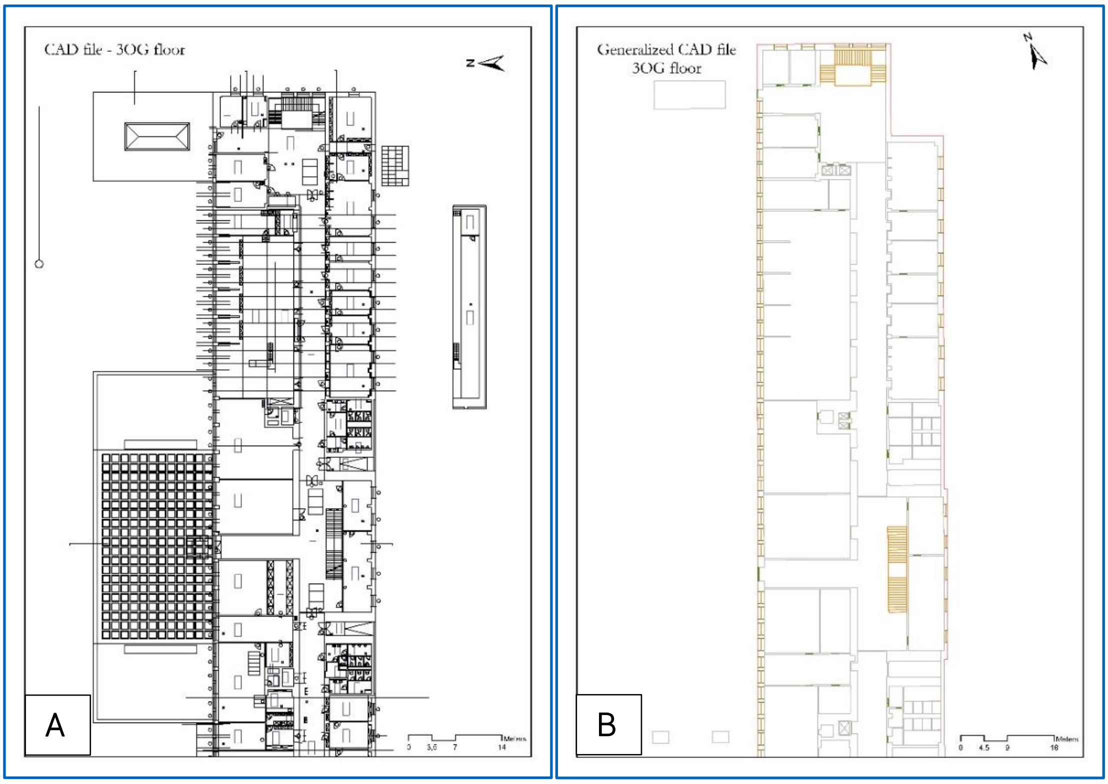


Figure 4-4. (A) Illustration of raw CAD data files, and (B) generalized view of CAD files depicting relevant architectural structure

Therefore, some of these layers should not be drawn, as they do not contain necessary information to create a CRS (figure 4-4 (A)). After deactivating the unnecessary layers of the CAD file, the levels of details are still high and not all this information is relevant. Some of these features include the presence of furniture, hydro sanitary equipment, telecommunication spots, etc. Therefore, unnecessary elements were deleted to achieve a neat representation of the TUM building floorplans.

In addition, part of the generalization process is also to take several notes about the representation of indoor spaces for each floor. This inspection consists of:

- A list of layers that will make up the floorplan lines for the building
- A list of layers that will make up the interior spaces for the building
- Layer(s) that define the building outline
- Layer(s) that define the building footprint

Based on the inspection of the provided CAD files for the TUM building, they do not provide information regarding the above conditions. There is no classification of interior lines and spaces based on their type (i.e., if an interior line is an interior wall, exterior wall, door, window, etc.), as well as no naming consistency across the building. Therefore, the provided CAD files cannot be used, as the creation of this case study CRS requires the classification of lines and spaces based on their type and function. However, the CAD files can be used as models to create new CAD files based on their high metric precision and location of each features in the indoor premises. The process of generating new CAD files, based on the provided CAD drawings, as well as defining their projection will be described in the following sections of this chapter.

Generation of the TUM CAD files

To generate new CAD files for the TUM main building an ArcMap document is created. This document consists of polylines (i.e., walls, doors, stairs, elevators, building outline, windows, etc.), polygons (interior spaces), and annotation features (area type and identification). To store the features six geodatabases are created, coinciding with the number of floors of the TUM main building. Special attention is paid on the consistency of the features names across each database. After creating the feature classes for each type of line and space, a manual digitizing process is performed, using the initial CAD drawings as a basemap. After completing the digitizing of interior features (polylines and polygons) two annotation features are created. The annotations store textual information regarding indoor spaces identification number and type of use. The annotations are used later on to classify indoor space based on their intended purpose of use (i.e., office, lecture hall, seminar room, library, etc.). Once all the manual digitizing process is finished for all the six floors, the feature classes can be converted to a CAD files (figure 4-5). This process generates six new CAD files, which will be used later to create and indoor GIS in ArcGIS Indoors.

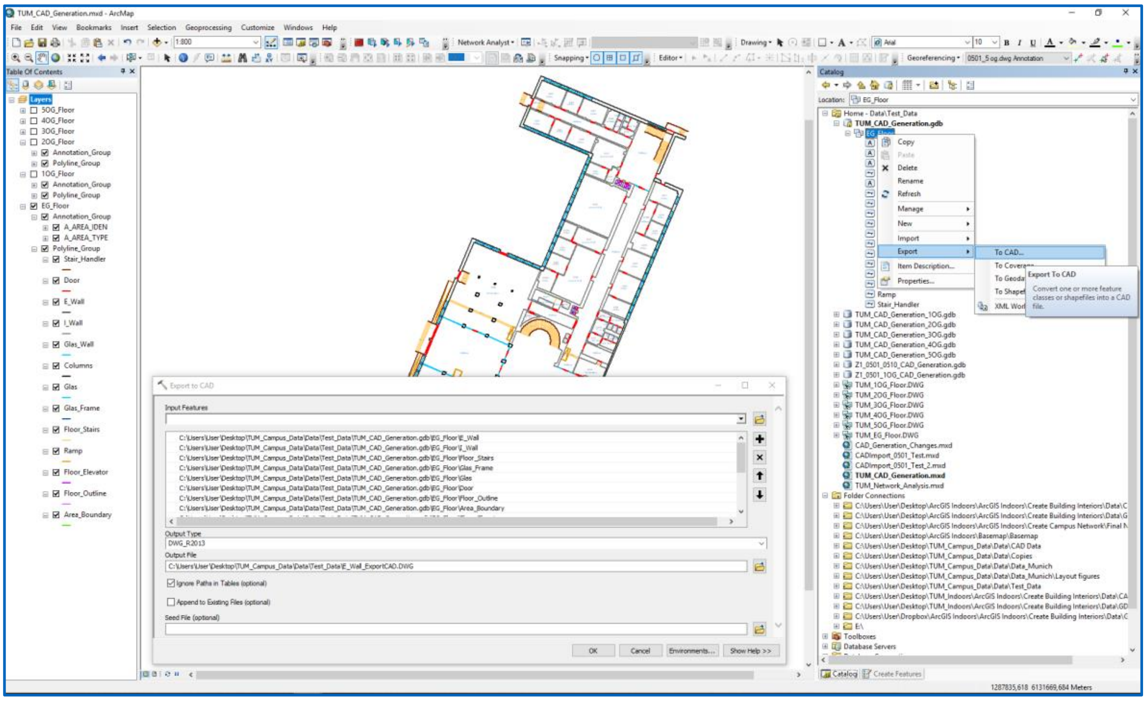


Figure 4-5. Creating and exporting feature class to CAD files

Projection

To align the created CAD drawings with other geospatial information they need to be georeferenced, therefore containing real world coordinate systems attributes. A prior campus basemap created for this project is used as the background for the georeferencing process. This basemap displays building footprints for the TUM main campus and the surrounding area. ArcGIS Pro gives the option to add only parts or specific features of the CAD drawing instead of adding all the information that the CAD drawing has. In this case, only the polylines of the CAD drawing are added. After adding the data to ArcGIS Pro, the CAD polyline is not drawing on the map, but in the middle of the ocean. The georeferencing is completed by adding two control points that will connect the CAD file to the GIS dataset used as a reference projection. Once the control points are added and applied, the CAD drawing aligns with the campus basemap. The projection used and defined for the case study CRS is Web Mercator Auxiliary Sphere, EPSG: 3857.

The drawback of the workflow used for the data pre-processing is the manual work that has to be accomplished to get a correct representation of the indoor features. However, this process is a prerequisite for the creation of a CRS if the CAD files fall short to meet the specified requirements. This data will undergo other transformations to create a CRS, explained in the data processing section.

4.3.2 Indoor data processing

The data processing step makes use of the generated CAD files to create the CRS. It goes through several steps that will be explained further in this section: (1) *create and publish campus basemap*, (2) *create building interiors*, (3) *visualize and design campus scene*, (4) *create campus network*, and (5) *publish campus scene and locator layers*.

Create and publish campus basemap

The first step in creating the CRS is to define a good basemap of outdoor spaces in the area of interest, in this case a basemap of the TUM main campus. The campus basemap contains spatial data regarding the buildings, streets and parks surrounding the TUM main campus area. The data is provided by the Chair of Cartography of the TUM in the shapefile file format, and is designed using ArcGIS Pro. After the visualization process, the campus map is shared as a Web Tile Layer (WTL) to ArcGIS Online. WTL is used due to the fact that it supports a fast map visualization in loading the basemap by using a collection of pre-drawn map tiles.

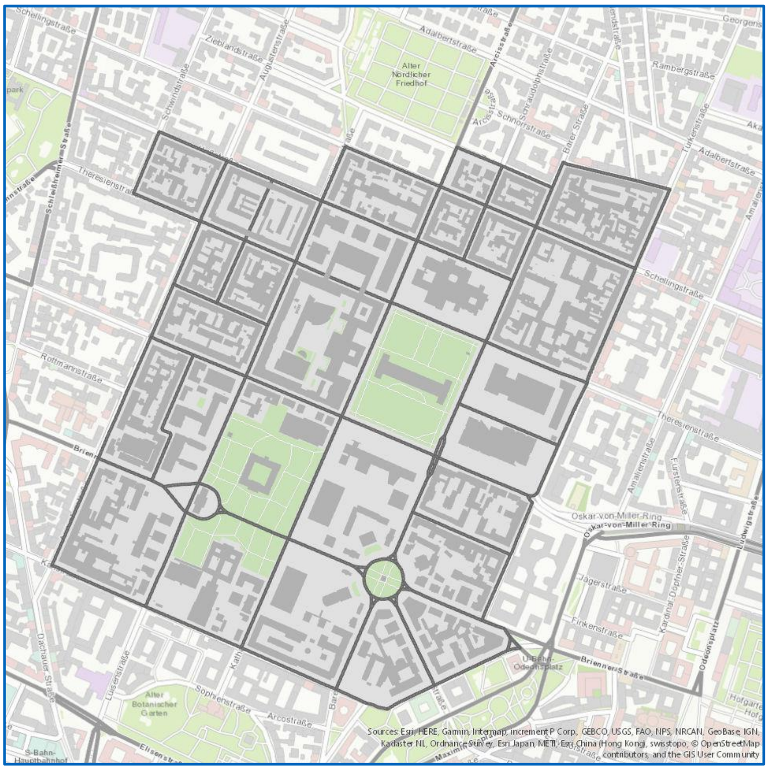
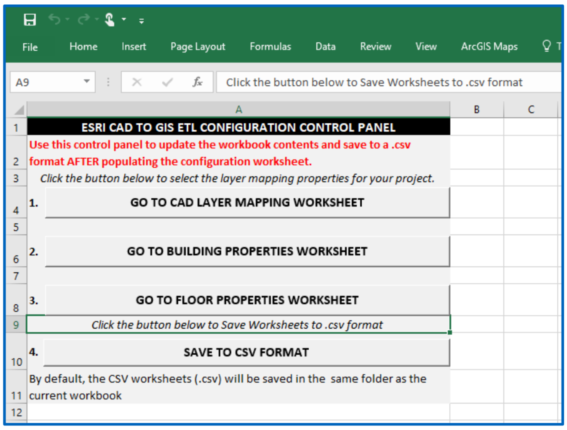


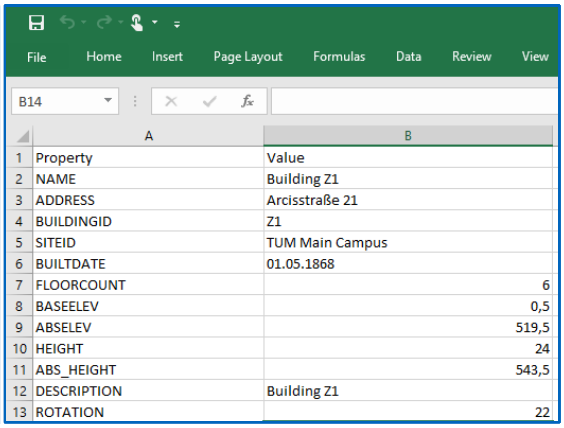
Figure 4-6. Creating and publishing the TUM campus basemap

Create building interiors

The pre-process of generating and georeferencing the CAD files for the main building of the TUM main campus results in different layers. These layers contain the floorplan lines, the interior spaces, the building floor outlines, and the building footprint. In addition, building elevation at ground level, elevation of each floor, ceiling height for each floor, roof height, and landing height and elevation on staircases, as well as information on building attributes (name, address, number of floors, vertical order, access restriction) is used to generate the interior spaces of the TUM main building. These information regarding building layers and properties is used to populate the configuration file provided as an excel spreadsheet in the ArcGIS Indoors folder (figure 4-7). The configuration file is used to link the different layers in the CAD with the feature classes in the ArcGIS Indoors geodatabase.

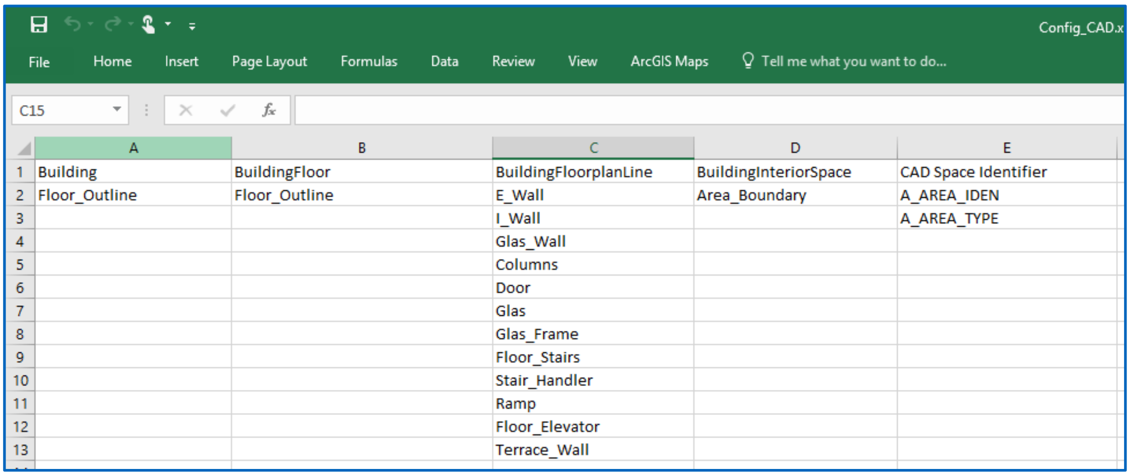


(a) *Configuration file control panel*



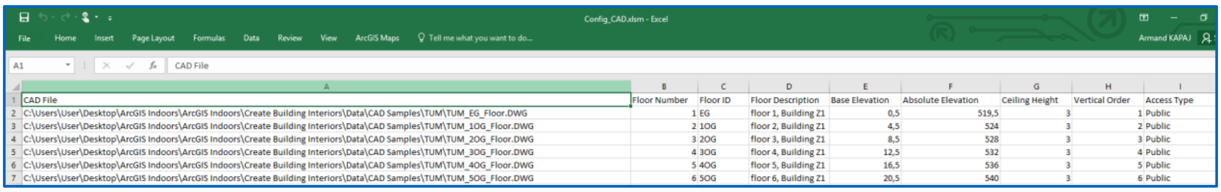
	A	B
1	Property	Value
2	NAME	Building Z1
3	ADDRESS	Arcisstraße 21
4	BUILDINGID	Z1
5	SITEID	TUM Main Campus
6	BUILTDATE	01.05.1868
7	FLOORCOUNT	6
8	BASEELEV	0,5
9	ABSELEV	519,5
10	HEIGHT	24
11	ABS_HEIGHT	543,5
12	DESCRIPTION	Building Z1
13	ROTATION	22

(b) *Building properties information*



	A	B	C	D	E
1	Building	BuildingFloor	BuildingFloorplanLine	BuildingInteriorSpace	CAD Space Identifier
2	Floor_Outline	Floor_Outline	E_Wall	Area_Boundary	A_AREA_IDEN
3			I_Wall		A_AREA_TYPE
4			Glas_Wall		
5			Columns		
6			Door		
7			Glas		
8			Glas_Frame		
9			Floor_Stairs		
10			Stair_Handler		
11			Ramp		
12			Floor_Elevator		
13			Terrace_Wall		

(c) *CAD layer mapping (first four columns map the output feature classes, and the fifth is for specifying the annotation layers)*



	A	B	C	D	E	F	G	H	I
1	CAD File	Floor Number	Floor ID	Floor Description	Base Elevation	Absolute Elevation	Ceiling Height	Vertical Order	Access Type
2	C:\Users\User\Desktop\ArcGIS Indoors\ArcGIS Indoors\Create Building Interiors\Data\CAD Samples\TUM\TUM_EG_Floor.DWG	1	EG	floor 1, Building Z1	0,5	519,5	3	1	Public
3	C:\Users\User\Desktop\ArcGIS Indoors\ArcGIS Indoors\Create Building Interiors\Data\CAD Samples\TUM\TUM_1OG_Floor.DWG	2	1OG	floor 2, Building Z1	4,5	524	3	2	Public
4	C:\Users\User\Desktop\ArcGIS Indoors\ArcGIS Indoors\Create Building Interiors\Data\CAD Samples\TUM\TUM_2OG_Floor.DWG	3	2OG	floor 3, Building Z1	8,5	528	3	3	Public
5	C:\Users\User\Desktop\ArcGIS Indoors\ArcGIS Indoors\Create Building Interiors\Data\CAD Samples\TUM\TUM_3OG_Floor.DWG	4	3OG	floor 4, Building Z1	12,5	532	3	4	Public
6	C:\Users\User\Desktop\ArcGIS Indoors\ArcGIS Indoors\Create Building Interiors\Data\CAD Samples\TUM\TUM_4OG_Floor.DWG	5	4OG	floor 5, Building Z1	16,5	536	3	5	Public
7	C:\Users\User\Desktop\ArcGIS Indoors\ArcGIS Indoors\Create Building Interiors\Data\CAD Samples\TUM\TUM_5OG_Floor.DWG	6	5OG	floor 6, Building Z1	20,5	540	3	6	Public

(d) *CAD file information (CAD name and path, floor id, elevation, access type, etc.).*

Figure 4-7. Populating the configuration file with information regarding the TUM main building

Once the configuration sheets are filled out and after performing a quality control, they are exported as .csv. These .csv files will be imported as tables in ArcGIS Indoors project. The most important advantage of these imported tables is that their information will be used automatically as input features to the "*Indoor CAD to GIS*" tool that converts CAD files into an indoor GIS (figure 4-8). This information includes the six CAD drawings for the six floors of the TUM building, floor information, elevation information, etc.

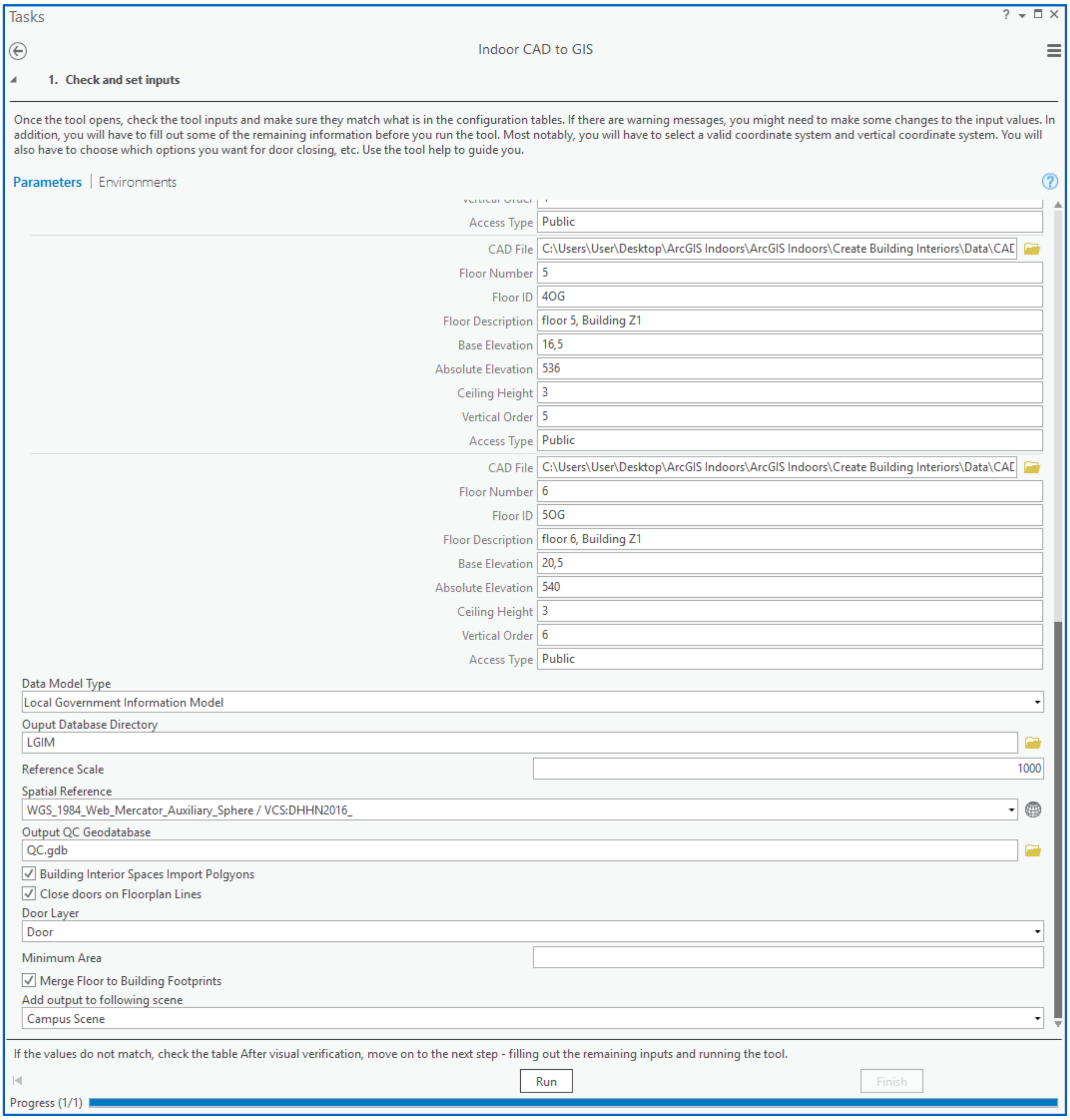


Figure 4-8. Converting CAD files into an indoor GIS

Additionally to the information coming from the CAD files, this tool requires some manual changes to its settings:

- *Spatial reference* will be used to specify the spatial reference information for the output data. A vertical or "Z" coordinate system should be set as the tool is designed to output 3D features. It is required that the input CAD drawing files have a valid world file in a known coordinate system. Since the projection of the CAD drawings was set to Web Mercator Auxiliary Sphere before, the same spatial reference is be used. For the vertical coordinate system, the German main height network "*DHHN2016 height*" is used.
- *Building interior spaces import polygons*, this option is used if the CAD drawing has a polygon layer for the interior space polygons. If so that layer can either be listed alongside the polyline layers on the CAD Layer to FC Mapping sheet in the configuration file, or just can be listed by itself in the column. In the described use case the box is checked, which means that the polygons are imported and the polylines are not be appended together.
- *Close doors on floorplan lines*, this option replaces the "swinging doors" features, which are common to many CAD drawings with a simple line that represents the doorways.
- *Merge Floor to Building Footprint*, this option merges the floor outlines for the building into a single building footprint polygon. This can be very useful if there is no building footprint available in the GIS.

The output of this tool is a 3D scene populated with building floorplan lines, interior spaces, floor and building footprint. These features constitute the basis for an indoor GIS created from the CAD drawings. Moreover, via mouse click on one of the indoor spaces a pop-up window will appear showing information for the indoor space that was stored in the configuration file and the annotation feature classes of the CAD drawings. This information will be used further to visualize and design the campus scene as explained in the following section.

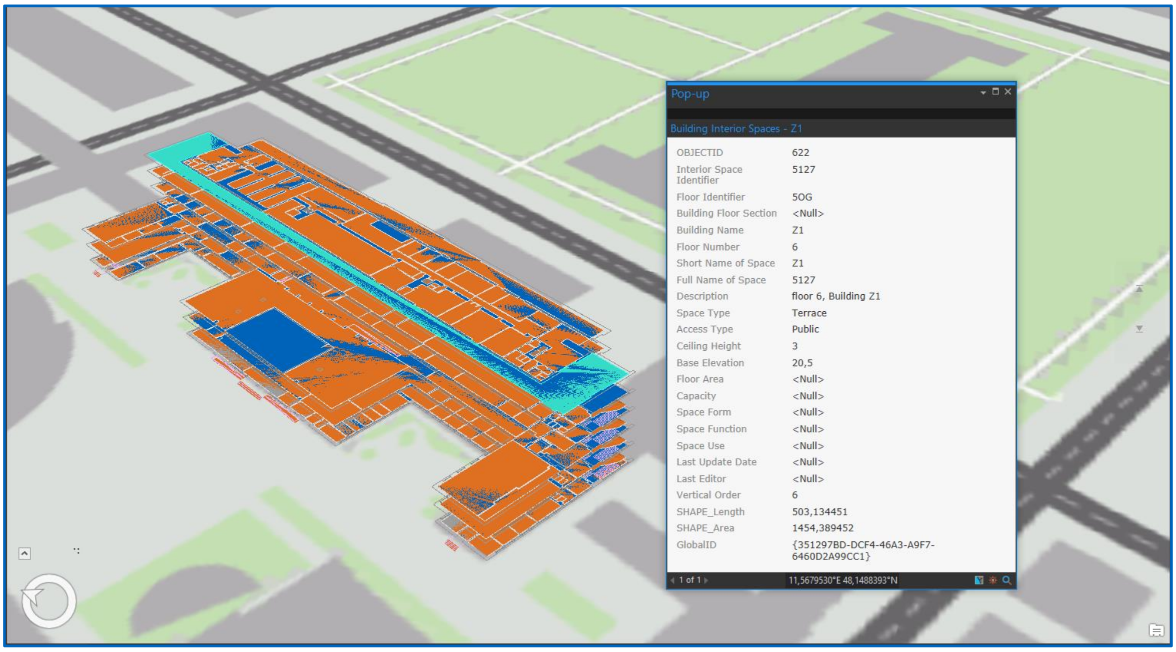


Figure 4-9. The result of the Indoor CAS to GIS python tool

Visualize and design campus scene

As mentioned before the converted CAD to GIS files contain information regarding *building floorplan lines*, *building interior spaces*, *floor* and *building footprint*. The next step is to visualize and design these features and create *Interior Walls and Doors, Interior Spaces and Interior Space Points, and 3D Building Facades*. The visualization and design process is based on the feature types of (1) building floorplan lines, (2) building interior spaces, and (3) building footprint.

1. *Building floorplan lines* are symbolized based on the layer type attributes to create *Interior Walls and Doors*. The *Layer type* is a descriptor of the floorplan lines, coming directly from the generated CAD files (i.e., Columns, Doors, etc.). This process is used to select non-traversable wall lines that are used to create the indoor network. The building floorplan lines feature is used to create three basic groups of line types according to the line type attribute: (1) *walls*, (2) *doors*, and (3) *stair handler*. As the floorplan lines will be visualized in a 3D map, they should contain also information regarding the elevation, vertical order, floor number, etc. This information is coming from the generated CAD files and the data stored in the configuration table. After applying an intuitive symbolization to the above floorplan lines, an extrusion is performed to visualize the data in 3D view. The extrusion height is set to 1m in order to create partial-height lines. 1m is appropriate to see the floorplan layout in 3D view. This predefined height is evaluated later by experts' user group (see chapter 5).

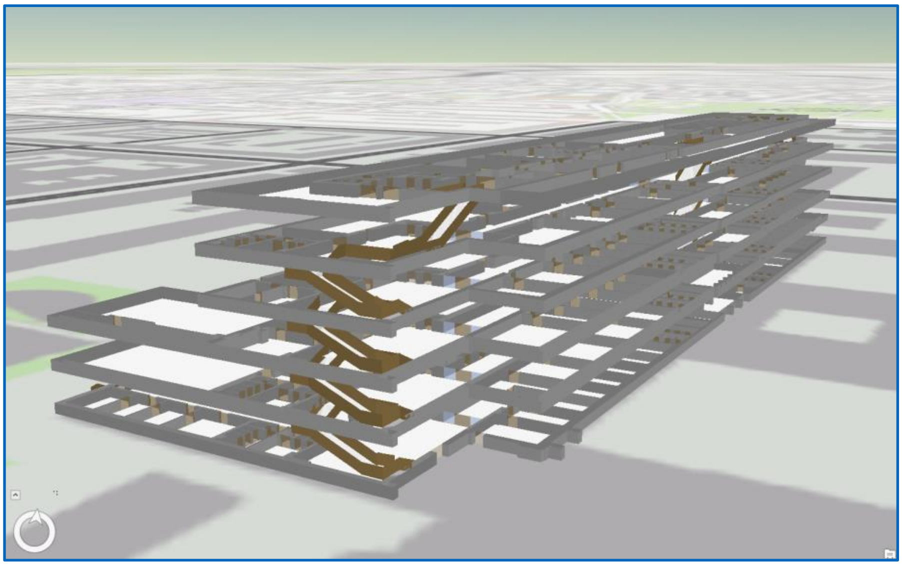


Figure 4-10. 3D visualization and design of the TUM building floorplan lines

2. The purpose of symbolizing the *Building Interior Spaces* is to create *interior space polygons* based to their space type attributes. The symbolization process is based on the *Space Type* attribute, which stores information according to their type of usage (i.e., office, lecture hall, library, toilets, etc.). This information is imported from the annotation feature classes, used during the CAD generation step, and is stored as the

full name of space. The full name of space allows searching for specific rooms/locations in the final campus routing application. To symbolize the interior spaces a predefined colour scheme is used, and evaluated later by the experts' user group (see chapter 5). Interior space polygons are also used to generate interior space points, which are used for network generation as "address" attribute for locating and routing between the interior spaces in the TUM campus routing web app.

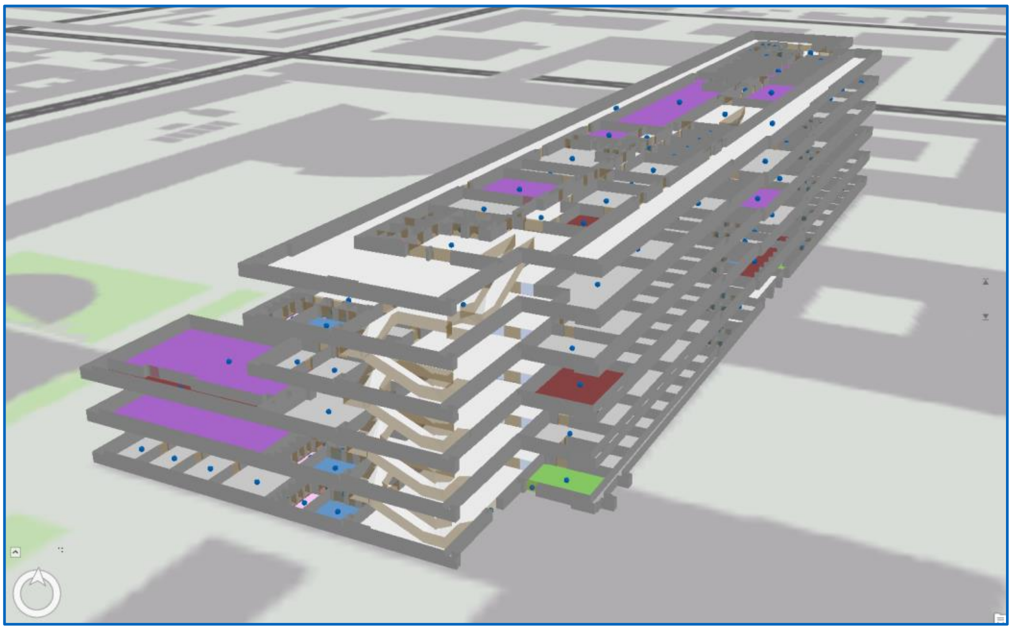
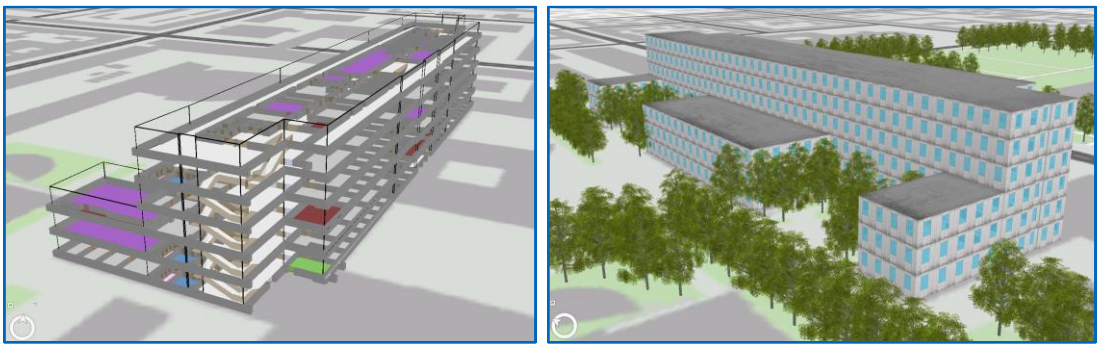


Figure 4-11. 3D visualization and design of the TUM building interior spaces and points

3. *Building footprint polygon* is used to create two different 3D façade forms: (1) *wireframe* and (2) *textured*. The building footprint polygons need to have *Height* and *Number of Floors* attributes imported from the configuration file. A predefined rule package is used to visualize and design the building façade. The parameters of this rule package are modified in order to create two different 3D façade forms, which are also evaluated later (see chapter 5).



(1) Wireframe *(2) Textured*

Figure 4-12. 3D visualization and design of the TUM building façade

Create campus network

Creating a campus network constitutes the most important step of the campus routing application, due to the fact that it enables a point-to-point routing in the campus routing web app. Based on the state of the art chapter (chapter two), the TUM CRS will be based on the shortest route algorithm to plan the indoor routes. This algorithm will create a lattice-based network that covers every walkable area of the building and will compute the shortest route, based on a more realistic approach of human walking behaviour in open spaces (walking diagonally instead of walking pass the walls) (see figure 2-1, chapter 2). The developed campus routing system for the TUM does not offer the possibility of localization and orientation to the users. Therefore, the users' will have to rely on visualized spatial structures such as doors, walls, windows, stairs, stair handlers, etc., to identify their position and to navigate within the TUM building. The process of creating the campus network for the TUM and its four steps are described below.

1. Create preliminary network lattices for each building floor. This step requires building, floor and space polygons, interior space points, and floorplan lines to run the "*Create Network Lattices*" python tool. Important to notice while filling out the information for this tool are the following fields:

- *Rotation*, which is used to align the lattice to the building footprint, based on true north. For the TUM building, the rotation value is 22° as specified in the configuration table.
- *Restricted space types*, which are specified to cut the lattice where no walkable areas exist (i.e., the open space in the middle of a stairway).
- *Restricted line types* (walls, columns, stair handles, etc.) are used to cut the lattice as they are not walkable areas
- *Lattice size*, represents the size of the square in the lattice and is defined as half the width of the standard doorway in the building. Lattice size is important to generate an indoor network that allows the users to walk in to every indoor space.

The "*Create Network Lattice*" tool creates a lattice network for each floor, cut it according to the space type (no walkable areas), and line type (walls, columns, stair handlers, etc.) specifications. After running the tool, the preliminary network features (1) *Pathways_Z1* (where Z1 is the Building ID for the TUM building) containing the preliminary network lattice (figure 4-13), and (2) *FloorTransitions* are added to the map. A quality check needs to be performed in order to check if the lattices need some manual connections. In case the amount of manual work is very high, the tool can be run with a smaller lattice size.

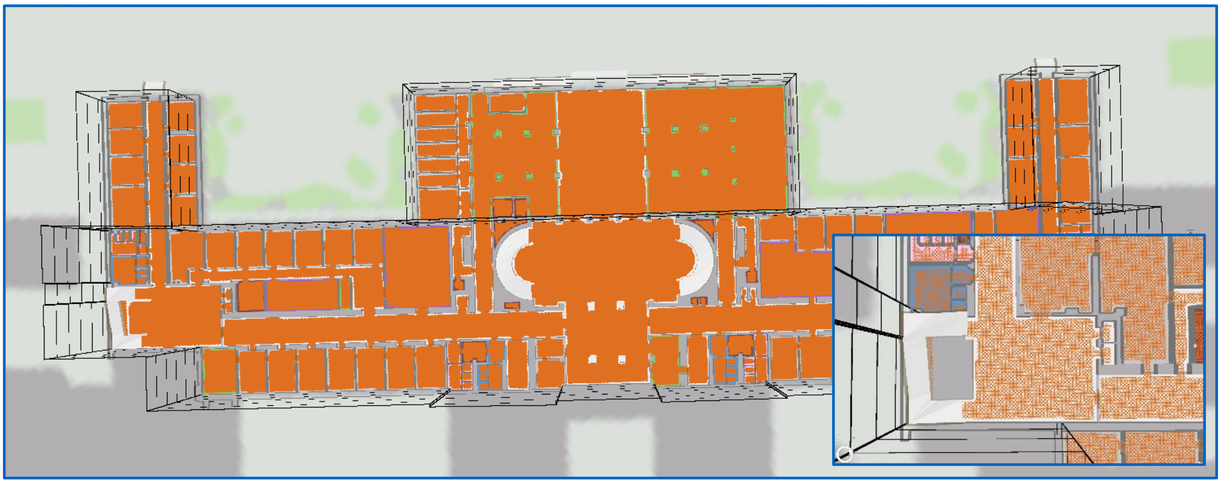


Figure 4-13. Preliminary network lattice created for the TUM main campus building

2. *Create floor transition lines* (elevators and stairs) to connect the individual floor lattices together. For this step, the preliminary network feature "*FloorTransitions*" added in the above step will be used. A line representing the elevators or stairs is manually created to connect the lattice of the lower floor with the lattice in the upper floor, and then the attribute table is configured with the necessary elements (elevation, floor id, vertical order, travel direction, etc.). The floor transition elements are used by the user if they prefer to generate a route following the stairs or elevators.

3. *Thin preliminary network lattice* by running the "*Thin Network Lattice*" tool to create a final transportation network for the TUM building interior spaces. This tool requires preliminary network lattice, floor transitions, and interior space points features (figure 4-14 (a)) created in the above steps. A preliminary and final network dataset templates (in the .xml file format) provided as part of the ArcGIS Indoors project folder are used. The tool pre-calculates every point-to-point route on each floor. This creates a much thinner network, which avoids walls and returns routes that lie near the centre of the hallway (figure 4-14 (b)). The thinned network constitutes the final network for the TUM CRS.

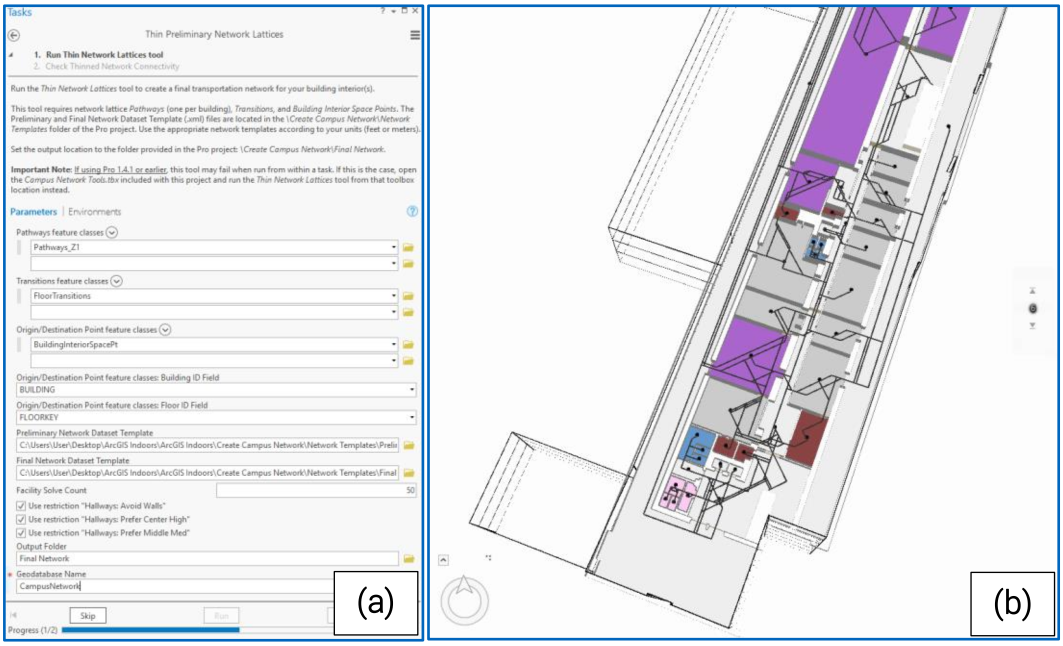


Figure 4-14. Thinned network for the TUM building (b), after running the "Thin Network Lattice" tool (a).

4. *Publish a route service to a server*: A point-to-point routing is used as the routing service of the TUM CRS. Therefore, the network dataset for the TUM building is added to an ArcMap document. A new route layer is created. In the new route parameters the following changes are performed: (1) *WalkTime* and *Length* attributes are enabled, and (2) *Search Tolerance* is set to 4 meters. These parameters are used to provide additional information to the users such as the distance to the destination and ETA. The network needs to be published as a service to an ArcGIS Server. In the service editor the default geometry precision is changed to 0.25 m. This ensures that the 3D route line created in the TUM CRS is not simplified to the extent that goes through walls or has conflicts with other interior features.

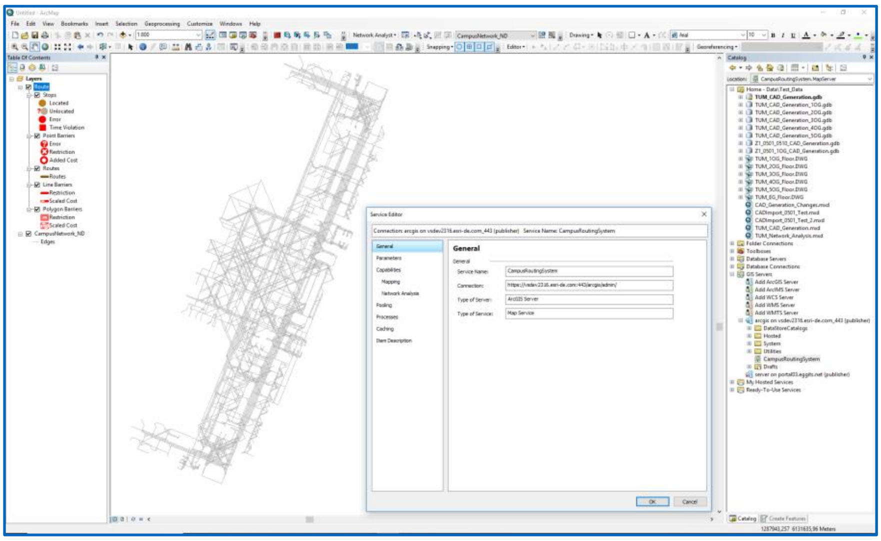


Figure 4-15. Publishing the TUM indoor network as a route service to an ArcGIS Server

In addition to creating indoor campus network this step can be used to create and connect outdoor pathways around buildings in case the campus consists of several buildings. The outdoor pathways are connected with the indoor pathways with the help of entry points placed in the entrances of each campus building.

Publish campus scene and locator layers

To visualize a 3D CRS for the TUM main building, the already created campus scene and the indoor space points need to be published and made accessible for everyone in an ArcGIS Online Portal. Therefore, for these purpose the TUM ArcGIS online Portal is used to store these data.

1. *Publish campus scene*. The TUM campus scene is shared as a web scene to the TUM ArcGIS Online Portal. The features that constitute this scene are (1) the multipatch indoor and outdoor features created during the above data processing steps, (2) the TUM campus basemap, (3) ESRI World Topographic basemap, and (4) additional multipatch features (surrounding buildings and trees). The portal is used to create two views for the TUM CRS: (1) *Home* and (2) *Interior*. The "*Home*" view is the default view when the campus routing web application is launched, and the "*Interior*" view is used during the indoor navigation process. For each view, the user can select the feature visible in the map.

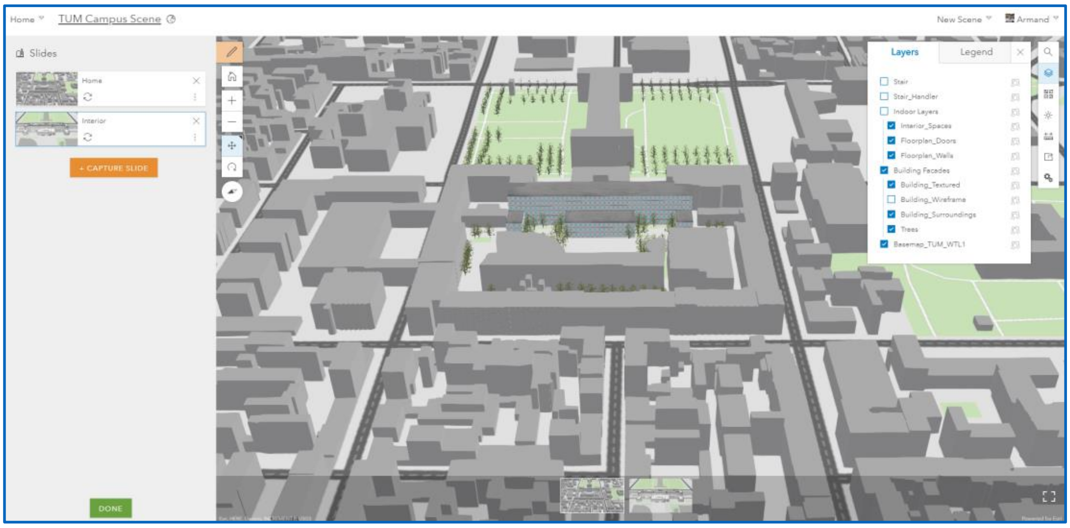


Figure 4-16. TUM campus scene published as a Web Scene to an ArcGIS Portal

2. *Publish locator layers*. The locator layers will act as address points for locating and routing between spaces and employees on the TUM main building. Therefore, in addition to the *interior space points* created above, a test table containing information regarding employees is created. This is a test table due to the fact that it does not show real employee information due to data protection policies. The employee table is converted to points and linked with the interior space number identification. Both layers

are shared as a feature service to the ArcGIS Online Portal to be used later for setting up the TUM Campus Routing web application.

Sharing the web scene and the locator layers is the last step of the data processing. The shared services (links and IDs) will be used to set up and configure the ArcGIS API for JavaScript 4.4 version, as described in the following subchapter.

4.3.3 Campus routing web application

This step is performed to set up and configure the CRS for the TUM main campus building as a 3D web application. With the ArcGIS Indoors folder, a web application template is included and it serves as the template in which the TUM CRS is based on. In the first step, the entire files of the web application template are copied into a valid web virtual directory. To change the web template for the TUM campus, the "*config.js*" a JavaScript file is updated with the services published in the data processing steps. To apply these changes, some software are required:

- A functioning web server such as Internet Information Services (IIS)
- Download and install ArcGIS API for JavaScript 4.4 on which the web application is based (https://developers.arcgis.com/downloads/apis-and-sdks?product=javascript)
- A viable JavaScript editing environment (Notepad++)
- Access to supporting services published in the data processing steps

The updates performed to the original *config.js* JavaScript file are listed below and the updated file is presented in Annex 1.

- *Title, logo image and link where it goes*. The title is changed to "*Campus routing System*" and the TUM logo is used as the logo image. Upon click on the logo it will be redirected to the TUM official website (www.tum.de).
- *"portalURL" value*. The portal URL is changed to match the selection of the ArcGIS Online Portal (*TUM ArcGIS Portal*) where the web scene was published.
- "*webSceneId*" *value*. The web scene value is generated after publishing the TUM campus scene and it is obtained by accessing the scene in a browser and copying the ID value from the URL (the last numbers and letters in the URL). Once the web scene ID is referenced in the congfig.js file, all the slides captured in the web scene (*Home* and *Interior*) appear in the change view widget in the app.
- *Floor picker widget*. To configure this widget all the floor layers are listed out also the name that these floors will be displayed in the widget.
- *"floorLayers"*. In this option are listed all the floor layers that are visualized when the "ALL" button in the floor picker widget is toggled. The "layerName" is case sensitive and it is set to match exactly the name of the layers as seen in the web scene.
- *"searchInfo" section*. This section will configure the "*Search box*" for the app. This section is where the most of the updates are performed to enable a smooth search

experience for users. The application supports multiple query sources in the search box, which allows the users to search for an interior space (by the space number) or for an employee by their name. To enable users to search for spaces and employees, the feature services of published locator layers is used as the "*queryURL*" and "*url*".

- *Routing service*. The route "taskURL" is replaced with the TUM building campus network shared as a routing service. This enables a point-to-point routing system between indoor spaces. This is the most important feature to create the TUM CRS.
- *Information and design changes*. The general information in the *info panel* is changed to match with the TUM CRS. In addition, general design changes are performed based on the TUM corporate design colors: blue, green, and orange.

Once the settings have been changed to match the TUM data, the config.js file is saved and the TUM CRS is ready. The main view of the TUM CRS is illustrated in figure 4-17 below and is composed by a campus web scene in 3D view and various functionalities like search panel, information panel, navigation buttons, etc.

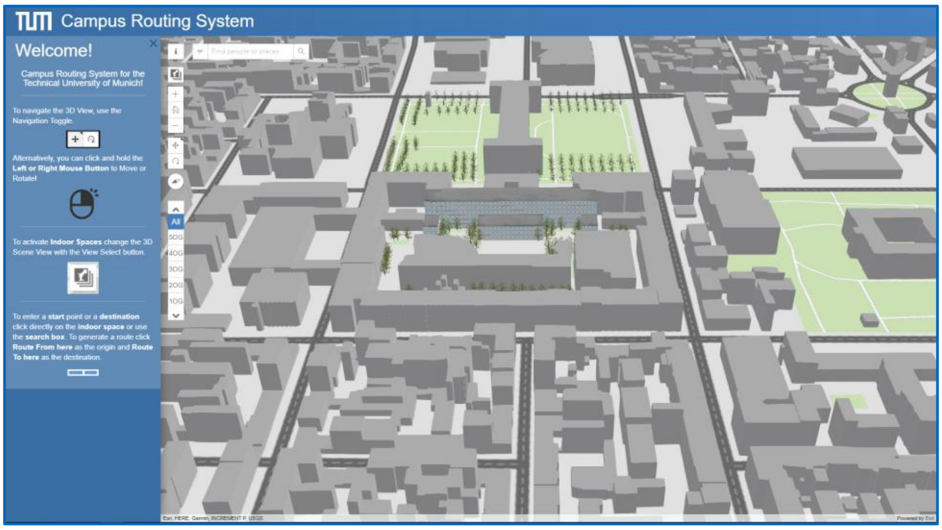


Figure 4-17. The main view of the TUM CRS upon lunching the web application

These functionalities are designed to provide information and ease the interaction of users with the system, and presented in the form of toggled buttons where each one of them contains information upon hover. These functionalities are provided as part of the web application template, and further changes are performed to adapt it to the TUM CRS.

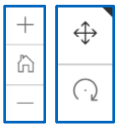
Functionalities	Description	Image
Information panel	Provides general information on how to interact with the application, how to search for indoor spaces, and how to generate a route	
View/Select	Allows the users to switch between the "Home" view and "Interior" view	
Interaction buttons	Allows the users to interact with the 3D view and with the application	
Floor buttons	Allows the users to select or deselect the floors of the TUM building	
Search panel	Allows the users to search for an interior space by its number or for an employee by their name	
Generate a route	Activated after clicking or searching for a space. Allows the user to assign an indoor space either as a starting point or as a destination	
Need an elevator?	Allows the users to recalculate the route to the destination by following the elevators	
Prefer the stairs?	The default option of the route, allows the user to change it by using elevators or change it back to stairs.	

Table 4-3. The TUM CRS implemented functionalities

Figure 4-18 demonstrates an example of the route communicated to the user. The below route shows the default route visualization that follows the stairs. As the starting point of the route serves an office on the first floor of the building (space number 0198A), and the destination point is the Voerholzer Forum (space number 5190). The route is communicated to the users in a 3D representation, in a form of the pipe. The colour to visualize the route that follows the stairs is based on the TUM corporate design green colour. In addition, the side panel provides users with the time and distance to reach the destination. If users toggle "Need an elevator?" button the route between this spaces is re-calculated and uses the closest elevator to generate a route to the destination. This route is also a 3D representation and is visualized using the TUM blue colour.

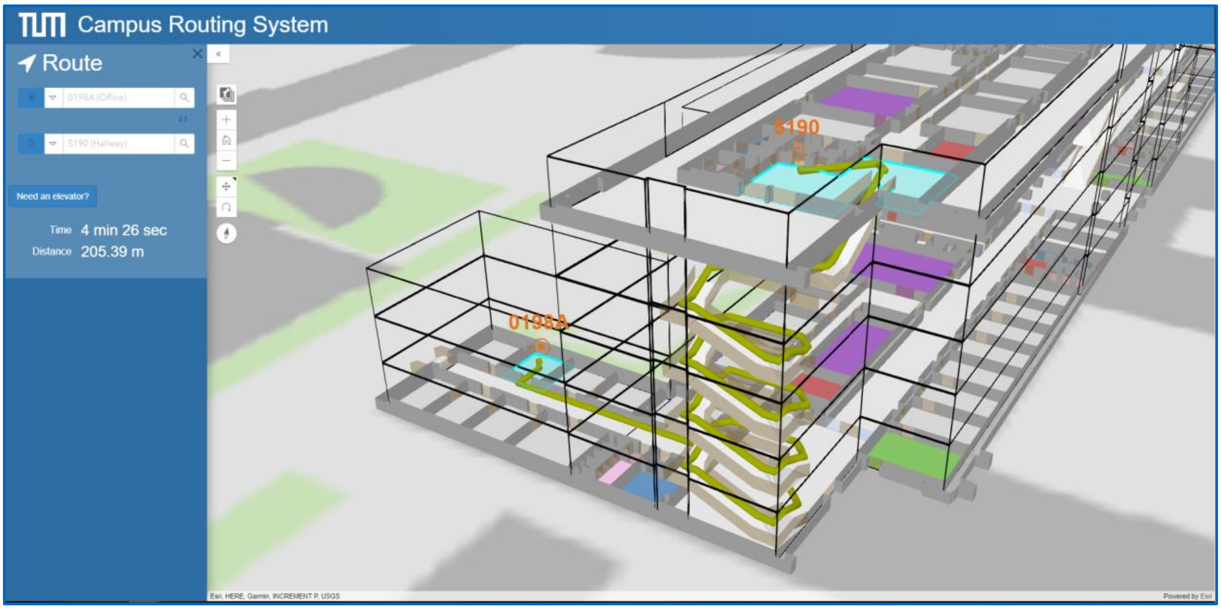


Figure 4-18. Route visualization of the TUM CRS

The CRS developed for this thesis can be defined as a spatial representation of building floorplans that depicts relevant indoor spaces and their spatial and textual features, and on top of which a routing system is integrated based on a chosen routing algorithm. Therefore, the main part of the TUM CRS is the campus map, which stores spatial information about the indoor spaces and the route planning and representation. To test the effectiveness and efficiency of the TUM CRS, the applied design principles, the interface and the route representation two user studies are carried out. These user studies will be further described on the following subchapter.

4.4 User Studies

For the evaluation process of the TUM CRS, two user studies were conducted. The methodologies adopted for these studies were varying from quantitative to qualitative, as well as mixed methods adopted for this purpose. A detailed description of these methodologies, evaluation goals, materials and participants, and project set-up will be discussed in details further on in the following subchapters.

4.4.1 First evaluation: Map design and visualization

The purpose of this survey is to evaluate whether the design principles and visualization techniques applied for the TUM indoor spaces are appropriate and cartographically appealing. In addition, the survey attempts to collect further suggestions for an improved user-oriented design of the TUM CRS.

Based on the methods proposed by Roth et al. (2017), the first evaluation is based on the *expert-based method*. *Expert-based methods* solicit input and feedback about an interactive map from consultants with training and experience in map and interface design and evaluation. It is important that an expert is a person from outside the project team, as it is necessary that he or she has little or no prior knowledge about the interactive map and the interface. Therefore, the selection of participants for this user study was chosen based on their background. The participants on this user study have a background in the field of cartography, geography, geosciences, urban planning, architecture, etc. The total number of participants filling out the survey was 41 participants, 17 male participants and 24 female participants. The aim of the survey was to reach as many cartographers as possible due to their background and knowledge related to visualization and design of geospatial data.

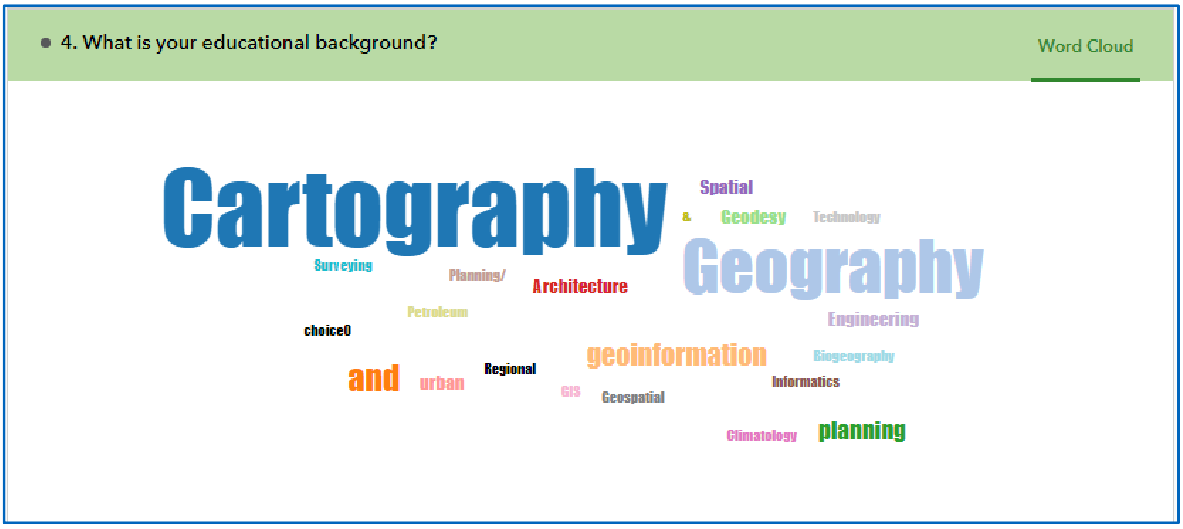


Figure 4-19. Background of the participants for the first evaluation

The user study is designed based on a *quantitative method*, in the form of an online questionnaire. The questionnaire consists of three main parts: (1) *general information about the user*, (2) *campus routing map design*, and (3) *campus routing map use*. The *general information* section (seven questions) obtains information about users personal attributes, and experience with interactive 3D maps. The *campus routing map design* section (eight questions) aims to gather users' opinions and suggestions based on the applied design for the development of the TUM CRS. The *campus routing map use* section (six questions) obtains information from the users regarding the biggest advantages of a 3D campus routing interactive application and what elements constitute the biggest success of such models. The information gathered is used to make the necessary changes in the map design and visualization before finalizing the TUM CRS.

Most of the questions for this evaluation are designed in the form of comparative evaluation, where the users are provided with various methods of design, illustrated with photos. Afterwards, a statement was formulated to gather users' opinion mostly on a Likert scale and yes or no questions. The test was distributed to various online groups (email, Facebook, LinkedIn), with the precondition that its users' meet the background criteria to be classified as expert users. The results of the first evaluation will be discussed in the following chapter (chapter 5), while the whole questionnaire can be found in Annex 2.

4.4.2 Second evaluation: Usability and utility

After gathering feedback from the first user study regarding map design and map usage of the CRS, and additional suggestions, a second user study was conducted. The purpose of this user study was to evaluate the usability and utility of the developed CRS for the TUM main building. It aims to measure the effectiveness and efficiency of the TUM CRS based on users' interaction and experience with the model. The evaluation process is built on the *user-based methods as* proposed by Roth et al. (2017).

The *user-based methods* solicit input and feedback about an interactive map and interface from a representative set of target users. The first time visitors are chosen as the target group to test the developed CRS due to their lack of familiarity with the TUM building. Their prior knowledge of the building spatial structure, naming and numbering system, presence of landmarks, etc. will not interfere during the interaction with the TUM CRS. Additionally, they are chosen, as they are the most unacquainted user group. Hence, if a visitor is able to use and navigate with the TUM CRS, it is assumed that the CRS is effective and efficient also for everyday users of the TUM premises (students and staff members).

A mixed-method of quantitative and qualitative data was adopted for this evaluation. The user study was built in two main parts: (1) an experiment conducted within the premises of the TUM main campus building, (2) a questionnaire form to gather feedback provided after finishing the experiment. Before starting the experiment, the model was shown to the users for five minutes in order to get them familiar with its design and interface. The experiment was designed as a task based on the model of the visitor scenario proposed in chapter 3.

"Scenario – visitor: "I have heard that you can get the best view of Munich from Voerholzer Forum at the rooftop of the TUM. In addition, I can enjoy a drink when I am up there. How can I reach the Voerholzer Forum (room number 5190) from the entrance door (hallway)? At the same time, I want to "explore" the interior spaces of the building while I navigate to the destination".

The test person entered the TUM building using the main entrance from the inner yard and was observed during the whole user test by the author of this thesis. After entering the building, the user was asked to interact with the CRS to identify the own position on the building, to enter the destination, and to generate the route that follows the stairs (figure 4-20). Based on the above scenario, users were requested to navigate to the destination using the stairs and "exploring" the TUM building. During the navigation process, users were asked to describe verbally what they are doing, following so the principles of the "*think aloud*" quantitative method. At the same time, a *user observation* qualitative method was performed on how they interact with the model during the navigation, in which points of the route do they pay attention to the model etc. Once reaching the destination users were asked to fill out a provided questionnaire. The questionnaire consists of three main parts: (1) *general information about the user*, (2) *interface design*, and (3) *map and route design*. The *general information* section (eleven questions) obtains information about users personal attributes, and experience with interactive 3D maps, and their navigation skills. The *interface design* section (eleven questions) aims to gather users' opinions and suggestions after their interaction with the model regarding the interface design of the TUM CRS. The *map and route design* section (thirteen questions) obtains information from the users regarding the route design during their indoor wayfinding task. At the end of the study, a coffee was offered to the users at the *Voerholzer Forum* rooftop cafeteria, where they could enjoy the great scenery of Munich. On the way back, users' were asked again to use the model to return to the starting point. In this case, the routing was performed using the elevator (figure 4-21). The whole questionnaire can be found in Annex 3.

Five users were recruited for this second evaluation, 2 female participants and 3 male participants, coming from different backgrounds. The only selection criteria was that they have not been to the main building of the TUM main campus before. The results of this second evaluation will be presented in the following chapter (chapter 5).

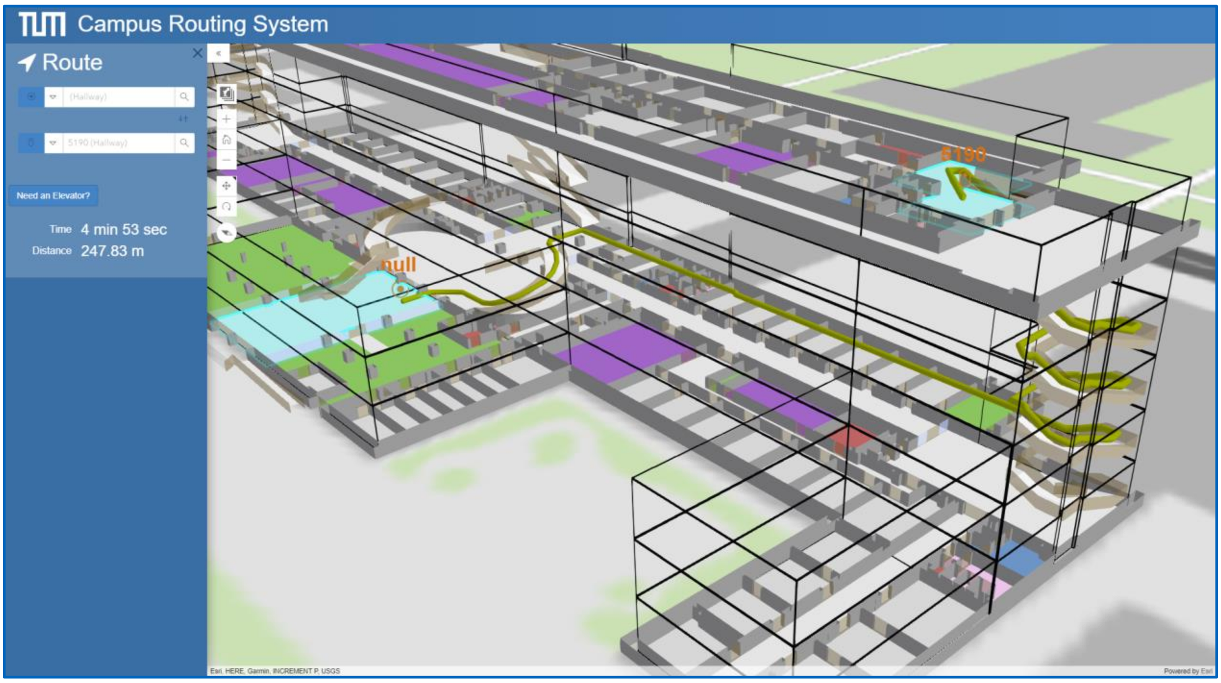


Figure 4-20. Overview of the proposed route following the stairs

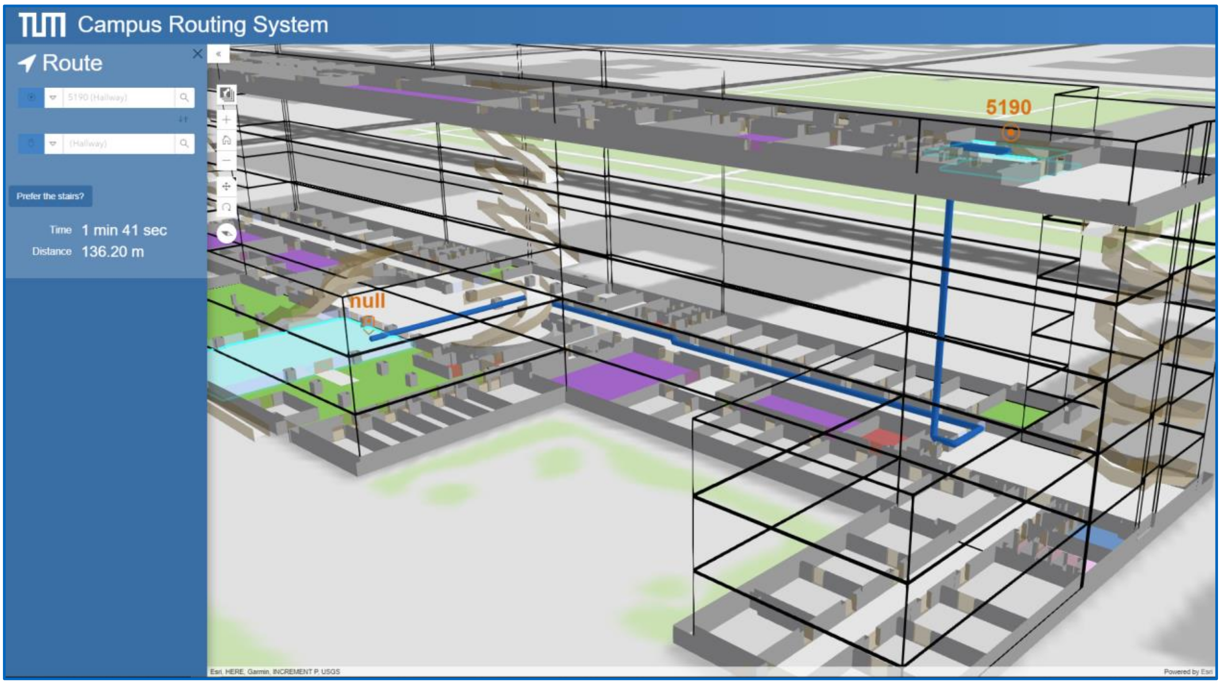


Figure 4-21. Overview of the proposed route following the elevator.

5 Results

The collected information from the two evaluations described in the previous chapter 4, will be presented in this chapter. This chapter consists of two parts, in accordance to the number of evaluation studies: (1) *map design and visualization* (chapter 5.1), and (2) *usability and utility* (chapter 5.2). The first part contains the results gathered regarding the design principles and visualization techniques applied for to the development of the TUM CRS. The second part contains the results gathered for the usability and utility evaluation to measure the effectiveness, efficiency and the user satisfaction with the developed model for the TUM routing application.

5.1 First evaluation: Map design and visualization

The purpose of this survey is to evaluate whether the applied design principles and visualization techniques applied for the TUM indoor spaces are appropriate. In addition, it attempts to collect further suggestions for a better design of the TUM CRS, and to develop general suggestions for campus map design. As mentioned before, the user study is designed based on a *quantitative method*, in the form of an online questionnaire. The questionnaire consists of three main parts: (1) *general questions about the user*, (2) *campus routing map design*, and (3) *campus routing map use*. The results gathered in each part are provided in the following subchapters.

5.1.1 General questions

Forty-one participants took part and filled the online questionnaire. Twenty-four participants are female and seventeen male. The dominant age group of participants is twenty-five to thirty-four. The dominant educational background field is cartography (18 participants) and geography (twelve participants). The educational level of participants is distributed as follow: Master (twenty-three participants), Bachelor (ten participants), PhD (five participants), and Higher than PhD (three participants). The predominant group of users by occupation (figure 5-1) are students from the carto-field and geo-field, and the rest is fairly distributed among other occupations such as cartographer, research assistant, etc. The questionnaire was filled out form participants based in various European countries (figure 5-2). Their location is gathered as part of the questionnaire and users' are asked for their permission.

In addition, users were asked to specify if they have ever been to the TUM main campus building at Arcisstrasse 21. Twenty-five participants answered this question "yes" and seventeen "no". To obtain information about the users' prior experience with 3D maps they were asked how often they use 3D maps (figure 5-3), and if so for what purposes. Only nineteen out of thirty-five participants specify that they use 3D maps on computer screens or mobile phones for navigation purposes.

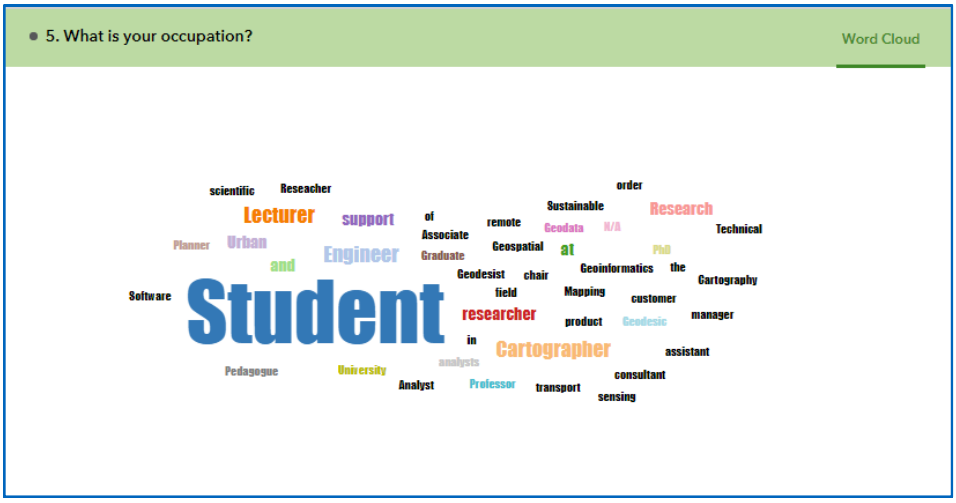


Figure 5-1. Occupation of participants

Figure 5-2. Distribution of participants filling out the questionnaire

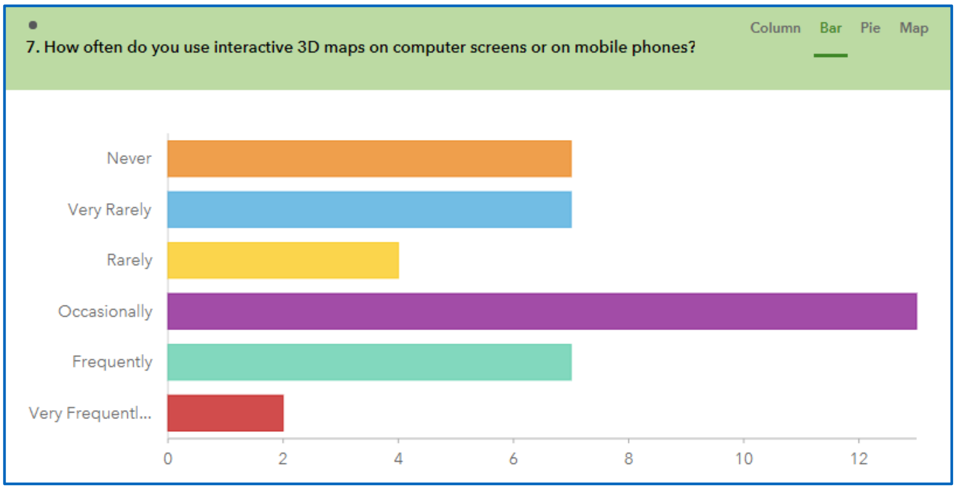
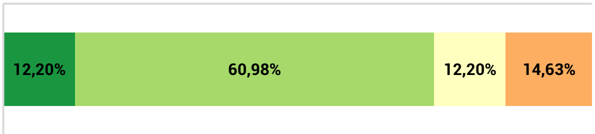
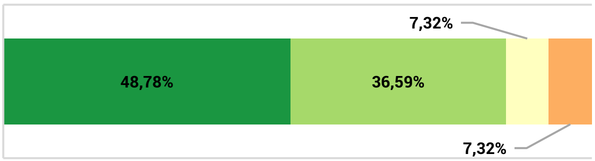
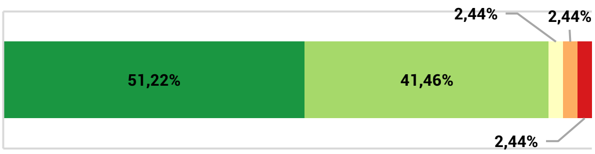
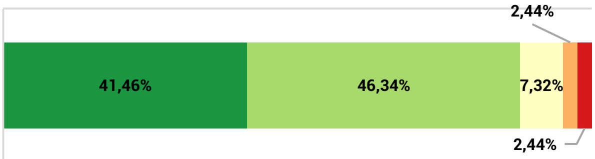
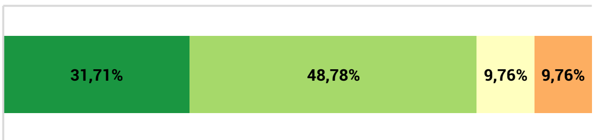


Figure 5-3. Prior experience of users' with 3D maps

5.1.2 Map design

In this section of the online questionnaire, participants were asked about their opinion regarding the applied design principles to visualize several indoor features. Most of the questions for this section are designed in the form of a comparative evaluation, where the users are provided with various design methods illustrated with screenshots taken from the Campus map. Afterwards, a statement was formulated to gather users' opinion. The questions built on a Likert scale and the result gathered from them are illustrated in table 5-1.

Statements	Results
To reach the destination and to be aware of the route, transparent doors represent better visualization option than opaque doors	
To visualize the whole route and to be aware of the surroundings, walls and doors extruded to 1m represent better visualization option than extruded to the ceiling	
To navigate among different floor levels, the 3D visualization of floor transition elements (stairs and stair handlers) represent a better option than a 2D visualization	
To visualize the whole route from the start point to destination, a fully transparent visualization of the exterior walls represents a better option than a textured model of the building	
Using different colours to differentiate the route that follows stairs and/or elevators will increase the users' understanding of the route and will improve the navigation	

Strongly agree Agree Neither Disagree Strongly Disagree

Table 5-1. Users' opinion regarding map design questions

In addition to the above questions, users' were asked to choose a method to visualize indoor spaces. The predefined methods illustrated with maps were:

A. Representation of the indoor spaces based on a qualitative colour scheme.
B. Representation of the indoor spaces based on symbols.

C. Representation of indoor spaces based on a combination of both: colours and symbols.

Despite the above three options users' were free to propose a new method by choosing the "none" alternative. None of the users' proposed new methods to visualize indoor spaces. Most participants (24) preferred a representation of indoor spaces with a combination of colours and symbols, eleven participants were in favor of indoor spaces visualized only with colours, while six participants chose to visualize indoor space with symbols.

The users' were asked to make an evaluation of the convenience of following a proposed route in order to reach the destination. The start point of the route was a space in the first floor (EG) and the destination was a space in the sixth floor. The route was shown as a 3D representation in the form of pipe. The results of this question are shown in figure 5-4. Nearly all participants responded that it was easy to follow the route. Additionally, they were asked to express their satisfaction with the 3D route representation, and the result is illustrated in figure 5-5. Most participants responded satisfied or very satisfied. A few of them were neither dissatisfied nor satisfied.

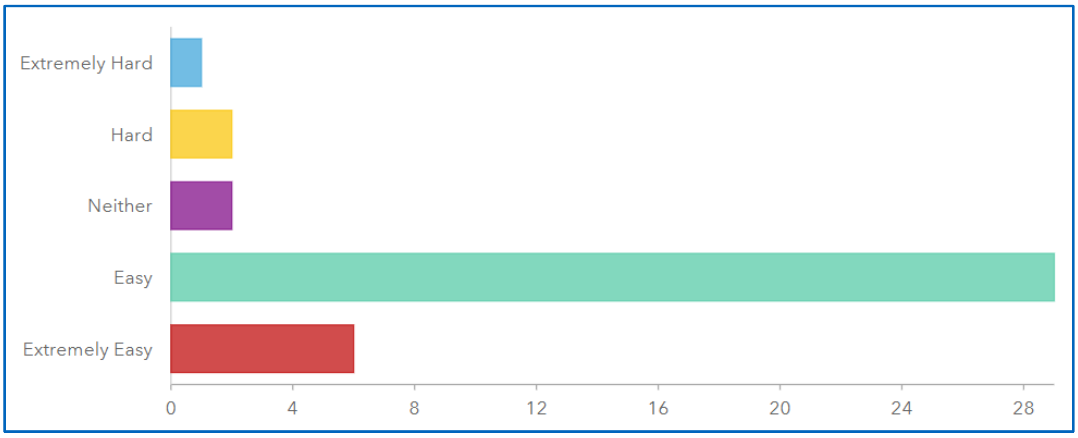


Figure 5-4. Results of the question "How convenient is for you to follow the route and reach the destination?"

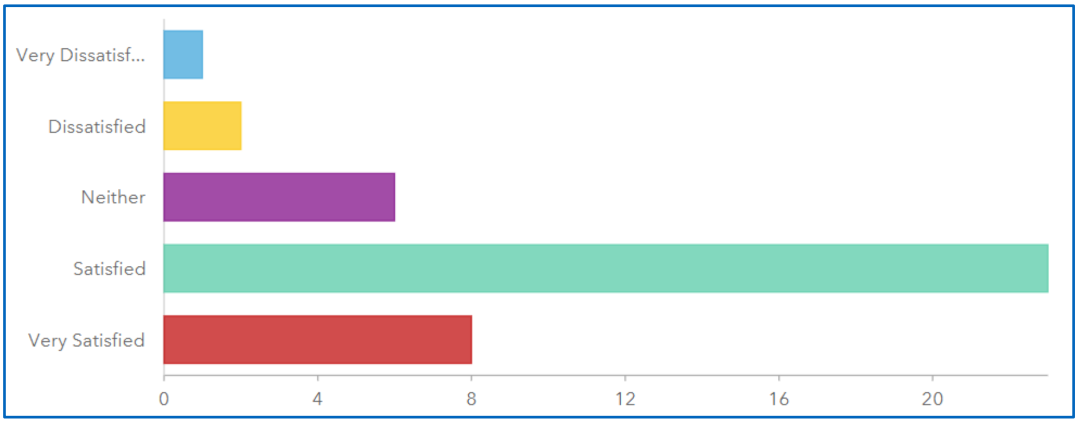


Figure 5-5. Results of the question "How satisfied are you with the 3D route representation?"

5.1.3 Map use

This section attempts to gather users' opinion regarding the advantage of representing indoor navigation system in a 3D map perspective and if they would like to use such models for completing indoor navigation tasks. The participants were asked to evaluate the developed campus routing system for the TUM main campus and to provide additional feedback regarding aspects that need to be improved.

For the question regarding the biggest advantage of a 3D map representation for indoor navigation systems several options were provided:

- Realistic representation of real world objects and features.
- Representation of vertical structures (walls, doors, stairs, etc.).
- Transition between floor levels.
- Recognition of surrounding objects (doors, passages, etc.).
- Directions (left, right, up and down).

In addition to these proposed alternatives, users' were able to propose other alternatives by choosing the option "*other*". The results of this question are illustrated in the figure 5-6 below. Nearly 50% of the test persons chose the realistic representation of the real world object as the biggest advantage. The representation of vertical structures (walls, doors, stairs, etc.), transition between route segments, and direction (left, right, up, and down) were chose as the second advantage, by nearly 45% of participants.

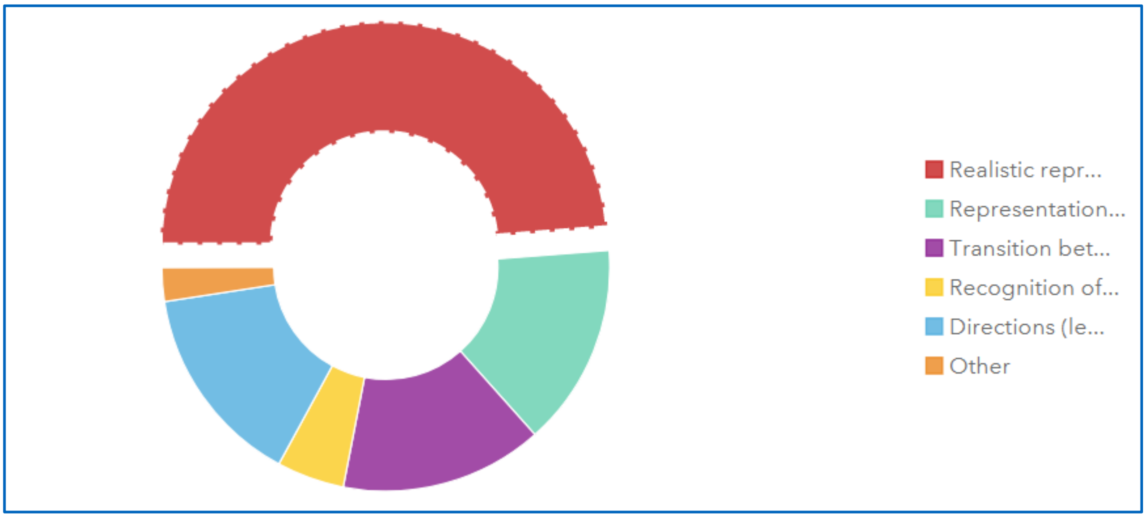


Figure 5-6. The biggest advantage of a 3D map representation for indoor navigation systems

The representation of indoor spaces in an interactive 3D map perspective is gaining significant importance nowadays. Therefore, users' were asked to provide their opinion if they would like to use interactive 3D maps for indoor navigation purposes (figure 5-7), and if they would prefer to use these interactive 3D models instead of conventional 2D maps for indoor navigation purposes (figure 5-8).

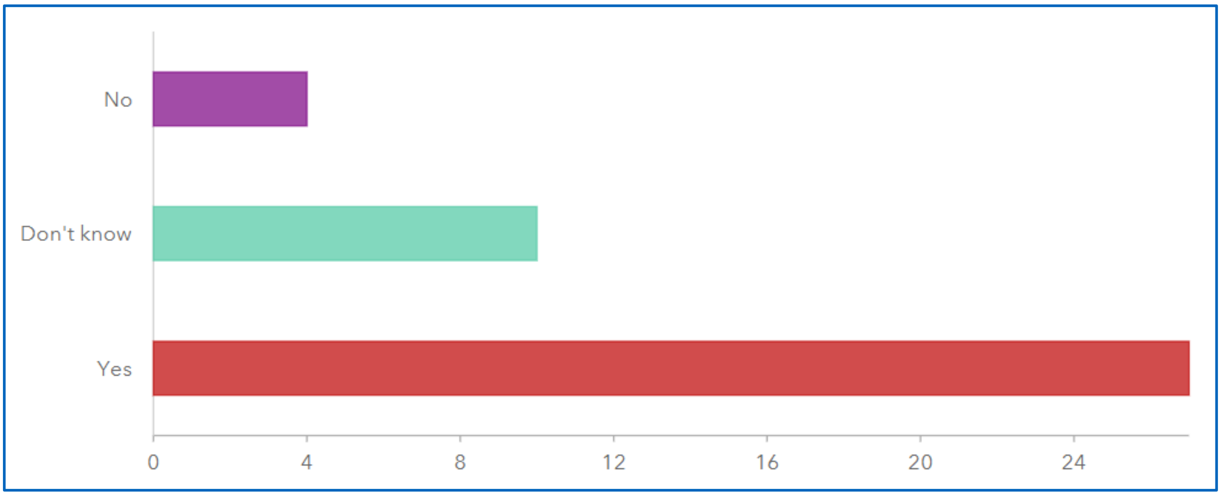


Figure 5-7. Results of the question "Would you like to use interactive 3D maps for indoor navigation?"

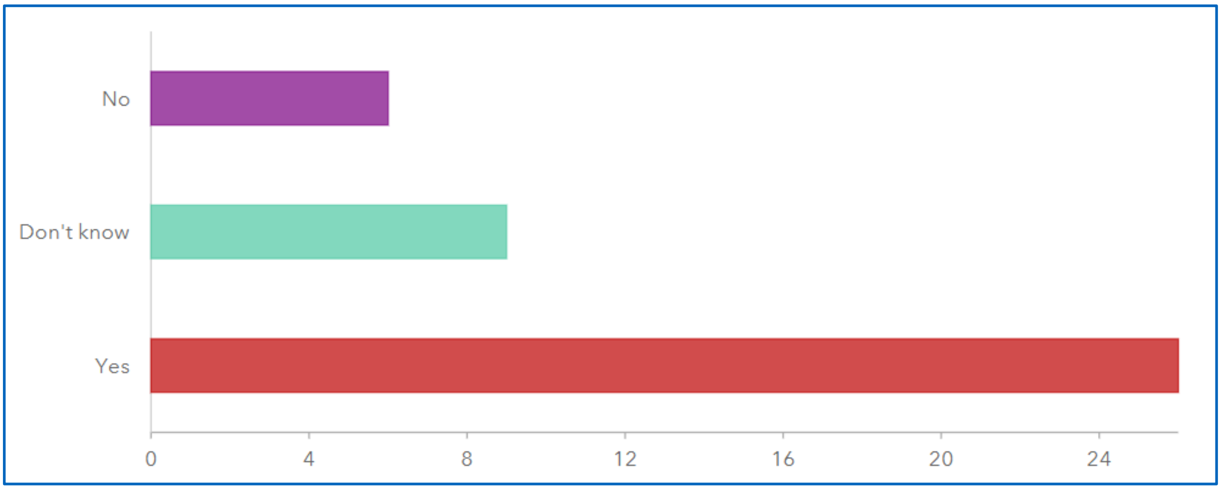


Figure 5-8. Results of the question "Would you prefer using interactive 3D maps instead of conventional 2D maps for indoor navigation?"

The participants who responded in favour of using interactive 3D maps for indoor navigation were equally divided between male and female participants. Only two male and one female responded that they would not use interactive 3D maps for the indoor navigation. The reasons were related to the complexity of 3D maps in general and that they would need to download the application to use it indoors.

Before providing feedback concerning further improvements, the users' were asked to evaluate the developed CRS for the TUM main campus based on the pictures provided along the questionnaire. The results of this question are illustrated below (figure 5-9), and 50% of the users' evaluate the developed model as "Above Average".

Figure 5-9. Results of the question "Based on what you have seen within this survey, how you would evaluate the developed campus routing model of TUM?"

After gathering feedback from this first user study regarding map design and map usage of the TUM CRS based on experts' opinion, the final version of the TUM CRS was developed based on these opinions. The final version of the TUM CRS is developed based on the following experts' opinions:

- Doors are visualized with a level of transparency, where the route is always visible
- Interior features are extruded to 1m height to allow a visualization of the whole route and visible floorplan
- Stairs and stair handlers are visualized in a 3D representation to facilitate users' indoor navigation among floor levels
- The textured model of the building is used as the main view of the TUM CRS, and when the users generate a route the exterior walls of the building will be transparent
- Two different colours are used to communicate the route that follows the stairs and elevators. Each colour is based on the TUM corporate design colours

To test the effectiveness and efficiency of the final version of the TUM CRS a second user study was conducted, whose result will be illustrated in the following subchapter.

5.2 Second evaluation: Usability and utility

The purpose of this user study is to evaluate the usability and utility of the developed CRS for the TUM main building. It aims to measure the effectiveness and efficiency of the TUM CRS based on users' interaction and experience with the model. A mixed-method of quantitative and qualitative data was adopted for this evaluation. The user study was built in two main parts: (1) an *user experiment* conducted within the premises of the TUM main campus building, (2) a *questionnaire* form to gather feedback provided after finishing the experiment. The results of both parts will be explained in the following two subchapters.

5.2.1 User experiment

The user experiment was designed based on providing a task. According to the task the users' needed to identify their position in the building by using structural features as orientation points. All the five users were able to identify their position, which was used later as a starting point of the route. The next step was to lock the destination "*Voerholzer Forum*" identified with the space number *5190*. To do so users had to make use of the search panel on the developed CRS. Having the starting point and the destination users generated a route that follows the stairs (figure 4-20, chapter 4).

As part of the thinking aloud adopted method, the users were asked to describe what direction they had to follow to reach the destination. The most used terms during the navigation process were "*now I have to go straight, take the stairs, turn right and then right again, follow the hallway, take the stairs up, etc.*" In addition, to thinking aloud users were asked to determine their position related to other structural features (stairs, doors, and stair handlers) as they moved along the route. Using these proposed landmarks, all the users were able to identify their exact location, even though the CRS does not offer the option of indoor positioning. As part of the *user observation method*, users were using the system every time they reached a decision point that required going up or down, or turning left or right. To determine their next move, they used the zooming, panning and rotation functions of the model. The result of the experiment, regarding the user interaction with the system, as well as the process of following the route are illustrated on the questionnaire that they had to fill out after finishing the experiment. The results of this user study will determine the effectiveness, efficiency and the user satisfaction with the developed CRS for the TUM main campus. These results are presented in the following subchapter.

5.2.2 Questionnaire

After completing the task, users' were asked to complete a questionnaire in order to gather feedback from their interaction with the TUM CRS. The questionnaire was divided in three major parts: (1) *general questions*, (2) *interface design*, and (3) *map and route design*.

General questions

The questionnaire section of general question aims to gather information and getting to know users' background with 2D and 3D maps for navigation and how often do they use these maps to enhance their wayfinding process. Five participants took part in the users study, 3 males and 2 females. The participants were recruited with the precondition to be considered as first time visitors. The test persons have different backgrounds: cartography, environmental geography, geospatial technologies, photography/arts, and psychology. The predominant occupation is student (3 participants) studying at the TU Dresden and University of Bayreuth. Regarding the question, "how often they use maps for outdoor navigation" the answers were frequently (three participants) and very frequently (two participants). While when it comes to the question of using maps for indoor navigation the answers were in the opposite side, two answered with never, two very rarely, and one rarely. The types of maps used for indoor navigation were university campus navigator (TU Dresden campus navigator, also described in this thesis), google maps when the indoor maps are available and university floorplans. In addition, users were asked to rank their navigation skills in unfamiliar environments and the predominant answer was "good" (four participants), and "excellent" (one participant).

Interface design

Before starting the experiment users were asked to interact with the developed model for approximately five minutes. The purpose was to measure users' interaction with the product. In addition to the prior interaction with the interface, upon entering the TUM main building users were asked to use the interface to generate the given route as part of the proposed scenario. The designed questions to measure the interface design and the participant results based on Likert scale are illustrated in table 5-2.

Statements	Results
The general information on how to use the developed indoor navigation system was relevant and useful	40% 60%
The search box to find an indoor space was easy to use	60% 40%
The process to generate a route between two spaces was easy to handle	60% 40%
The integrated buttons and their tooltips were needed and helpful to use the system	80% 20%
The TUM indoor navigation system helped me to be more effective while navigation in indoor spaces	80% 20%
I found the TUM indoor navigation system easy and simple to use	60% 40%
The TUM indoor navigation system requires a minimum number of steps to complete the task	40% 60%
I learned to use the TUM indoor navigation system quickly and remember how to use it	60% 40%
I am satisfied with the TUM indoor navigation system and it is pleasant to use it	60% 40%
The graphical user interface is clearly arranged and user friendly designed	60% 40%

Strongly agree   Agree   Neutral   Disagree   Strongly Disagree

Table 5-2. Users' feedback regarding interface design questions

Based on the users' opinion gathered for the above statements, the following is concluded for the interface design of the TUM CRS:

- *The general information provided on how to use the TUM CRS is relevant and useful*
- *The search box to find an indoor space I easy to use*
- *The process to generate a route between indoor spaces is easy to handle*
- *The buttons and tooltips are needed and helpful to use the CRS*

The interface section concludes with the question if the users' would like to use a similar indoor navigation system for other indoor spaces in the future. All the participants replied with yes to this question, based on their interaction experience with the TUM CRS.

Map and route design

When it comes to indoor navigation systems, the route planning and route communication elements constitute the most important parts of a CRS. The route planning uses the shortest path, and the route information is conveyed to users in a 3D map perspective. As a result, this section covers questions related to route design visualized in a 3D campus routing system. Due to the lack of indoor positioning systems in the developed CRS, this section contains questions regarding the presence of indoor structural features that are used as indoor landmarks. The participants were asked to provide feedback based on a Likert scale, illustrated in table 5-3.

Statements	Results	
I could visualize the whole route from the starting point to the destination	100%	
The map was easy to understand and I knew right away which way I had to go	100%	
I was always sure if I had to turn left or right	80%	20%
I was always sure if I had to walk up or down	100%	
I was always sure on which floor I currently was	80%	20%
The route guidance was unmistakable	60%	40%
I had no problems at all finding my way	100%	
Floor transition elements (stairs, stair handlers) were clearly marked on the map	80%	20%
Doors and hallways were clearly marked on the map	60%	40%
The presence of landmarks was in the right amount	100%	
I would like to use this kind of map in the future for indoor navigation	60%	40%

Completely agree — Agree — Disagree — Disagree completely

Table 5-3. Users' feedback regarding map and route design questions

Based on the above statements regarding map and route design, users' responded that the map was easy to understand and they knew right away which way they had to go, and all the users' reached the destination without any problem.

As part of the route and map design section, participants were asked to identify the most useful visual or structural element that facilitated their indoor navigation process. A list of options was provided for this question:

- Doors
- Walls
- Stairs and stair handlers
- Colour coding of indoor spaces
- Other

All the five participants found stairs and stair handlers as the most useful visual structure during the indoor navigation process.

The results of both evaluations conducted for this thesis will be used as the foundations for the following subchapter. These results and findings will be used to answer the research question on which this thesis is based on.

5.3 Summary and conclusion of results

An empirical research to evaluate the map design and visualization method of interior spaces as well as the usability and utility of the developed CRS was used. The purpose of this method was to answer the two research questions of this thesis, which are stated here again:

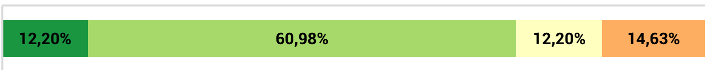
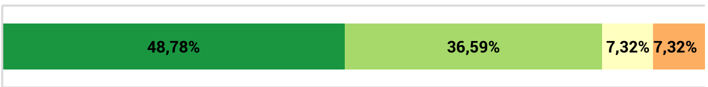
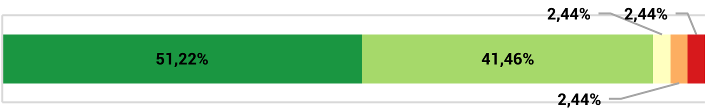
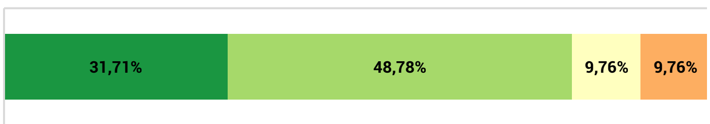
- *What map design principles and visualization techniques are appropriate for a campus routing system?*
- *What map elements, navigation network elements, and user interactions are needed for an effective and efficient campus routing system?*

To answer the research questions, a literature review was performed, and a case study for the TUM campus developed. Two user studies were designed and conducted by adopting different methods as described in the methodology chapter (chapter 3). The first user study aimed to test whether the applied designed principles for the modelling of indoor spaces realized in the case study were appropriate based on experts opinion and what can be further improved. The second user study aimed to evaluate the effectiveness, efficiency and user satisfaction with the developed CRS for the TUM based on the design principles drawn from the first evaluation. Therefore, the design of the second test (experiment and questionnaire) is focused on the usability and utility of the developed CRS. A summary and conclusion of the findings from these two evaluations are presented in the following subchapters.

5.3.1 First evaluation: Map design and visualization

Based on the results of the user study conducted by Lorenz et al. (2013), 3D maps have a considerable advantage for an indoor navigation system where a realistic perspective, smooth transition between floor levels, representation of vertical and horizontal structures, and recognition of surrounding objects like doors and passages, is of crucial importance. 3D maps seems more appropriate for the representation of the vertical structures in an indoor environment as they can visualize height information as well as 3D object such as stairs, star handlers, doors, etc.

The TUM CRS is based on existing floor plan lines. Before visualizing these floorplans data pre-processing steps were performed. First, the floorplans are generalized for the data processing steps. This involves the selection of relevant architectural structures, geometric simplification, and removal of non-necessary indoor data for an indoor navigation system. Second, these generalized floorplans were used to create an indoor GIS, which served as the base for the indoor route planning and communication. Various design principles were used to visualize the indoor features, and an evaluation was performed to gather users' opinion for the applied design. Questions related to applied design for the indoor features, and the expert opinion is presented in the table 6-1.

<table>
<tr><th>Statements</th><th>Results</th></tr>
<tr><td>Transparent doors represent better visualization option than opaque doors</td><td>
</td></tr>
<tr><td>Walls and doors extruded to 1m represent better visualization option than extruded to the ceiling</td><td>
</td></tr>
<tr><td>The 3D visualization of floor transition elements (stairs and stair handlers) represent a better option than a 2D visualization</td><td>
</td></tr>
<tr><td>To visualize the whole route from the start point to destination, a fully transparent visualization of the exterior walls represents a better option than a textured model of the building</td><td>
</td></tr>
<tr><td>Using different colours to differentiate the route that follows stairs and/or elevators will increase the users' understanding of the route and will improve the navigation</td><td>
</td></tr>
</table>

Strongly agree · Agree · Neither · Disagree · Strongly Disagree

Table 5-4. Map design statement related to visualization of indoor features and expert opinion

Based on the experts' opinion gathered for the above statements, the following is concluded for the visualization of indoor features:

- *It is preferable to represent the doors with a level of transparency as they represent features that allow the movement of users in the indoor spaces.*
- *To visualize the whole route and to be aware of the surroundings, the walls and doors should be extruded to a certain height.*
- *A transparent visualization of exterior walls should be used when users will generate a route between indoor spaces.*
- *Different colours should be used when the route follows the stairs or elevators. Based on various suggestions, these colours should be carefully chosen (i.e., the red colour should be avoided as it might indicate an emergency).*

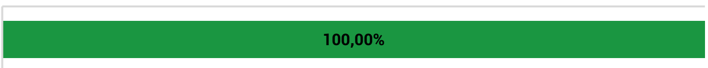
For the visualization of indoor spaces, the majority of experts were in favour of using a combination of colour scheme and symbols (58.54%). The rest was divided between using only a colour scheme (26.84%) and using only symbols (14.63%). However, for the final version it was decided to use only a colour scheme, as it will minimize the cognitive load of users. In addition, users will be able to search for a space not only by the space number, but by its space function as well. By using these design principles, a final model for the TUM CRS is developed and its usability and utility results will be discussed below.

5.3.2 Second evaluation: Usability and utility

The results of the usability and utility evaluation are used to measure the effectiveness, efficiency and users' satisfactions with the developed model for the indoor navigation process. In addition, the results of this evaluation will serve as the basis to prove whether the proposed hypothesis stand for this thesis:

- *Users can navigate in indoor campus environments with only a few or no landmarks, as long as the map design is intuitive and the route planning as well as the route representation avoid confusions among the users.*
- *It is possible for the users to reach their destination in indoor campus navigation systems without the aid of indoor positioning and orientation techniques.*

To measure the effectiveness, efficiency and users' satisfaction, a set of questions were designed to gather users' opinion after their interaction with the model, illustrated in table 5-5.

Effectiveness	Results
The TUM indoor navigation system helped me to be more effective during the indoor navigation task	
The map was easy to understand and I knew right away which way I had to go	

Statement	Strongly agree	Agree
The route guidance was unmistakable	60,00%	40,00%
I had no problems at all finding my way	100,00%	
Efficiency		
I found the TUM indoor navigation system easy and simple to use	60,00%	40,00%
The TUM indoor navigation system requires a minimum number of steps to complete the task	40,00%	60,00%
Users' Satisfaction		
I am satisfied with the TUM indoor navigation system and it is pleasant to use it	60,00%	40,00%
The graphical user interface is clearly arranged and user friendly designed	60,00%	40,00%
I would like to use this kind of map in the future for indoor navigation	60,00%	40,00%

Strongly agree | Agree | Neither | Disagree | Strongly Disagree

Table 5-5. Results of effectiveness, efficiency and users' satisfaction with the TUM CRS

Based on the opinion of the first time visitors gathered for the above statements, the following is concluded for the effectiveness, efficiency and users' satisfaction with the TUM CRS during the interaction:

- *Effectiveness: The TUM CRS helps users for a more effective indoor wayfinding process as they did not manifest any problems during the task and reached the destination easily.*
- *Efficiency: The TUM CRS represent an easy and simple to use indoor navigation system and requires a minimum number of steps to generate an indoor route.*
- *Users' satisfaction: The TUM CRS represent a pleasant indoor navigation app with a user friendly interface.*

Landmarks presence

Lorenz et al. (2013) state that presenting the indoor route without context would make it difficult to find one's way in a building. Therefore, the readers needs a certain minimum level of context information to link the map to the reality. In an indoor environment, several objects can be used as *natural landmarks* such as fire extinguishers, garbage cans, etc. In contrast to natural landmarks, several object can be installed in the building to facilitate users' indoor navigation. These objects are classified as *artificial landmarks*. The TUM CRS developed for this thesis is based in a minimum number of landmarks used. The landmarks that are used in this model are architectural structures such as doors, walls, stairs and stair handlers.

A set of statements were designed to test whether this minimum number of structural landmarks is acceptable and allows an effective and efficient campus routing. These statements are illustrated in the table 5-6 below.

Statements	Results
Floor transition elements (stairs, stair handlers) were clearly marked on the map	80,00% 20,00%
Doors and hallways were clearly marked on the map	60,00% 40,00%
The presence of landmarks was in the right amount	100,00%
The route guidance was unmistakable	60,00% 40,00%
I had no problems at all finding my way	100,00%

Strongly agree Agree Neither Disagree Strongly Disagree

Table 5-6. Statements related to the presence of landmark in the developed CRS

Based on the opinion of the first time visitors gathered for the above statements, the following is concluded for the presence of structural landmarks in the TUM CRS:

- *Floor transition elements (stairs and stair handlers) as well as doors and hallways are clearly marked on the TUM CRS.*
- *The presence of structural landmarks is in the right amount and allows an effective and efficient indoor navigation.*

Indoor positioning and orientation

Fallah et al. (2013) state that despite the latest developments and technological achievements, localization and orientation remain one of the biggest challenges that indoor navigation systems are facing. In addition, the existence of various indoor localization techniques with their benefits and drawbacks poses further obstacles to their implementation. Furthermore, currently none of these techniques have achieved large-scale deployment due to issues with cost, accuracy, and usability.

Due to these factors, the developed campus routing system for the TUM does not offer the possibility of localization and orientation to the users. Therefore, the users' will have to rely on visualized spatial structures such as doors, walls, windows, stairs, stair handlers, etc., to identify their position and to navigate within the TUM building. Table 5-7 illustrates whether it is possible for the users to navigate in indoor spaces without the aid of positioning and orientation techniques.

Statements	Results
I could visualize the whole route from the starting point to the destination	100,00%
The map was easy to understand and I knew right away which way I had to go	100,00%
I was always sure if I had to turn left or right	80,00% 20,00%
I was always sure if I had to walk up or down	100,00%
I was always sure on which floor I currently was	80,00% 20,00%
I had no problems at all finding my way	100,00%

Strongly agree Agree Neither Disagree Strongly Disagree

Table 5-7. Statement related to the lack of indoor positioning and orientation techniques

Based on the opinion of the first time visitors gathered for the above statements regarding the lack of indoor positioning and/or orientation techniques on the TUM CRS, the following is concluded:

- *The map design and visualization of indoor spaces for the TUM CRS is intuitive and the user understands immediately which way has to go to reach the destination*
- *With the help of structural landmarks user knows which way has to go (left or right, up or down) in order to reach the destination. Furthermore, the user can identify its position at any time in the indoor space.*

It can be finally concluded, that the TUM campus routing system is an indoor navigation application, which makes use of structural features to plan and convey the route to various users in an effective and efficient way. The tested users expressed that they were satisfied with the 3D model and would like to use it for other university campuses and/or indoor complex building such as shopping malls, airports, etc.

6 Discussion

The main goal of this thesis was to *design and develop a web campus routing application that facilitates orientation and navigation of various user groups (students, staff members, and visitors) on the TUM main campus. Based on the goal two research questions were proposed for this thesis, which are stated here again:*

- *What map design principles and visualization techniques are appropriate for a campus routing system?*
- *What map elements, navigation network elements, and user interactions are needed for an effective and efficient campus routing system?*

To answer the research questions, a literature review was performed, and a case study for the TUM campus was developed. Two user studies were designed and conducted by adopting different methods as described in the methodology chapter (chapter 3).

The process of literature review was focused on indoor navigation systems and their components, indoor data visualization, evaluation of interactive web map applications, and existing campus routing applications. However, the literature review on developing and designing a CRS is meagre due to missing literature and only little research that has been conducted in this specific field until now. Additionally the number of exciting CRS taken into consideration to perform an interactivity evaluation could be expanded and more CRS should have been evaluated to identify functionalities that an indoor navigation system should provide.

The technology adopted for the case study is entirely based on Esri software products. It should be clear that the steps proposed in the methodology chapter (chapter 3) for the creation of a CRS could be generated by using any GIS software, either commercial or open source. The developed CRS for the TUM main campus visualizes the indoor spaces by using a visual variable, colour. More literature review is needed to identify how and what visual variables should be applied for each interior space based on their type and what colour is better perceived by users during the indoor navigation process. Furthermore, the integration of a legend would be helpful for the users to identify what each colour represents. In addition, the amount of manual work needed to complete the data pre-processing step was very high. More research is needed to identify if there exist other means of visualizing indoor steps without having to go through the amount of manual work.

As mentioned in chapter 4, two user studies were designed and conducted for this thesis. The first user study aimed to test whether the applied designed principles for the modelling of indoor spaces realized in the case study were appropriate based on experts' opinion and if they needed further improvements. Forty-one participants, mostly with a cartography and geography background, filled out the survey. The questionnaire was built in the form of statements, where users provided their opinion based on a Likert scale after comparing two images. Due to the fact that the developed model was a 3D interactive model, comparing static images did not provide the best feedback from users. Therefore, a better method to design the questionnaire would have been to provide users with access to the model and then gather their feedback. In addition to the expert-based method, the user-based method might be helpful to test the developed CRS for the TUM main campus. This method could have provided feedback from users' who benefit directly from a CRS and can provide valuable insights if the model addressing their everyday challenges with the indoor wayfinding.

The second user study aimed to evaluate the effectiveness, efficiency and user satisfaction with the developed CRS for the TUM based on the design principles drawn from the first evaluation. Therefore, the design of the second test (experiment and questionnaire) was focused on the usability and utility of the developed CRS. A drawback of the designed experiment was that the users had to use a laptop to navigate with the model, and stop during the route to find a suitable place to interact with the model and identify their position. This process could have been much easier if the TUM CRS would be available as a mobile application. The number of test persons recruited for the task was five participants, which is rather a smaller number to make statistical evaluations. In addition to the first time visitors used for this evaluation, everyday users could have been taken into consideration. In this case, a comparative study could have been performed, which would have provided feedback how the prior knowledge of the building architectural structure affects the indoor wayfinding task. Furthermore, everyday users represent a target group that can identify better the functionalities that the TUM CRS should provide to facilitate the indoor navigation in this specific campus

Based on the literature review, and the results and findings of the user studies the answer to the research questions of this thesis is presented:

Campus routing systems need to be visualised as interactive 3D application to allow a realistic perspective of horizontal and vertical structures and a smooth transition between building floors. The structural interior features are used for the route planning and route communication to generate an effective and efficient point-to-point indoor routing network that covers every walkable area. A user-friendly interface design that allows zooming, panning, rotating, querying and generating an indoor route with minimum steps increases users' satisfaction with the 3D CRS.

7 Research findings and future work recommendations

In this thesis, the elements of an indoor navigation system as well as the medium to visualize indoor spaces are summarized. The process of literature review identified the 3D map perspective as the most appropriate visualization medium to represent indoor spaces in an indoor navigation application. Additionally these systems should be presented to the users in the form of interactive online web map applications. Therefore, the exemplarily developed CRS for TUM main campus is a 3D web map application designed to facilitate the indoor navigation process of various user groups. The TUM CRS represents a cartographically appealing web application consisting of a neat representation of the TUM main building and the categorization of its structural features, representation of the surrounding area, and a set of functionalities well arranged in the context of interface design.

A methodology is proposed to generate a CRS that focuses on university campuses, but could be applied to other campuses, including shopping malls, airports, etc. This methodology presents all the steps needed, starting from data pre-processing, data processing, software that can be used, and finally deploying the web application to make it accessible for the users. In addition, several methods are listed as possible methods to evaluate the design and visualization aspects of a CRS as well as its effectiveness and efficiency.

The methodology steps are applied in practice to develop the TUM CRS. This indoor navigation system makes use of the raw CAD files to create a 3D web application. A detailed description of the steps carried out to create the TUM CRS is provided. In addition, the GIS software chosen to complete the data pre-processing and processing steps is described. The GIS software used to generate and complete most of the steps is ArcGIS indoors, an indoor mapping platform provided by Esri. ArcGIS Indoors is built into two main parts: (1) ArcGIS Indoors built in as an ArcGIS Pro project, including all the necessary steps to complete the data processing steps, and (2) web application folder, which contains a set of folders used to create a web application template. The web application folder is based on the ArcGIS API for JavaScript 4.4, which is applied for the map and interface visualization process.

Further important elements described in this thesis are the user studies. Two user studies were carried out to evaluate the map design principles and visualization techniques as well as the effectiveness, efficiency and users' satisfaction with the developed TUM CRS. The user studies were based on methods proposed by Roth et al. (2017). The first user study aimed to evaluate whether the design principles and visualization techniques applied for the TUM indoor spaces were appropriate and cartographically appealing and what further improvements were needed. This user study was based on the expert-based method and gathered opinion from users with experience in map design and visualization. The purpose of the second user study was to evaluate the usability and utility of the developed CRS for the TUM main building. It aimed to measure the effectiveness and efficiency of the TUM CRS based on users' interaction and experience with the model. The evaluation process was based on the user-based method, which solicit input and feedback about an interactive map and interface from a representative set of target users. The first time visitors were chosen as the target group to test the developed CRS due to their lack of familiarity with the TUM building. Additionally, they were chosen, as they are the most unacquainted user group. Hence, if a visitor was able to use and navigate with the TUM CRS, it was assumed that the CRS is effective and efficient also for everyday users of the TUM premises (students and staff members).

Based on the experts' opinion gathered from the first evaluation, the following can be concluded for the visualization of indoor features:

- It is preferable to represent the doors with a level of transparency as they represent features that allow the movement of users in the indoor spaces.
- To visualize the whole route and to be aware of the surroundings the walls and doors should be extruded to a certain height.
- A transparent visualization of exterior walls should be used when users will generate a route between indoor spaces.
- Different colours should be used when the route follows the stairs or elevators. Based on various suggestions, these colours should be carefully chosen (i.e., the red colour should be avoided as it might indicate an emergency).

The results of the second user study were also used to answer the proposed hypotheses for this thesis. Based on the results of the second evaluation, the following can be concluded for the process of indoor navigation:

- Users can navigate in indoor environments with only a few or no landmarks as long as the map design, route planning and route communication is presented in an intuitive way.
- Users can navigate in indoor environments without the help of indoor positioning and/or orientation techniques. To complete the indoor navigation tasks user rely on the presence of structural features (doors, walls, stairs, etc.) to reach their destination.

Based on the results of the evaluation tests it can be concluded that the TUM campus routing system is an indoor navigation application, which makes use of structural features to plan and convey the route to various users in an effective and efficient way. The tested users expressed that they were satisfied with this model and would like to use it for other university campuses and/or indoor complex buildings such as shopping malls, airports, etc. However, there are some shortcomings of this study in the design and visualization of indoor spaces, map evaluation and methodology as well as the area taken as a case study and components of an indoor navigation system. Therefore, the future research work should focus on overcoming the followings aspects:

- Further research is needed in the correlation between the symbology that should be applied to indoor spaces and the intended use of space.
- Various evaluation methods in the design and visualization phase should be applied, as well as testing the model with a wide range of users is recommended.
- A better observation of the user behaviour while using the model to navigate can be done and documented. .
- A CRS that connects all the building of the TUM main campus into one indoor navigation system can be created. Furthermore, more research is needed on how all the TUM campuses in Munich can be integrated in one CRS application (generalization, navigation between different buildings with different structure etc.).
- In addition to the 3D web map application, a mobile application should be deployed in the future.
- The position and orientation functions for users should be enabled. This can be done with the help of additional services offered as external services with the help of APIs.

This thesis represent a step forward towards innovative design and visualization approaches for complex campus buildings to create effective and efficient user-oriented and user-friendly campus routing systems that will facilitate the indoor navigation process.

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NOTE: All online resources were last accessed on 14th of September 2018.

Annex 1 – JavaScript API file

config.js

```
/*
| Copyright 2016 Esri
|
| Licensed under the Apache License, Version 2.0 (the "License");
| you may not use this file except in compliance with the License.
| You may obtain a copy of the License at
|
| http://www.apache.org/licenses/LICENSE-2.0
|
| Unless required by applicable law or agreed to in writing, software
| distributed under the License is distributed on an "AS IS" BASIS,
| WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
| See the License for the specific language governing permissions and
| limitations under the License.
*/
define(function() {

    return {

        app: {
            headerTitle: "Campus Routing System",
            logoImage: "app/images/tum_logo.GIF",
            headerLink: "http://www.tum.de"

        },

        //PORTAL URL
        portalUrl: '//tu-muenchen.maps.arcgis.com',

        //WEB SCENE ID
        webSceneId:  "0b5472b542184111a1084bb0f173c1fb",

        // PROXY
        // proxyUrlPrefix: "",
        // proxyUrl: "",


        //NAME FOR INTERIOR SPACES/ROOMS(TO IDENTIFY SPACES LAYER IN A GROUP LAYER)
        spaceLayerStringIdentifier: "Interior_Spaces",

        //FLOORPICKER
        floorPickerInfo: {
            1 :  { buttonLabel: "EG", value: "1"},
            2 :  { buttonLabel: "1OG", value: "2"},
            3 :  { buttonLabel: "2OG", value: "3"},
            4 :  { buttonLabel: "3OG", value: "4"},
            5 :  { buttonLabel: "4OG", value: "5"},
            6 :  { buttonLabel: "5OG", value: "6"}
        },

        //HERE, LAYER NAME IS THE NAME OF LAYER AS SEEN IN TOC OF SCENE VIEWER
        floorsLayers: {
          "all": [
                { layerName: "Interior_Spaces", floorNumberFld: "FLOOR", floorIDFld: "FLOORKEY"},
                { layerName: "Floorplan_Doors", floorNumberFld: "FLOOR", floorIDFld: "FLOORKEY"},
                { layerName: "Floorplan_Walls", floorNumberFld: "FLOOR", floorIDFld: "FLOORKEY"}
            ]
        },

        // FIELD SPECIFYING FLOOR NUMBER
        floorField: "FLOOR",

        // DEFAULT PLACEHOLDER FOR SEARCH WIDGET
        allSearchPlaceholder: "Find people or places",

```

config.js

```
        //SEARCH INFO
        searchInfo: {
            1 :  {
                name: "Rooms",
                dropdownSearch: {
                    placeholder: "Search for rooms",
                    queryUrl: "https://services1.arcgis.com/DbPykcCwUUYq5zKq/ArcGIS/rest/services/Space_Points/FeatureServer/0",
                    queryFields: ["LONGNAME"],
                    suggestionTemplate: "{LONGNAME} ({SPACETYPE})"
                },
                outFields:["OBJECTID", "LONGNAME", "SHORTNAME", "FLOOR", "SPACEID", "BUILDING", "SPACETYPE", "FLOORKEY" ],

                // associated info (Instead of Related Tables)
                associatedInfo: {
                  //url: "http://services2.arcgis.com/z2tnIkrLQ2BRzr6P/ArcGIS/rest/services/EmployeeInfoPt_2017F/FeatureServer/0",
                  url: "https://services1.arcgis.com/DbPykcCwUUYq5zKq/ArcGIS/rest/services/BuildingInteriorSpace_People/FeatureServer/0",
                  outFields:["KNOWNAS", "EMAIL", "EXTENSION"],
                  queryField: "LONGNAME",      // for this layer query
                  queryFieldType: "TEXT" ,    //or number
                  matchingQueryField: "LONGNAME",    // for the dropdownSearch layer
                },

                // INFO DISPLAYED IN SIDE PANEL
                displayInfo: {
                    SPACETYPE: {class:"sp-info__subtitle", prefix:"", suffix:"" },
                    LONGNAME: {class:"sp-info__office" },
                    KNOWNAS: {class: "sp-info__name"},
                    EMAIL: {class:"sp-info__email" },
                    EXTENSION: {class:"sp-info__desc", prefix:"ext. ", suffix:"" }
                },

                // TEXT TO IDENTIFY CORRESPONDING SCENE LAYERS
                correspondingSceneLyrName: "Interior_Spaces",

                // SYMBOLOGY FOR SELECTED SPACE/ROOM
                selectionRendering: {
                    // this field is used to get label info
                    rendererField: "LONGNAME",

                    color: [231, 76, 60],
                    symbol: "\ue61d", //esri-icon-map-pin https://developers.arcgis.com/javascript/latest/guide/esri-icon-font/index.html
                    symbolColor: "#E37222",
                    symbolFont: {      // https://developers.arcgis.com/javascript/latest/api-reference/esri-symbols-Font.html
                                size: 30,
                                family: "CalciteWebCoreIcons"
                              },

                    labelColor: "#E37222",
                    labelFont: {
                                size: 25,
                                family: "sans-serif",
                                weight: "bold"
                              },
                    labelSymbolSpacing: "\n\n"

                }
            },

            2 :  {
                name: "People",
                dropdownSearch: {
                    placeholder: "Search for people",
                    //queryUrl: "http://services2.arcgis.com/z2tnIkrLQ2BRzr6P/ArcGIS/rest/services/EmployeeInfoPt_2017F/FeatureServer/0",
                    queryUrl: "https://services1.arcgis.com/DbPykcCwUUYq5zKq/ArcGIS/rest/services/BuildingInteriorSpace_People/FeatureServer/0",
                    queryFields: ["LONGNAME", "KNOWNAS"],
```

config.js

```
                suggestionTemplate: "{KNOWNAS} ({LONGNAME})"
            },
            outFields:["OBJECTID", "LOCATION", "LONGNAME", "BUILDING", "KNOWNAS", "EMAIL", "EXTENSION" ],

            // associated info (Instead of Related Tables)
            associatedInfo: {
              url: "https://services1.arcgis.com/DbPykcCwUUYq5zKq/ArcGIS/rest/services/Space_Points/FeatureServer/0",
              outFields:["SPACEID", "LONGNAME", "SHORTNAME", "FLOOR", "SPACETYPE", "FLOORKEY"],
              queryField: "LONGNAME",      // for this layer
              queryFieldType: "TEXT" ,    //or number
              matchingQueryField: "LONGNAME",    // for the dropdownSearch layer
            },

            // INFO DISPLAYED IN SIDE PANEL
            displayInfo: {
                SPACETYPE: {class:"sp-info__subtitle", prefix:"", suffix:"" },
                LONGNAME: {class:"sp-info__office" },
                KNOWNAS: {class: "sp-info__name"},
                EMAIL: {class:"sp-info__email" },
                EXTENSION: {class:"sp-info__desc", prefix:"ext. ", suffix:"" }
            },

            // TEXT TO IDENTIFY CORRESPONDING SCENE LAYERS
            correspondingSceneLyrName: "Interior_Spaces",

            // SYMBOLOGY FOR SELECTED SPACE/ROOM
            selectionRendering: {
                // this field is used to get label info
                rendererField: "LONGNAME",

                color: [231, 76, 60],
                symbol: "\ue61d", //esri-icon-map-pin https://developers.arcgis.com/javascript/latest/guide/esri-icon-font/index.html
                symbolColor: "#E37222",
                symbolFont: {      // https://developers.arcgis.com/javascript/latest/api-reference/esri-symbols-Font.html
                                size: 30,
                                family: "CalciteWebCoreIcons"
                              },

                labelColor: "#E37222",
                labelFont: {
                                size: 25,
                                family: "sans-serif",
                                weight: "bold"
                              },
                labelSymbolSpacing: "\n\n"

            }
        }
    },

    // HIGHLIGHT COLOR FOR SPACES
    defaultHighlight: {
        color: [0, 255, 255, 1],
        haloOpacity: 1,
        fillOpacity: 0.25
      },

    // SECONDARY COLOR FOR CLICKED SPACE
    spaceClickSecondaryColor: {
        color: [255, 255, 193, 0.5],
        outline: [255, 255, 21, 1]
    },

```

```
        // ROUTING INFO
        routingEnabled: true,

        routing: {
          filterFld: "FLOORKEY",
          taskUrl: 'https://portal03.eggits.net/server/rest/services/Routing/TUM_Campus_Routing/NAServer/Route',
          restrictions: {
              stairs: 'Prohibit: Elevators',
              elevator: 'Prohibit: Stairs'
          },

          // SYMBOLOGY
          // stairs route
          stairPathColor: [162,173,0],        //  [0,183,0],
          stairPathSize: 0.5,

          // elavator route
          elevatorPathColor: [0,101,189],
          elevatorPathSize: 0.5,

          // start/stop symbols
          startSymbol : {
              symbol: "\ue613",
              color: "#E37222",
              font: {
                      size: 25,
                      family: "CalciteWebCoreIcons"
                  }
          },

          endSymbol : {
              symbol: "\ue61d",
              color: "#E37222",
              font: {
                      size: 25,
                      family: "CalciteWebCoreIcons"
                  }
          },

          // vertical offset to place marker above route
          symbol_zOffset: 1,

          // offset for the rendered route
          path_xOffset: 0,
          path_yOffset: 0,
          path_zOffset: 1

        },

        // ZOOM-IN LEVEL FOR SEARCH
        viewZoom: 22,
        viewTilt: 35,

        // space/room rendering info from feature layers - first renderer specified here is the default renderer for search and routing
        // fieldname is required - rendering field in Spaces layer may be different from the url rendering field
        // slide name : [url, fieldname]
        spaceRenderersForWebSlide: {
            'Interior': ['https://services1.arcgis.com/DbPykcCwUUYg5zKg/ArcGIS/rest/services/Building_Interior_Spaces/FeatureServer/0',"SPACETYPE"]
        }

    };
});
```

Annex 2 – First evaluation: Map design and visualization

Design Principles and Visualization of Indoors Spaces for TUM

Dear participants,

Thank you for your time in completing this survey. This survey is part of my master thesis as a student of the Cartography master programme. The main goal of my thesis is to design and develop a campus routing system, as a web application, to facilitate the navigation of various user groups in indoor spaces. The study area used for this purpose is one of the buildings of the Technical University of Munich (TUM) main campus. The developed campus routing system can be used in desktop and mobile phone screens.

The purpose of this survey is to evaluate whether the applied design principles and visualization techniques for the indoor spaces are appropriate and what can be further improved. This survey should take approximately 20 min to complete, and it will be a great help for my work. If you are interested in the results of this thesis or if you have any further comments or suggestions I would be happy to hear from you.

NOTE: For detailed and larger images, please right click on the image and open it in a new tab. Due to storage restrictions, the maximum length of a comment in the text field is 250 characters.

Thank you for your help!

Armand KAPAJ

General questions

1. What is your gender?

- Male
- Female

2. What is your age?

- 18 to 24
- 25 to 34
- 35 to 44
- 45 or older

3. What is your highest educational level?

Select the highest level already achieved.

- Bachelor
- Master
- PhD
- Higher

4. What is your educational background?

Please comment below (e.g. Geography, Cartography, Geoinformation, etc.).

5. What is your occupation?

6. Have you ever been to TUM and do you know the main campus building at Arcisstrasse?

- ○ Yes
- ○ No

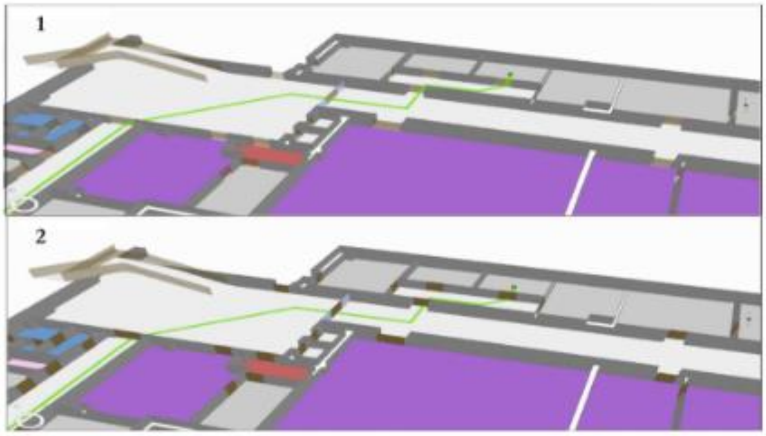
7. How often do you use interactive 3D maps on computer screens or on mobile phones?

○ Very Frequently ○ Frequently ○ Occasionally ○ Rarely ○ Very Rarely ○ Never

Map design

1. You would like to navigate to a specific space within the university building. Based on the figures below, two visualization options are possible:

- Figure 1: Transparent doors. The route to reach the destination is always visible, or
- Figure 2: Opaque doors. The doors are visualized as in reality.



Please give your opinion to the following statement: To reach the destination and to be aware of the route, the visualization shown in Figure 1 represents a better option.

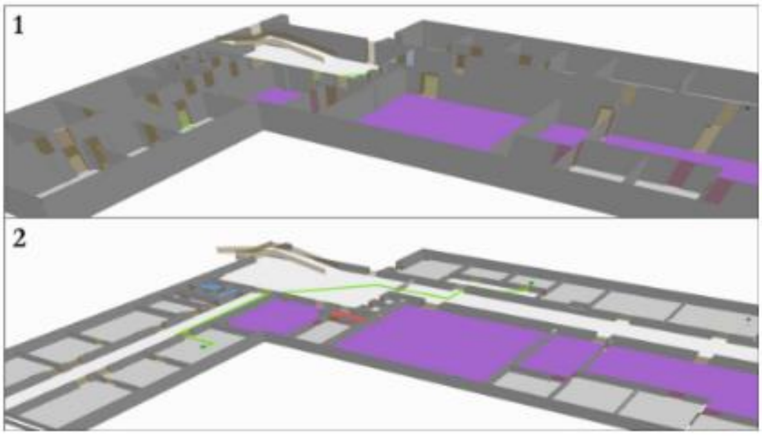
Strongly Agree | Agree | Neither | Disagree | Strongly Disagree

Comments:

In case of additional comments and/or suggestions, please type here.

2. Different methods exist for visualizing walls and doors in indoor spaces. One of these methods is to extrude walls and doors to a certain height level.

- Figure 1: Extrusion all the way up to the ceiling, which is a more realistic representation of the building walls, and
- Figure 2: Waist height extrusion (1 m), where the route, destination and floor-plan view is visible.



Please give your opinion to the following statement: To visualize the whole route and to be aware of the surroundings, the visualization shown in Figure 2 represents a better option.

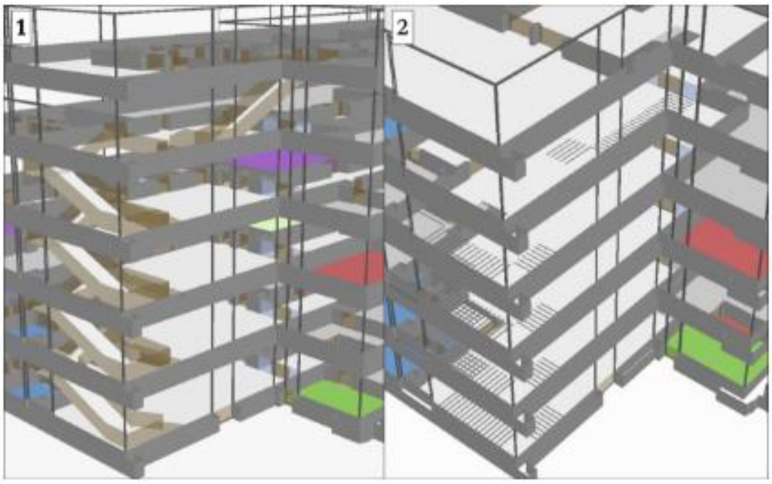
Strongly Agree | Agree | Neither | Disagree | Strongly Disagree

Comments:

In case of additional comments and/or suggestions, please type here.

3. The floor transition elements (stairs, stair handlers) can be visualised in two ways:

- Figure 1: 3D representation. Stairs are shown in a white colour, while the stair handlers are shown in transparent brown colour.
- Figure 2: 2D representation. Stairs are shown by horizontal lines on the floor.



Please give your opinion to the following statement: To navigate among different floor levels, the visualization of the floor transition elements (stairs and stair handlers) shown in Figure 1 represents a better option.

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree
○	○	○	○	○

Comments:

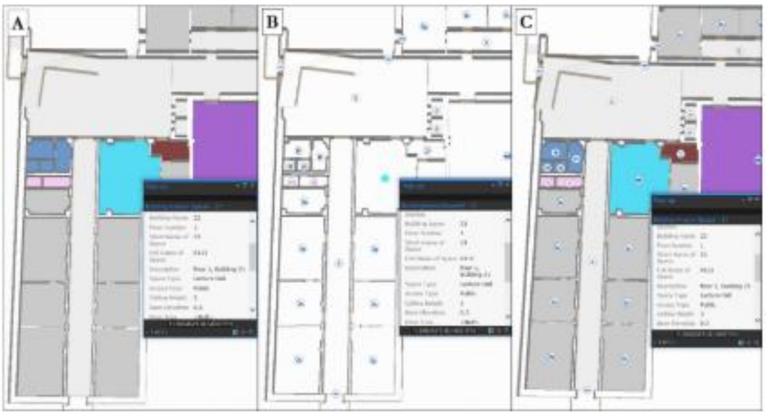
In case of additional comments and/or suggestions, please type here.

4. The indoor spaces in a campus routing system can be visualized using three different methods:

- Figure 1: Representation of the indoor spaces based on a qualitative colour scheme,
- Figure 2: Representation of the indoor spaces based on symbols, or
- Figure 3: Representation of indoor spaces based on a combination of both: colours and symbols.

Note:

- The different colours showing the following indoor spaces: light grey - hallway and passage; dark grey - office; blue - WC men; pink - WC women; purple - lecture hall, seminar room, lab, and meeting room; brown - storage, IT, monitoring.
- Symbols are chosen to be self-explanatory of the indoor space type they represent, e.g. typical WC symbol.



Please give your opinion to the following question: Which design method do you think is better to visualize indoor spaces and their intended usage?

○ A

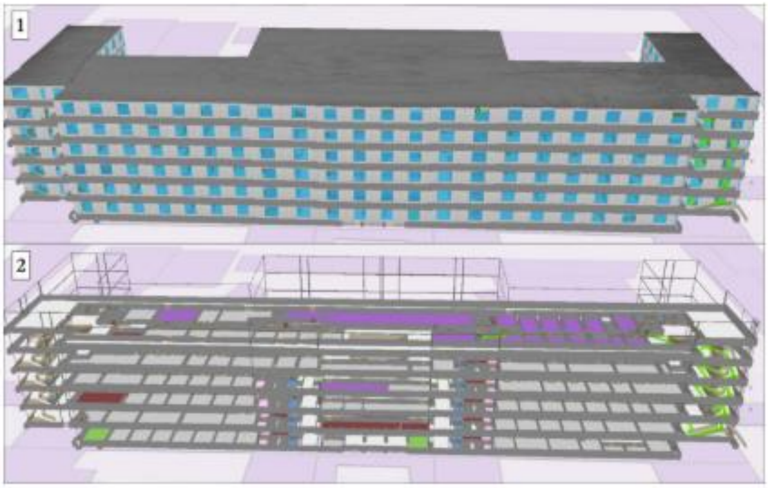
○ B

○ C

○ None

5. The final product of the TUM campus routing system is a web application. Users will be able to switch between two different views:

- Figure 1: Textured model of the TUM main campus building.
- Figure 2: Fully transparent representation of the building's exterior walls. The interior walls are extruded to a waist height, which allows users to have a clear understanding of barriers and the whole floor-plan.



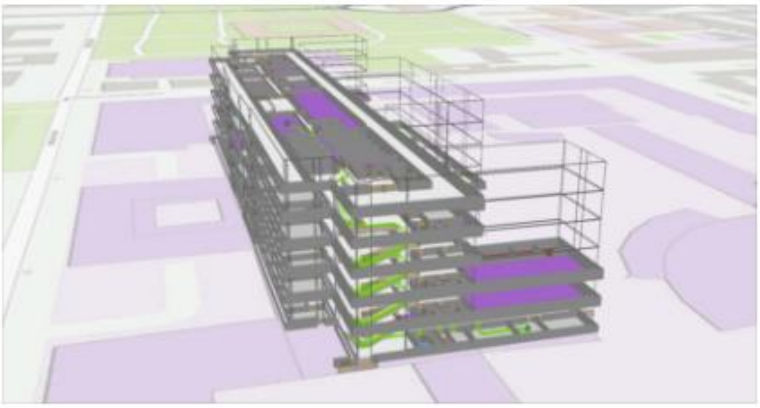
Please give your opinion to the following statement: To visualize the whole route from the start point to the destination point, the visualization shown in figure 2 represents a better option.

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree
○	○	○	○	○

Comments:

In case of additional comments and/or suggestions, please type here.

6. You have to navigate from one space on the first floor to another space on the sixth floor, as illustrated in the figure below. The route is represented in green colour and follows the stairways at the corner of the building.



Please give your opinion to the following question: How convenient is it for you to follow the route and reach the destination?

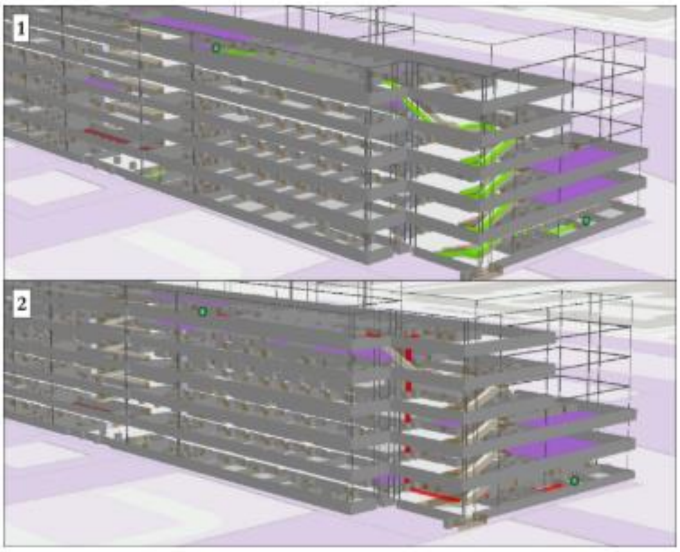
○	○	○	○	○
Extremely Easy	Easy	Neither	Hard	Extremely Hard

7. How satisfied are you with the 3D representation of the TUM campus routing system shown in the figure above?

○	○	○	○	○
Very Satisfied	Satisfied	Neither	Dissatisfied	Very Dissatisfied

8. While navigating between different floor levels of the building, users have two options to choose:

- Figure 1: Stairs. The route is shown in green colour, or
- Figure 2: Elevators. The route is shown in red colour.



Please give your opinion to the following statement: Using different colours to differentiate the route that follows stairs and/or elevators will increase the users' understanding of the route and will improve the navigation.

Strongly Agree | Agree | Neither | Disagree | Strongly Disagree

Comments:

In case of additional comments and/or suggestions, please type here.

Map use

1. What do you consider as the biggest advantage of a 3D map representation for indoor navigation?

- ○ Realistic representation of real world objects and features
- ○ Representation of vertical structures (walls, doors, stairs, etc.)
- ○ Transition between route segments (transition between floor levels)
- ○ Recognition of surrounding objects (doors, passages, etc)
- ○ Directions (left, right, up and down)
- ○ Other

2. Would you like to use interactive 3D maps for indoor navigation?

- ○ Yes
- ○ No
- ○ Don't know

3. Would you prefer using interactive 3D maps instead of conventional 2D maps for indoor navigation?

- ○ Yes
- ○ No
- ○ Don't know

4. What kind of map are you currently using for indoor navigation (e.g. building floorplans, 2D or 3D maps, mobile or web applications, etc.)?

5. Based on what you have seen within this survey, how would you evaluate the developed campus routing model of TUM?

Excellent | Above Average | Average | Below Average | Very Poor

6. Is there anything else that needs to be improved further in the developed campus routing model?

Please write here any additional comments, feedback, suggestions, etc.

Location

The data gathered will be completely anonymous. However, it will be helpful to show a geographic distribution of participants carrying out this survey. Please set your location by using either the search bar or "Find my location" button.

Set Location

Submit

Annex 3 – Second evaluation: Usability and utility

Usability and utility evalution

Dear participant,

Thank you for your time and participation in this user study. This user study is part of my master thesis as a student of the Cartography master programme. The main goal of my thesis is to design and develop a campus routing system, as a web application, to facilitate the navigation of various user groups in indoor spaces. The study area used for this purpose is one of the buildings of the Technical University of Munich (TUM) main campus.

The purpose of this user study is to evaluate the effectiveness and efficiency of the developed Campus Routing System based on your interaction and experience with the model. As part of the user study, this questionnaire should take approximately 10 minutes to fill it out.

If you are interested in the results of this thesis or if you have any further comments or suggestions I would be happy to hear from you.

Thank you for your help!

Armand KAPAJ

General questions

1. What is your gender?

- ◯ Male
- ◯ Female

2. What is your age?

- ◯ 18 to 24
- ◯ 25 to 34
- ◯ 35 to 44
- ◯ 45 or older

3. What is your highest educational level?

Please specify the highest level already achieved.

- ◯ Lower than Bachelor
- ◯ Bachelor
- ◯ Master
- ◯ PhD
- ◯ Higher

4. What is your educational background?

Please comment below (e.g. Geography, Economics, Engineering, etc.).

5. What is your occupation?

6. Have you ever been inside of this building before?

- Yes
- No

7. How often do you use maps as a tool for outdoor navigation?

Never | Very Rarely | Rarely | Occasionally | Frequently | Very Frequently

8. How often do you use maps as a tool for indoor navigation?

Never | Very Rarely | Rarely | Occasionally | Frequently | Very Frequently

8.a. What kind of maps are you currently using for indoor navigation (e.g. building floorplans, 2D or 3D maps, mobile or web applications, etc.)?

Please specify if your answer for question 8 was not "never"!

8.a. What kind of maps are you currently using for indoor navigation (e.g. building floorplans, 2D or 3D maps, mobile or web applications, etc.)?

Please specify if your answer for question 8 was not "never"!

9. How often do you use interactive 3D maps on computer screens or on mobile phones?

Never | Very Rarely | Rarely | Occasionally | Frequently | Very Frequently

10. How do consider your abilities to orient yourself and navigate with the help of a map in places that you visit for the first time?

Poor | Fair | Good | Excellent

11. How do you consider your abilities to orient yourself and navigate with the help of a map in places that you have visited before?

Poor | Fair | Good | Excellent

Interface design

1. The general information on how to use the developed indoor navigation system was relevant and useful.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

2. The search box to find an indoor space was easy to use.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

3. The process to generate a route between two spaces was easy to handle.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

4. The integrated buttons and their tooltips were needed and helpful to use the system.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

5. The TUM indoor navigation system helped me to be more effective while navigation in indoor spaces.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

6. I found the TUM indoor navigation system easy and simple to use.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

7. The TUM indoor navigation system requires a minimum number of steps to complete the task.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

8. I learned to use the TUM indoor navigation system quickly and remember how to use it.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

9. I am satisfied with the TUM indoor navigation system and it is pleasant to use it.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

10. The graphical user interface is clearly arranged and user friendly designed.

Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree

11. I would like to use a similar indoor navigation system also for other indoor spaces in the future.

Yes | No | Don't know

Map and route design

1. I could visualize the whole route from the starting point to the destination.

Completely Agree | Agree | Disagree | Disagree Completely

2. The map was easy to understand and I knew right away which way I had to go.

Completely Agree | Agree | Disagree | Disagree Completely

3. I was always sure if I had to turn left or right.

Completely Agree | Agree | Disagree | Disagree Completely

4. I was always sure if I had to walk up or down.

Completely Agree | Agree | Disagree | Disagree Completely

5. I was always sure on which floor I currently was.

Completely Agree | Agree | Disagree | Disagree Completely

6. The route guidance was unmistakable.

Completely Agree | Agree | Disagree | Disagree Completely

7. I had no problems at all finding my way.

Completely Agree | Agree | Disagree | Disagree Completely

8. Floor transition elements (stairs, stair handlers) were clearly marked on the map.

Completely Agree | Agree | Disagree | Disagree Completely

9. Doors and hallways were clearly marked on the map.

Completely Agree | Agree | Disagree | Disagree Completely

10. The presence of landmarks was in the right amount.

The term landmark in this study refers to doors, walls, and elevators.

Completely Agree | Agree | Disagree | Disagree Completely

11. What visual or structural elements the map do you find the most useful?

- Doors
- Walls
- Stairs and stair handlers
- Color coding of spaces
- Other

12. I would like to use this kind of map in the future for indoor navigation.

Completely Agree | Agree | Disagree | Disagree Completely

13. Is there anything else that needs to be improved further to facilitate the indoor navigation process?

Submit