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Constraints and concepts for the support of different locomotion types in indoor navigation

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List of Abbreviations

ADA	American with Disabilities Act
ADAAG	American Disabilities Act Accessibility Guidelines
BIM	Building Information Modeling
B-Rep	Boundary Representation
CAD	Computer Aided Design
COLLADA	Collaborative Design Activity
GPS	Global Positioning System
CityGML	City Geography Markup Language
CSG	Computer Solid Geometry
DHF	Dual Half Edge
ETL	Extraction Transformation Load
FME	Feature Manipulation Engine
GIS	Geographic Information Sciences
GML	Geography Markup Language
GNSS	Global Navigation Satellite Systems
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
IndoorGML	Indoor Geography Markup Language
INSM	Indoor Navigation Space Model
ISO	International Standards Organization
KML	Keyhole Markup Language
LAN	Local Area Network
LBS	Location Based Services
LoD	Level of Detail
MLSEM	Multilayered Space-Event Model
OGC	Open Geospatial Consortium
ONALIN	Ontology and Algorithm for Indoor Routing
RFID	Radio Frequency Identification
SDBMS	Spatial Database Management Systems
S-MAT	Straight Medial Axis Transformation
TIM	Topographic Information Modeling
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UML	Unified Modeling Language
WLAN	Wireless Local Area Network
3D	3-dimensional
2D	2-dimensional

Abstract

Individuals spend most of their time in indoor environments making the indoor navigation an important area for research. Consequently, other types of moving objects (e.g., wheelchair, Unmanned Aerial Vehicle (UAV)) also spend their time in indoor environments to perform various activities. For all types of moving objects or locomotion, there is a need to determine navigable spaces to carry out their specific tasks smoothly (particularly in public buildings like airports and train stations). There are several frameworks to determine navigable spaces for indoor navigation of different types of locomotion. However, most of indoor navigational frameworks focus on one single type of locomotion, i.e., either driving, flying, or walking. This selection of single type of locomotion is often very important with regard to the representation of indoor environments, because these representations typically cannot be used for other types of locomotion. For instance, a graph-based abstraction of indoor environment for a wheelchair is not sufficient for a flying UAV. Thus, it creates the problem of not supporting different types of locomotion for their indoor navigation.

This thesis contributes to address the problem of not supporting different types of locomotion in indoor navigation by means of determining their navigating requirements. The definition, classification, and validation of these requirements lead to the induction of individual constraints for each type of locomotion. Based on individual constraints, the conceptual constraint model for the locomotion types is presented. The conceptual constraint model allows for the modelling of physical requirements of each type of locomotion to navigate in a semantically enriched indoor environment. Furthermore, this model plays a crucial role in the determination of navigable and non-navigable indoor spaces for the specific type of locomotion, leading effectively to differentiate 3-dimensional subspaces. This thesis further contributes by presenting a subspacing method to compute navigable subspaces for the different locomotion types which are embedded in the framework of the Multi-layered Space-Event Model (MLSEM). There are different semantic 3-dimensional building modelling standards (e.g., IFC and CityGML) which have different approaches of geometric and semantic representations. Thus, to apply a homogeneous subspacing method, a two-step transformation process is presented, which translates Building Information Models (in IFC format) to Topography Information Models (in CityGML LoD4) and, then transforms them into IndoorGML building data models (IndoorGML is an application schema of the MLSEM and a new Open Geospatial Consortium standard for indoor building models).

The main scientific contribution of this thesis is the development of a conceptual constraint model and the subspacing method. The constraint model facilitates indoor navigation for the different locomotion types and the subspacing method computes navigable subspaces for different types of locomotion using semantic 3-dimensional building models. Another contribution of this thesis is the coupling of IndoorGML with a cloud-based system to simplify the IndoorGML model dataset for the common user to modify and interact, and use for context aware indoor routing.

The concepts and methods presented in this thesis can be utilized for the disciplines

of indoor navigation and building information modeling. In indoor navigation, it can be used for computing navigable subspaces and context aware indoor routing using semantic 3-dimensional building models for different types of locomotion. Similarly, in the field of building information modeling, the methods presented in this thesis can be utilized to determine navigable subspaces and extract network graphs from BIM models to use for analyses, simulations, and facility management in different scenarios (e.g., simulation of a rescue operation).

In the future, based on this thesis a series of research works can be initiated. The conceptual constraint model can be extended to include the body part constraints of locomotion types, subspacing method can be integrated with utility networks of building models for the utilization of indoor resources in the field of facility management, and conceptual constraint models can be used for the semantic interpretation of 3-dimensional geometric building models.

Abstract

Menschen verbringen einen Großteil ihrer Zeit in Innenräumen, weshalb die Innenraum-Navigation ein wichtiger Forschungsbereich ist. Infolgedessen verbringen auch andere sich bewegende Objekte (z.B. Rollstuhl, unbemanntes Luftfahrzeug (UAV)) Zeit in Innenräumen, um dort unterschiedliche Aktivitäten durchzuführen. Für alle Arten sich bewegender Objekte bzw. Fortbewegungsarten ist es nötig, navigierbare Räume (besonders in öffentlichen Gebäuden wie Flughäfen und Bahnhöfen) zu bestimmen, in denen sie ihre spezifischen Aufgaben problemlos durchführen können. Es existieren mehrere Frameworks, mit denen navigierbare Räume für die Innenraumnavigation verschiedener Fortbewegungsarten bestimmt werden können. Die meisten Frameworks für die Innenraumnavigation beschränken sich jedoch nur auf eine einzige Fortbewegungsart, d.h., entweder auf Gehen, Fahren oder Fliegen. Diese Auswahl einer einzelnen Fortbewegungsart ist oft im Hinblick auf die Art und Weise, wie Innenräume repräsentiert werden, sehr wichtig, da diese Repräsentationen typischerweise nicht für andere Fortbewegungsarten verwendet werden können. Zum Beispiel ist eine graphbasierte Abstraktion von Innenräumen für einen Rollstuhl nicht für ein fliegendes UAV ausreichend. Dies führt zu dem Problem, dass verschiedene Fortbewegungsarten im Bereich der Innenraumnavigation nicht gleichzeitig unterstützt werden.

Diese Dissertation behandelt das Problem der fehlenden Unterstützung unterschiedlicher Fortbewegungsarten in der Innenraumnavigation, indem ihre entsprechenden Navigationsanforderungen festgelegt werden. Durch die Definition, Klassifizierung und Formalisierung dieser Anforderungen können die individuellen Einschränkungen (Constraints) für jede Fortbewegungsart explizit festgelegt werden. Auf Basis individueller Constraints wird das konzeptuelle Constraint-Modell für die Fortbewegungsarten vorgestellt. Dieses Modell ermöglicht die Modellierung der physikalischen Anforderungen jeder einzelnen Fortbewegungsart, um in einem semantisch angereicherten Innenraum navigieren zu können. Außerdem spielt das Constraint-Modell eine entscheidende Rolle bei der Bestimmung der navigierbaren und nicht-navigierbaren Innenräume für jede spezifische Fortbewegungsart, was schließlich zur Aufteilung in dreidimensionale Teilräume (Subspaces) führt. Diese Arbeit stellt außerdem einen Subspacing-Ansatz vor, um navigierbare Teilräume für die unterschiedlichen Fortbewegungsarten zu berechnen, die in das Framework des Multilayered Space-Event Model (MLSEM) eingebettet sind. Für die semantische 3D-Gebäudemodellierung (z.B. IFC und CityGML) existieren verschiedene Standards, die unterschiedliche Ansätze bzgl. geometrischer und semantischer Repräsentationen aufweisen. Um einen homogenen Subspacing-Ansatz anwenden zu können, wird ein zweistufiger Transformationsprozess vorgestellt, der zunächst Bauwerksdatenmodelle (im IFC-Format) in topographische Informationsmodelle (in CityGML LoD4) umwandelt. Im zweiten Schritt werden diese Modelle dann in IndoorG-ML-Gebäudedatenmodelle transformiert (IndoorGML ist ein Anwendungsschema des MLSEM und ein neuer Standard des Open Geospatial Consortium für Innenraummodelle).

Der wichtigste wissenschaftliche Beitrag dieser Arbeit ist die Entwicklung eines konzept-

uellen Constraint-Modells und des Subspacing-Ansatzes. Das Constraint-Modell ermöglicht die Innenraum-Navigation für die verschiedenen Fortbewegungsarten und der Subspacing-Ansatz berechnet die navigierbaren Teilräume für verschiedene Fortbewegungsarten mittels semantischer 3D-Gebäudemodelle. Ein weiterer Beitrag dieser Arbeit ist die Kopplung von IndoorGML mit einem cloudbasierten System, um den IndoorGML-Datensatz zu vereinfachen, damit dieser durch den normalen Benutzer modifiziert und für kontextabhängiges Innenraum-Routing verwendet werden kann.

Die in dieser Arbeit vorgestellten Konzepte und Methoden können für die Disziplinen der Innenraumnavigation und des Building Information Modeling (BIM) eingesetzt werden. Bei der Innenraumnavigation können diese für die Berechnung navigierbarer Teilräume und für kontextabhängiges Innenraum-Routing für verschiedene Fortbewegungsarten mittels semantischer 3D-Gebäudemodelle genutzt werden. Ebenso können die in dieser Arbeit vorgestellten Methoden im Bereich des Building Information Modeling verwendet werden, um für Analysen, Simulationen und Facility Management in verschiedenen Anwendungsszenarien (z.B. Simulation einer Rettungsoperation) navigierbare Teilräume zu bestimmen und Netzwerk- Graphen aus BIM-Modellen zu extrahieren.

Künftig kann auf Grundlage dieser Arbeit eine Reihe weiterer Forschungsarbeiten angestoßen werden. Das konzeptuelle Constraint-Modell kann um die Körperteil -Constraints der Fortbewegungsarten erweitert werden, im Bereich des Facility Managements kann der Subspacing-Ansatz mit Versorgungsnetzwerken aus Gebäudemodellen zur Ausnutzung von Innenraumressourcen integriert werden und schließlich können konzeptuelle Constraint-Modelle auch für die semantische Interpretation dreidimensionaler geometrischer Gebäudemodelle genutzt werden.

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Chapter 1

Introduction

1.1 Introduction

Navigation comprises mainly three tasks; these are: 1. determination of position and orientation (localization), 2. addressing and route planning, and 3. route tracking of a subject or object (Becker et al., 2009b). The first task needs a localization method and technology communicating the position to a user requires a map. The second task requires geo-information about the navigable space, a coordinate system, and an addressing schema. The last task commonly carried out in navigation is route tracking. This involves alignment with the start position and target position of an object or subject and control of the motion of the object to keep the object on track towards its target. When these navigation tasks or activities are carried out within the interior of a built environment then it is referred to as indoor navigation.

Navigation in an outdoor environment is very common and most of its activities become standardized due to the availability of the Global Positioning System (GPS). However, indoor navigation has been explored only for last one decade. In indoor navigation, the use of new technologies like Blue-tooth, wireless LAN, and Ultrasound for localization and its important applications in Location Based Services (LBS) make indoor navigation more sophisticated. Moreover, indoor navigation deals with more dimensions (multiple story buildings) as compared to 2-dimensions in outdoor navigation and it needs higher accuracy as well as a higher level of detail to deal with human-scaled navigation in complex indoor structures of a building. The complexity of indoor navigation further increases when the context of navigation is considered (Becker et al., 2009b). When the context of navigation is taken into account then the type of locomotion and its navigation constraints become one of the important factors to consider for indoor navigation because in most of the applications, e.g., route planning, there is always a need to determine the navigable and non-navigable area for the specific locomotion type and the constraints of the locomotion type play a very important role in deciding the navigability of an area.

In the following sections, the motivation of this thesis and the main research challenges faced by indoor navigation today are discussed. Furthermore, based on those challenges, the research scope and objectives of this thesis will be elaborated.

1.2 Motivation

In indoor environments, different types of locomotion (like with robots) have helped mankind by performing different functions from the micro (e.g., operation theaters in medical industry) to the macro level (e.g., robots in the manufacturing industry). For all types of locomotion, including human beings, there is a need for route planning and guidance during navigation or tracking in buildings (particularly in public buildings like hospitals and airports). The route planning task, which normally includes determining an interested navigable space for a locomotion type, always needs information about the type of locomotion and its related operating environment (Becker et al., 2009b; Kolodziej and Hjelm, 2010). Once a specific type of locomotion is considered for indoor navigation, specialized requirements to navigate in indoor space must be determined. When these requirements are examined and formalized, they then result in the determination of specialized constraints for each type of locomotion. During the indoor navigation of each particular locomotion type, these specialized constraints play an important role in distinguishing the indoor space into navigable and non-navigable space. Now it has to be determined what are those requirements, constraints, and constraint types that define a navigable and non-navigable space for the specific locomotion type.

The specialized locomotion types performing unique functions in various operating environments remain the focus of study in distinct fields (Siegwart et al., 2011). In the indoor navigation field, most of the indoor navigation frameworks have a focus on one single type of specialized locomotion, e.g., walking, flying, or driving (Grzonka et al., 2009; Khatib et al., 2008; Lertlakkhanakul et al., 2009; Stoffel et al., 2007). This decision of selection of the type of locomotion have important affects the indoor space representation. This is because each type of locomotion needs specialized indoor space representations and these representations cannot be used for other types of locomotion for their indoor navigation (e.g., indoor space's network model representation for a driving locomotion cannot be used for a flying vehicle). Therefore, there is a need to address the problem of supporting different locomotion types in indoor space. Thus, the author will focus on common and differing requirements for indoor navigation of the different locomotion types which will help to determine common or specialized 3-dimensional subspaces. This process of subspacing will result in specialized 3-dimensional subspaces for the specific locomotion types which also need to be in a framework that must be based on sound mathematical rules and must also utilize semantic, geometric, and topological information of semantic 3-dimensional indoor building models. However, there are already established subspacing schemas of indoor building models which are determined according to different building modeling standards, e.g., CityGML, but the author is interested in determining further subspaces of these building models based on the different types of locomotion.

The focus of this study is on generalized locomotion types where most of the locomotion types share common characteristics. In this research, only those locomotion types which are in common use in indoor environments will be considered. The common use locomotion types are distinguished based on their mobility mechanism, i.e., walking, driving, and flying. Flying refers to taking flight in the air, walking refers to leg based movement, and driving refers to wheeled based locomotion types. Moreover, an example of each type of locomotion, which is commonly used and represents the distinguished mobility mechanism in indoor environment to define its constraints and to determine navigable and non-navigable space (e.g., wheelchair as a driving locomotion type), is considered.

1.3 Challenges to Indoor Navigation

Studies have shown that human beings spend most of their time (around 90 percent) indoors (Jenkins et al., 1992). However, indoor space applications which support indoor navigation activities are well behind outdoor space applications using GPS and GIS technologies. Nevertheless, the increasing trend in the number of complex buildings (e.g., hospitals, shopping malls, and airports) and requirements to facilitate users in indoor activities have intensified the development of location-based service applications. This growth of location-based service applications has further motivated the use of informatics support for indoor space applications. To effectively support the informatics for indoor space applications, there is a need for several technologies (e.g., sensor networks) and methods (e.g., geocoding). An indoor navigation system has to implement appropriate methods considering the indoor navigation activities which mainly consist of localization, routing, and tracking or guidance (Worboys, 2011). In the following, the challenging tasks in indoor navigation and solutions already in place with respect to each activity of indoor navigation are discussed.

1.3.1 Localization

There is always a need to determine correct locations for use in different outdoor navigation applications such as emergency evacuation from a building, earth observation, and route planning applications. For the last several decades, the determination of one's location has been carried out through different approaches. They include: pilotage, which relies on recognizing landmarks to know where you are and how you are oriented; dead reckoning, which depends on the information where you started from, some form of heading knowledge, and some estimate of speed; celestial localization, which uses time and the angles between local, vertical, and known celestial objects to estimate position; radio localization, which depends on radio-frequency sources with known locations; inertial localization, which relies on information of one's initial position, velocity, and attitude. Furthermore, these localization techniques can be and are also used in combination to ensure more accuracy and integrity. The most common outdoor localization technology used for outdoor navigation systems is based on Global Navigation Satellite Systems (GNSS) (Grewal, 2011). It provides location information through satellite constellations in a global spatial reference system which generate signals that can be received anywhere on the earth's surface. However, GNSS based systems (e.g., Global Positioning Systems or GLONASS) lack reliable signals inside buildings, resulting in the initiation of alternate indoor localization techniques.

The required type of location information may vary depending on the type of application. The main types of location information include physical, absolute, relative, and symbolic location. The physical location is represented in the form of coordinates, which represents a point on a 2-dimensional or 3-dimensional map. Symbolic location represents a location in natural-language (e.g., office). Absolute location uses a reference grid to represent exact location of the located objects, and relative location information is normally based on the proximity to already known reference points. Several types of technologies are used to determine indoor location information. Some of them are radio-frequency identification (RFID), cellular-based, ultra-wideband, wireless local area network (WLAN), Bluetooth, ultrasound, inertial navigation sensors, and ultra-high frequency (UHF). These technologies have different levels of accuracy, complexity, and solution systems (Liu et al., 2007). Most of them have limitations for continuous coverage of indoor space and have insufficient degrees of accuracy. Moreover, they have specialized solutions for the specific applications which make them unsupportive of other localization methods and technologies. Therefore, there is a need of a common localization standard system for the different localization technologies to take advantage of each other strengths. The localization standard can be formed from different technologies through a common representation model abstracted from where they share common localization methodology (e.g., method of determining location, making use of different types of measurement of signals, angle, and signal strength or location sensor infrastructure), spatial characteristics (e.g., signal coverage area), measuring principles (e.g., signal strengths or time difference of arrival), and positioning algorithms (e.g., triangulation). The standardization of the localization methods and technologies cannot guarantee the reliability of the system to determine location of the user unless the user device or user has capabilities to adjust and respond with different localization technologies. Therefore, it is important to make the end-user devices capable of using different technologies. This capability becomes very crucial when there is an emergency situation and the end-user device does not have support for the localization technology that is available within a building.

Different localization technologies provide physical, absolute, or relative positions of a user (e.g., provides coordinates using a specific reference system), while a normal user may be more interested in knowing his symbolic location information (e.g., near or within office). Hence, there is a need to integrate these localization methods with context-aware indoor space models so that the end user will be able to get his location information in his/her preferred type. This integration step may be involved in a multi-step transformation process of coordinate systems; from global to local, local to indoor, and from indoor to symbolic reference systems.

One of the important challenges to deal with during the localization of indoor navigation systems is the privacy of user location information. This is because the information of the location of the user opens the possibility to provide him/her highly personalized services and applications but the unauthorized use of that information can be a threat to his/her privacy. Therefore, there is a need to regulate and legislate the privacy of personal data protection in many parts of the world (Adusei et al., 2004).

1.3.2 Path Planning

Path planning is one of the main activities of navigation. It consists of computing the optimal route from the initial location to the target location. Often, determining the optimal route depends on different criteria, e.g., time. These different criteria depend on the user and the environmental context. A change in criteria results in different paths even if the initial and target points of interests are not changed. For example, a flying vehicle can fly through a window to reach the target, whereas a wheelchair cannot or a person in a normal situation always walks on the floor. Hence, the context of user or environment (e.g., emergency situation) plays a very important role in route planning. Therefore, there is a need to consider context-aware path planning approaches which should also consider user preferences and constraints, environmental constraints, situations types, etc. (Goetz and Zipf, 2011).

The road networks which are simple linear structures in outdoor environments have less complexity in route planning as compared to indoor spaces. The GNSS based systems like GPS have made outdoor localization an easy task. The availability of GNSS based systems for localization and well advanced technologies to acquire outdoor data have enabled car navigation systems to employ 3-dimensional road maps and models of cities to facilitate users with visualization of the route, position, and route instructions. In contrast, in indoor spaces there are objects such as pillars and rooms in huge halls and they need to be considered for route planning, which results in a complicated indoor route planning. The availability of huge public buildings such as hospitals or airports and their internal complex structures for the normal user to navigate have intensified the importance of indoor routing as well as its complexity. Indoor routing is not only dealing with the objects laying within the building but also there are many other dimensions which need to be considered; some of those include many floors of the building, and nested configurations and hierarchical composition of rooms.

The computation of the navigable route for an object to reach the target location always needs to determine navigable and non-navigable space as a prerequisite. The determined subdivision of navigable and non-navigable space does not necessarily need to be parallel with the decomposition of the real building model parts as it depends on the navigational requirements of the navigating locomotion type. For example, floor surface areas may be non-navigable for a flying vehicle (e.g., quadrocopters) but for a wheelchair it always needs a navigable floor surface to hold and to drive. Thus, each type of locomotion defines its own subspace of interior spaces which do not necessarily need to coincide with the subdivision of the building model (subdivision of the building model may be based on some criterion, e.g., semantic or geometric criterion). In addition, there are constraints from the environment which also affect the navigability of the navigating object or subject. For example, accessibility restrictions to a building's part for specific users. Again, subdivision of navigable and non-navigable space after the realization of environmental constraints may not be parallel to the subdivision of the real built environment. There is a need to consider the different dimensions of constraints (e.g., environmental constraints and locomotion types' constraints) to compute subspaces of interior spaces which should result in accurate route planning for the considered object or subject.

The normal users of built environments use symbolic referencing for the locations during route planning. For example, finding a route from office A to office B or near the desk no-2. Whereas, the referencing of indoor locations is done with coordinates of the spatial reference system. There is a need of coordinate reference system to be designed with the symbolic or semantic data model of indoor spaces. Thus, the end user could query and get response from the system in the symbolic reference. Furthermore, there is a need to facilitate the end user with location-based services (e.g., finding the nearest restaurant by means of neighborhood queries) by modelling distance functions with the integration of symbolic reference models. In this way, the end user can query for neighborhood queries in the symbolic reference (e.g., finding the nearest garments shop from the desk no-2) and can get the response with the routing instructions.

Route planning is a very old problem in the field of robotics. In robotics, researchers have solutions for the navigating objects to determine the navigable route from the source to the target location while avoiding the obstacle spaces or non-navigable areas. The results of these solutions are very accurate and contain higher level of detail as compared to the graph based solutions in the field of GIS. For example, computing a navigable route by means of the configuration space method (Lozano-Perez, 1983) in robotics as compared to the computation of route on abstracted nodes (network models) in the field of GIS. However, most of the route planning in robotics is done at the geometric level without considering the semantics of the built environment. There are requirements for a higher level of detail and accuracy to deal with complex objects (e.g., human beings) in complex indoor infrastructures (e.g., complex building architectures) with the considerations of contextual information in indoor spaces. Thus, there is a need to integrate GIS based solutions for route planning which considers contextual information with the solutions of robotics that only depend on geometric solutions having accurate and higher level of detail in route planning. So, this integration can support both fields to take benefit from each other's specialization strengths. For example, the field of robotics can take benefit from the GIS in considering contextual information from an environment using semantic 3-dimensional building models, while the GIS community can take advantage of already existing accurate solutions in route planning from the field of robotics.

From the above discussed challenges it can be noticed that indoor path planning deals with many complex issues due to the different types of users and locomotion types, different methods of computing navigable spaces, different indoor infrastructures (physical, logical, and thematic representations), different indoor data models, requirements for more level of detail and accuracy, and different reference systems.

1.3.3 Tracking and Guidance

Tracking activity in navigation is performed by alignment of the object's or subject's current position with the start position and target position, and control of the motion of the object to keep the object on track towards its target. The tracking process consists of localization of the object with the given localization infrastructure and using algorithms to match the current location of the object against the navigation space model. The main challenges during this process are the accuracy of the localization method and technology as well as dealing with the different spatial reference systems for transformation of location information which may lead to errors during this transformation. As compared to outdoor navigation, indoor navigation needs more precision to track users in indoor spaces (e.g., tracking users in corridors and halls). There are different accurate solutions in indoor spaces in the field of robotics using specialized localization technologies (Fuchs et al., 2011). There are many tracking solutions which use precise location information with the indoor space models to have more accuracy and to facilitate users with symbolic reference interactions (Jensen et al., 2009). Therefore, tracking in indoor spaces poses challenges for having different localization technologies and indoor space models. There is no standard or commonly accepted solution for tracking using both localization technologies and indoor space models.

Route guidance guides the subject or object from the initial location to the target location assistance by providing route instructions, visuals, or textual aids. Support for this guidance can be in any form using static or dynamic media. Most outdoor car navigation systems display the route map together with the route instructions as well as the spoken commands. These route instructions and commands are strongly connected with specific points of road networks (e.g., motorway exits). The interior spaces which are complex as compared to outdoor linear structures have free spaces to move around for the subject or object and it will be very difficult to give instructions within free areas or non-navigable areas as these are given in the outdoor spaces. There is not any commonly accepted way of how to identify indoor marks or points, and route instructions to facilitate users in a standardized way.

Visualization of 3-dimensional maps is common in car navigation systems that guide users for routing but giving route instructions and visualizations of routes for indoor users is still in the development phase. Research questions that still need to be addressed include: which building features should be displayed, which symbols and route instructions need to be included, 2-dimensional or 3-dimensional views, facilitating indoor space visualizations and instructions on hand-held devices, and real-time or augmented reality solutions in emergency situations. In addition, automatic facilitation for different users with their understandable descriptive route instructions according to their physical or conceptual capabilities is still a challenge (Anagnostopoulos et al., 2005).

1.3.4 Navigation Context

An indoor navigation system has to deal with many different contextual requirements. They include: different environmental constraints, types of locomotion and their constraints, and user's preferences (Becker et al., 2009b). Furthermore, it also has to deal with configurations of the different localization techniques and infrastructures as well as different end-user devices. Once the contextual information in indoor navigation is considered, then there is a requirement of a formal model which should capture the contextual information of different types of locomotion and their constraints, and facilitate reasoning based on captured knowledge to determine the navigable subspace of the indoor space. All locomotion types possess physical and logical requirements for their indoor navigation. Their physical requirements always take precedence and they need to be taken into consideration as a prerequisite. In this thesis, the direction of investigation will be focused on physical requirements and their formal representations, in order to address how they impact indoor navigation for the different types of locomotion.

1.3.5 Hybrid Challenges

The importance of the consideration of the context in indoor navigation has been discussed by many researchers (Anagnostopoulos et al., 2005; Goetz and Zipf, 2011; Lertlakkhanakul et al., 2009; Stoffel et al., 2007; Yuan and Schneider, 2011). Once the context of indoor navigation is considered, then considering different types of locomotion becomes one of the most important factors (Becker et al., 2009b). Most of the research in indoor navigation of navigable subspaces for the different locomotion types has been based on their capabilities and preferences. The subspacing for the different locomotion types is done at the graph level (e.g., computation of the network model for a specific locomotion type and further subspaces are computed based on that network model). This method leads to a problem of not supporting indoor navigation for the different locomotion types because, a network model computed for the wheelchair cannot be further subspaced to generate a route plan for a flying vehicle. Therefore, there is a need to determine methods to provide support for different types of locomotion and a requirement to implement subspacing at the geometric level while considering the actual contextual information of the environment. The challenge to support different locomotion types will influence other aspects of navigation. For example, different locomotion types will determine different navigable route plans, tracking routes, and they may need different routing guidance.

On the one hand, an indoor navigation system has to consider different locomotion types. On the other hand, there may be different types of 3-dimensional building models representing the navigation environment for the locomotion type. Some may be semantically enriched (e.g., CityGML or IFC 3-dimensional building models) and others may be only geometrical representations. The different types of 3-dimensional building models have different building data models and they may affect path planning techniques, tracking, route guidance, and localization techniques of the indoor navigation. Therefore, there is a requirement for the indoor navigation system to consider how to address the issues of using different 3-dimensional indoor building data models for indoor navigation activities for the different types of locomotion.

The main purpose of indoor navigation activities is to facilitate persons or objects in navigating in indoor space and provide him or it with state-of-the-art location based services. Most of the indoor data models representing indoor spaces are complex and may create hurdles or may be difficult for the normal end-user to directly interact with and make changes according to his/her contextual needs. Therefore, there is a requirement to investigate how to use modern distributed technologies (e.g., cloud computing) and 3-dimensional visualization tools that should support an end-user to directly interact in the easiest possible way, do changes according to his contextual requirements, and make accessible those new changes to other end-users of the indoor navigation system instantly.

1.4 Research Scope and Objectives

1.4.1 Research Scope

The research in this thesis focuses on the support for different types of locomotion (e.g., flying, walking, driving) for indoor navigation in (semantically enriched) 3-dimensional virtual environments. The importance of considering different types of locomotion and their relevance in the context of each navigational aspect has been discussed in the previous section.

The main objective of this thesis is to design a conceptual constraints model for different locomotion types that meets the challenges of supporting the different locomotion types in indoor navigation. Furthermore, this model can act as a foundation for the implementation of indoor navigation systems to compute navigable subspaces for different locomotion types. The main objective can be categorized into sub-objectives.

Definition of the navigation requirements

The first sub-objective of this thesis is to define navigation requirements based on the properties of the different locomotion types (e.g., driving). This will allow the navigation system to distinguish different locomotion types based on their navigation requirements. The navigation properties and requirements to navigate for the locomotion type at the micro level (e.g., body parts level) are discussed in the robotics field. In this research, the main focus will be on macro level (navigating object's body level) of locomotion type's properties and requirements. Therefore, the geometric and contextual requirements of the locomotion types are determined at the generalized level (e.g., over all body level) and their geometric, semantic, and topological information is also represented at the generalized level.

Definition of the navigation constraints and development of the constraints model

The second sub-objective of this research is to define navigating constraints of the locomotion types which are required to be fulfilled for their navigation. These constraints will be formed based on the requirements of the specific locomotion type. These constraints also need to be categorized based on the types of navigating requirements. Based on that categorization, further conceptual modeling for the different types of constraints according to different locomotion types needs to be done. The conceptual constraints model for the different locomotion types will act as a common model to represent the constraints for each locomotion type and it will also act as a knowledge base in deciding navigable or non-navigable areas for the considered locomotion types in the indoor space model.

Subspacing method for the computation of navigable subspaces

The third sub-objective of this work is to develop a method to compute navigable subspaces for different locomotion types based on their navigation constraints in a semantically enriched 3-dimensional virtual environment. The method should utilize the information from constraints of the locomotion type and navigational cells of 3-dimensional building models to compute the navigable subspace for the locomotion type. The method needs to be facilitative in supporting different locomotion types for indoor navigation and furthermore has to accurately compute navigable subspaces of the complex indoor spaces. The focus of this thesis will remain to compute navigable subspaces which can be further used for route planning (e.g., the shortest route plan) and other purposes (e.g., facility management) as well.

Integration of different semantic 3D building models to use for the computation of subspaces

The fourth sub-objective of this thesis is to integrate different semantic 3-dimensional building models to treat different standards in a homogeneous way and apply the subspacing method to compute the navigable subspace for the specific locomotion type. This is because there are different semantic 3-dimensional building modeling standards (e.g., IFC models and CityGML models) which creates the need for an approach that can use these building modeling standards to extract geometric, semantic, and topological information to determine subspaces for the different locomotion types.

Realization of approach on real 3D building model

The fifth sub-objective is to realize the methods described in earlier sections on a real semantic 3-dimensional building model. The lessons learned, issues faced with real datasets, and use of this approach on other datasets have to be presented.

1.5 Research Hypotheses and Questions

This research work is developed along the following research hypothesis and questions.

1.5.1 Hypothesis: The semantic, geometry, and topology constraints derived from the locomotion type and its environment are sufficient for determining navigable and non-navigable space for the locomotion type in indoor space.

The consideration of the different locomotion types and their context for indoor navigation were not sufficiently addressed in previous work. Likewise, the constraints for the different locomotion types have not been formally expressed by a data model so far. Therefore, in this thesis, the consideration of the context for different locomotion types with concepts of constraints, constraints types, and constraints data model from its properties and environment are a main research task of this thesis. The research task is further elaborated and verified based on the following research questions.

1. What are the physical constraints for different types of locomotion namely flying, walking, and driving?
2. To which extent are physical constraints of the locomotion type deciding factors for the navigability of indoor space?
3. Is there any need to model physical constraints of the locomotion type conceptually?
4. How can those physical constraints be classified and modeled?

1.5.2 Hypothesis: There is a need of a 3-dimensional subspacing method to support indoor navigation for different types of locomotion. The 3-dimensional subspacing method integrates common and differing requirements for indoor navigation of the different types of locomotion. Besides, it determines a common or a specialized 3-dimensional subspace.

The graph-based 3-dimensional subspacing methods are not sufficient to support for different types of locomotion for indoor navigation. Therefore, in this research work, the computation of 3-dimensional subspaces to support the different locomotion types for indoor navigation is one of the primary goals. This primary goal is tested within this thesis along the following research questions.

1. Why do we need a subspacing method?
2. What are the factors that will play a role in 3-dimensional subspacing for the different locomotion types?
3. What information is required for each locomotion type? How much and what type of semantic/geometric/topologic information is required?

4. Is there any need to define a procedure to carry out subspacing?
5. How can the required 3-dimensional building model entities for the navigation according to a specific locomotion type be determined?

1.5.3 Hypothesis: The proposed subspacing method based on the different types of locomotion works within the framework of MLSEM and conforms to its subspacing approach.

The MLSEM provides a subspacing approach but it has never been tested on a real dataset (e.g., 3-dimensional building model) with different locomotion types. As a research task in this thesis, the subspaces based on the different types of locomotion are to be computed within the framework of MLSEM and to be verified concerning its subspacing approach. Furthermore, the task will be evaluated based on the following research questions.

1. How will the proposed subspacing method be integrated with the subspacing approach of MLSEM?
2. The representation of the locomotion context can be completely captured by MLSEM by using its subspacing feature.

1.5.4 Hypothesis: The proposed 3D subspacing framework supports indoor navigation for the different types of locomotion. Furthermore, it is capable to use different types of 3D building model standards and to generate the relevant abstracted models (graph models) for indoor navigation activities from them.

The first part of this hypothesis confirms the main objective of this research work. The second part is verified within this research, based on the following questions which deal with the fundamental aspects of indoor environment representation.

1. To what extent do the existing 3-dimensional building models provide support for indoor navigation in general and for different types of locomotion in particular?
2. Is it possible to treat 3-dimensional building models according to different standards in a homogeneous way and apply the subspacing method?
3. How are the different types of 3-dimensional building models representing different domains integrated into an indoor representation model, i.e., IndoorGML?
4. What are the considerations during the transformation from different 3D building models to IndoorGML because of the subspacing process?
5. Why do we need a context aware route planning in indoor environments?
6. Why is there a need to use advanced distributed technologies (cloud computing based systems)?
7. How can the resulted model in IndoorGML be used for context aware route planning using cloud computing technology?
8. To what extent can the system be adjusted to the dynamic aspects of entities of 3-dimensional building and with respect to the context of the moving object or subject?

1.5.5 Hypothesis: Limitations of today's 3-dimensional GIS and Spatial Database Management Systems (SDBMS) can be overcome to compute indoor subspacing.

For the realization of 3-dimensional subspacing there is a need of state of the art 3-dimensional GIS and SDBMSs which should support and compute subspaces for the different locomotion types smoothly. But there are limitations with the currently available SDBMSs in computing indoor subspaces. The identification of those limitations and the verification to overcome those limitations is to be done using the following research questions:

1. Can the required operations be performed by today's available SDBMS? What is missing? How can those can be overcome?
2. What additional formalities for 3-dimensional GIS and SDBMS would be useful/helpful to overcome its limitations?

3. How can limitations of today's 3-dimensional GIS and geo DBMS be overcome to compute indoor subspacing?
   (a) Which type of DBMS will be used to store and update the 3-dimensional geometric and network model of buildings, and also 3-dimensional subspacing for the different locomotion types?
   (b) What are the limitations and strengths of DBMSs to compute subspaces for the different locomotion types?
   (c) How can those limitations be overcome and subspaces can be computed?
   (d) How is 3-dimensional subspacing within the framework of MLSEM stored, managed, and subspaces are computed?

1.6 Structure of the Thesis

The thesis is structured into seven chapters whose short description is given in the following.

Chapter 2 presents the different approaches available for the representation of indoor spaces in indoor navigation and identifies their limitations for indoor navigation activities. The chapter also discusses how different types of locomotion use indoor space models for indoor navigation. It highlights the issues that need to be addressed in this thesis which include the problem of not supporting indoor navigation for the different types of locomotion, requirements for the integration of different indoor space models into a specific indoor model, and the development of a method to compute accurate navigable subspaces for the considered types of locomotion. Overall, the chapter reviews the limitations and strengths of the related work in dealing with the challenges to indoor navigation.

Chapter 3 proposes a conceptual constraint model for the different locomotion types in indoor navigation. It represents information about locomotion type's navigational requirements to be fulfilled and provides support for determining navigable subspace in indoor environments. The conceptual constraint model addresses some of the challenges described in the previous chapter in providing support for different locomotion types in indoor navigation. The chapter defines requirements, forms and classifies constraints, and develops a conceptual constraint model for different locomotion types for indoor navigation.

Chapter 4 identifies requirements for a subspacing framework and presents a subspacing method to compute accurately the navigable subspace for the various locomotion types while considering their navigation constraints in 3-dimensional semantics building models. The main objective of the subspacing method is to support indoor navigation for the different locomotion types.

Chapter 5 describes a multi-step transformation process to automatically generate Indoor Geometry Markup Language (IndoorGML) datasets from existing indoor building models data given in either Industry Foundation Classes (IFC) or City Geometry Markup Language (CityGML) Level-of-Detail 4 and compute subspaces for the different types of locomotion. The transformation step addresses the challenge of indoor navigation to deal with various types of semantic indoor space models to compute navigable subspaces.

Chapter 6 illustrates a use case to generate navigable subspaces for the different locomotion types using a portion of the main building of the semantic 3-dimensional building model of the Technical University of Munich (TUM). The chapter also illustrates the transformation steps from Building Information Modeling (BIM) to Topographic Information Modeling (TIM) and IndoorGML. In addition, the chapter also presents a method and illustrates how to couple IndoorGML with a cloud-based system to facilitate context aware indoor route planning. Moreover, the chapter describes the lessons learned and an evaluation of the method used in this use case.

Chapter 7 summarizes the main results of the thesis with respect to the objectives described. It reviews the results of the research, discusses scientific contributions, and outlines the possible future research directions of this work.

Apart from these seven chapters of this thesis, seven appendices with supplementary information are provided. Appendix A provides the FME workbench for transformation from IFC to CityGML (which implements the concepts presented in chapter 5). Appendix B contains a summary of a Java language program to translate from a CityGML dataset to IndoorGML for the implementation of the approach discussed in chapters 5 and 6. Appendix C provides a summary of a Java language program for the realization of the method presented in chapters 3 and 4. Appendix D provides some examples of indoor navigation constraints considered for different locomotion types. Appendix E illustrates and explains the translation process and FME workbench to couple IndoorGML with a cloud-based system discussed in chapter 6. Appendix F presents a simplified IndoorGML database schema used to store and manage the IndoorGML building model of TUM main building and its subspaces. Appendix G provides a small use case to show subspacing using geometric 3-dimensional building model discussed in chapter 4.

1.7 Publications

Following is the list of publications. Contents of chapters in this thesis are based on these published papers.

1. Khan, A. and Kolbe, T. (2012). Constraints and their role in subspacing for the locomotion types in indoor navigation. In Proceedings of International Conference on Indoor Positioning and Indoor Navigation (IPIN), 13-15 November 2012, Sydney, Australia, pages 1–12. IEEE.

2. Khan, A. A. and Kolbe, T. H. (2013). Subspacing Based on Connected Opening Spaces and for Different Locomotion Types Using Geometric and Graph Based Representation in Multilayered Space-Event Model (MLSEM). In Isikdag, U. (Ed.): Proceedings of the 8th 3D GeoInfo Conference, 27-29 November 2013, Istanbul, Turkey, ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, volume II-2/W1, pages 173–185.

3. Khan, A. A., Donaubauer, A., and Kolbe, T. H. (2014a). A multi-step transformation process for automatically generating indoor routing graphs from semantic 3D building models. In Breunig, M., AlDoori, M., Butwilowski, E., Kuper, P., Benner, J., Haefele, K. (Eds.): Proceedings of the 9th 3D GeoInfo Conference, 11-13 November 2014, Dubai, UAE.

4. Khan, A. A., Yao, Z., and Kolbe, T. H. (2014b). Context aware indoor route planning using semantic 3D building models with cloud computing. In Breunig, M., AlDoori, M., Butwilowski, E., Kuper, P., Haefele, K. (Eds.): 3D Geoinformation Science, pages 175–192. Springer Cham. (Lecture Notes in Geoinformation and Cartography).

Chapter 2

Indoor Modeling and Navigation

The 3-dimensional modeling of indoor environments for the purpose of indoor navigation is a relatively new area of research (for the last two decades). Authors have presented different approaches to represent indoor spaces for the purpose of indoor navigation. Researchers have also presented indoor navigation systems to demonstrate methods of using indoor spaces to support the different locomotion types for indoor navigation activities (e.g., human way finding). The proposed approaches differ in their representations, spatial descriptions, and enrichment of the semantic information of their environments.

This chapter discusses the related work that defines the basic concepts and describes the approaches and methods used to represent indoor information as well as its usage for indoor navigation activities. The first section of the chapter focuses on the different approaches of modeling of indoor spaces and its usage for indoor navigation activities; namely, route planning, tracking, and localization. This section, on the one hand, describes the available different approaches to represent indoor spaces for indoor navigation. On the other hand, it identifies the limitations of these approaches for use in indoor navigation activities. The second section of the chapter discusses related work in which different types of locomotion are used for indoor navigation. Furthermore, it gives details about how different indoor space models are used for the different locomotion types for indoor navigation. It underlines the problem of lacking support for indoor navigation for the different types of locomotion. Overall, requirements for the integration of the different indoor space models into a specific indoor model, support for indoor navigation of different locomotion types, and the development of an approach which should use geoinformation about the built environment and taking into account the locomotion type to compute accurate navigable spaces for the different locomotion types are highlighted. On the whole, the review highlights the limitations and strengths of related work in dealing with the challenges to indoor navigation as described in chapter 1.3.

2.1 Modeling of Indoor Spaces for Navigation

This section discusses fundamental approaches to the representation of indoor spaces for indoor navigation. The basic representation models for indoor spaces are classified into four types: symbolic space models, geometric space models, semantic space models, and hybrid space models. The following sections give details about these different models.

2.1.1 Indoor Space Models

Symbolic Space Models

Symbolic space models classify the indoor environment into logically closed areas. These areas share characteristics either in their visual or in spatial properties. The main advantage of these models is that they provide human-readable descriptions about indoor spaces based on indoor space points of interest and/ or structural parts (e.g., building name, room identifier, room name, etc.). There are several symbolic space models proposed by different authors (Baras and Moreira, 2010; Heiniz et al., 2012). Some of them are discussed in the following.

Symbolic space models use different approaches to model indoor spaces. Those include topological based structures, which are graphs based on connectivity and accessibility between indoor space objects, and indoor space's containment or hierarchies. However, they are divided into two fundamental types: set-based models and models based on graph.

In the set-based models, the indoor space unit's identifiers are stored into sets and subsets. The sets describe spatial relations between elements of an indoor space. For example, a building is represented by a set of all its building parts' symbols and can be further organized by a subset containing all floors' symbols of each building part. Furthermore, set-based models are further classified into two types: models based on place and object-oriented models. The place-based set models contain place identifiers which are distinguished based on the architectural characteristics of an indoor space (Becker and Dürr, 2005; Li and Lee, 2008), whereas the object-oriented set models draw interested objects with semantic information with respect to the properties of the indoor space shown in figure 2.1. The main difference between place-based models and object-oriented models is the level of abstraction. The place-based models consider places and develop a relation considering the containment relationship. For example, places of each floor makes a building and each room consists within a floor. A superset is determined as the set of floor numbers and subset for each floor containing all its rooms. Object oriented models store set entities as objects with their relations and attributes. For example, the Industry Foundation Classes (IFC) data model, provides entities of space (e.g., doors, floors) as objects (Bhatt et al., 2009). The main advantage of this modeling approach is that it models all the entities in an indoor environment along with all the characteristics attached to them.

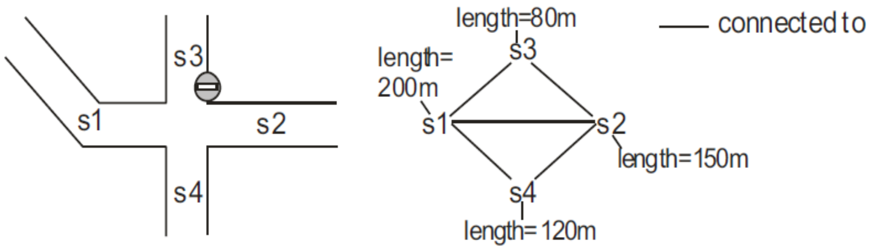


Fig. 2.1 Road geometry (left) and road topology (right) (Becker and Dürr, 2005).

Graph-based models represent an indoor space as nodes and edges in which nodes represent locations (e.g., place, point of interest) and edges depict connections between locations. For instance, a graph that represents a floor plan of a building reflects rooms from the real space (reffered as primal space) as nodes in the dual space (the real space or objects are depicted as nodes based on mathematical rules, i.e., Poincare duality). In contrast, edges in dual space represent doorways from primal space showing the connectedness relationship between the building's objects. The overall graph model representing places facilitates path queries in indoor space. Moreover, human-readable descriptions support the person in wayfinding depending on the graphs. For example, place graphs, where nodes represent places and positions within an environment and edges describe the connectivity between nodes (Gerald et al., 2005).

Symbolic space models facilitate human location-awareness with descriptive labels and provide human-friendly reference frames to deal with path and neighborhood queries. However, they lack metric information to compute distance queries and are not supportive for guidance along the paths which depend on the metric information. Furthermore, there is no formal standard for the derivation of space symbols, and symbolic models are created and managed according to the application domain. Therefore, they need more modeling effort. Moreover, the accuracy of a model is subject to the level of abstraction of the data model. However, symbolic models are often not supportive for highly accurate indoor positioning systems as they lack metric information (Afyouni et al., 2012).

Geometric Space Models

Geometric spatial models, which are also referred as metric or coordinate-based approaches, contain a finite number of non-overlapping areas representing n-dimensional indoor space with one or more coordinate reference systems. These non-overlapping areas or cells, which are subdivided from given 3-dimensional or 2-dimensional indoor space, facilitate the modeling capability to extract adjacency information between boundary sharing cells. There are two main types of division: regular and irregular division of space into cells. The former divides space into the equal shape and size cell (e.g., square or hexagonal shaped cells), whereas the latter divides indoor space into cells with different shapes and sizes, providing an opportunity to represent complex indoor structures (e.g., to represent obstacles).

A famous regular space division geometric space model is the grid-based model, which divides the indoor space into rectangular (or hexagonal) cells. A grid-based space is used to represent navigable and non-navigable regions in indoor space by associating each cell with a specific value representing whether it is occupied by an obstacle or free to navigate with a mobile robot. The grid uniformly covers the whole indoor space continuously. Furthermore, a regular grid forms a graph structure in which each node represents a cell and an edge expresses an adjacency relationship between cells. The graph structure based on a grid can be used for metric queries (e.g., shortest paths, neighborhood search) because of metric embeddedness. The accuracy of the metric queries depends on the grid resolution. Therefore, to increase accuracy, the parameters of the extent and level of granularity for the derivation of the grid have to be considered. Grids are frequently used in the robotics field for the space representation for autonomous mobile robots (Lin et al., 2013; Yuan and Schneider, 2011).

A fine-grained grid can provide very accurate results but may also introduce more processing workloads. In a huge indoor environment the number of cells may increase exponentially leading to an increase in processing time and the usage of more resources. In addition, the regular cell methods do not represent whole obstacles with arbitrary shapes resulting in either inaccurate representation of indoor space (e.g., narrow pathways to be missed in the modeling) or jagged obstacle boundaries. These problems are dealt with by 2-dimensional quadtrees to represent space in hierarchically-organized grid-based structures. This approach divides the grid into quadrants until all cells in one quadrant capture the whole obstacle or free space (Ali and Abidi, 1988; Jung and Gupta, 1996). However, the main disadvantage of this method lies in its lack of flexibility, particularly when handling a highly dynamic environment. Whenever there is a change in objects (e.g., users, sensors, obstacles), a whole update of space may require in quadtree to adjust with a new update of space. Octrees

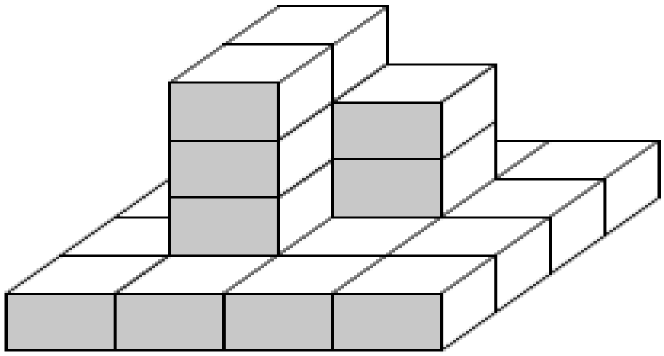


Fig. 2.2 Representing space by using cubes (Yuan and Schneider, 2011).

have the same benefits and issues in representation of 3-dimensional space as those which are in 2-dimensional space through quadtrees (Jung and Gupta, 1996). Overall, tree-based approaches are more space efficient than fine-resolution grids (Afyouni et al., 2012).

Irregular geometric space models divide only free space and use accurate cell division methods to represent complex indoor spaces. Amony others two commonly used types of division are trapezoidal and triangulation in irregular geometric space models. Both division types are formed based on the endpoints of the boundary lines of the obstacles. Trapezoidal division is constructed by projecting a line from each endpoint of an obstacle through the free space until it collides with another obstacle. The resulting trapezoidal cells are extracted to graph structures to deal with the route queries (Oksanen and Visala, 2007). Triangulation-based decomposition is built by edges among boundaries' endpoints lacking any edge crossings. A technique termed Delaunay triangulation is a well-known triangulation-based division method which divides space into triangles (Chew, 1989). Many authors presented triangulation-based approaches to automatically determine the irregular decomposition of free space (Kallmann et al., 2004; Weatherill and Hassan, 1994). Moreover, each cell segment's midpoint is mapped onto a node and boundary sharing between two adjacent cell segments is mapped onto an edge. Therefore, an adjacency graph, which provides distance queries, is constructed from cell decompositions. Another type of irregular geometric space models is the Voronoi diagram, in which the indoor space is divided based on a network of one-dimensional curves whose points are equidistant to the two nearest obstacles. This approach has been used in the field of robot path and motion planning (Liao et al., 2003; Wallgrün, 2005). Irregular space divison approaches are expensive to construct in huge indoor spaces. Thus, they are integrated with regular space division approaches to reduce resources and its expenses (Thrun and Bücken, 1996).

Geometric-based models have metric properties and can deal precisely with localization, direction, and distance queries. As they divide space only based on geometric properties, their resulting cells may not coincide with their symbolic locations (e.g., corridor) in indoor space. The unavailability of semantic or symbolic information and the availability of only coordinates to guide the user in indoor space make these models difficult to use for the common user. In contrast, these models are mostly used for mobile robot navigation because they can navigate only on coordinates information. In addition, the main advantage of these models is that they are accurate and have well-defined automatic methods to map indoor space into graph structures.

Semantic Space Models

Symbolic space models provide meaning to objects of indoor space with qualitative labels. For instance, an "exit door" is a door that can be used for exit in case of extraordinary situations. From this textual description, a user can also infer possible actions (e.g., to walk through this door in case of emergency) offered by this space. These symbolic labels and qualitative reasoning about their meaning is dependent on previous knowledge of environment or situation. But these symbolic space approaches do not provide any formal representation of this knowledge. For the applications on indoor spaces, the geometrical, graphical, and symbolical considerations are not the only important to consider. The semantics of objects must also be considered. For example, in an emergency situation, calculating the safe doors or windows, and computing the impact on specific rooms in case of fire in a specific part of a building requires the semantic properties of objects. These applications require formal representation of spaces with their associative semantics. Thus, purely geometrical and symbolic space models are inadequate for these applications. Furthermore, semantic space models provide a conceptual perspective against the qualitative and quantitative considerations of space in symbolic and geometric space models. They make the spatial knowledge of objects explicitly defined and enable users to share and reuse this knowledge. Additionally, they describe concepts by considering different aspects like types, meaning, their properties, and relationships of spaces (Gröger and Plümer, 2012; Worboys, 2011).

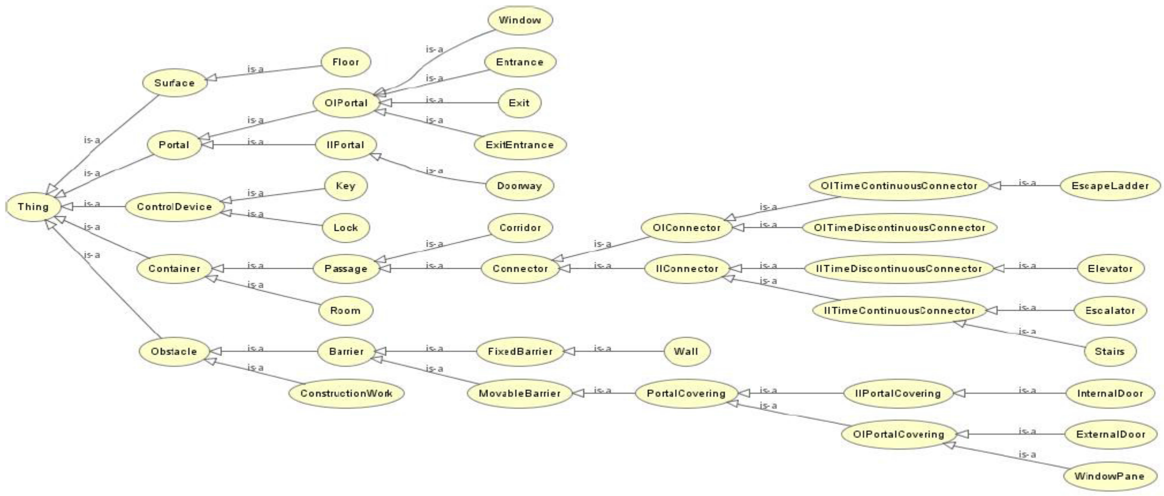


Fig. 2.3 Structure ontology of indoor space (Worboys, 2011).

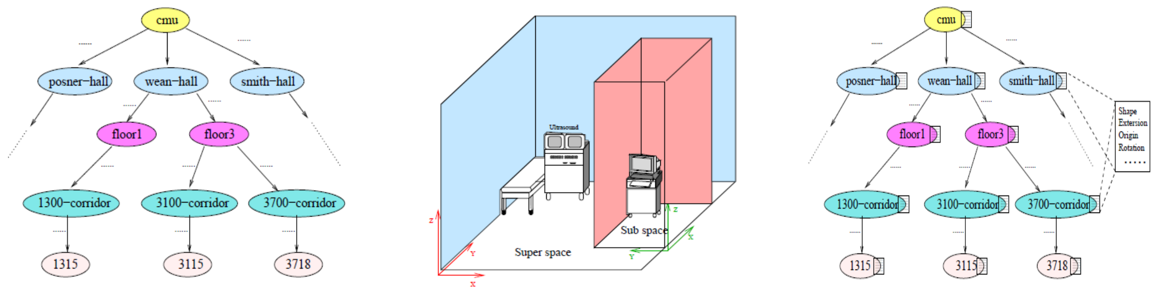
There are two main approaches through which semantic information is presented formally: conceptual models and ontologies. Conceptual models are frequently used in the GIS community and ontologies are typically used in the field of Artificial Intelligence. Conceptual models are realized through formal modeling languages and graphical representations of semantic objects. For instance, Unified Modeling Language (UML) and Entity Relationship diagrams are very commonly used to describe objects' semantic descriptions (Modeling, 2014). Meanwhile, ontologies define a specific domain with the support of classes, properties and relationships (Smith, 2008). Apart from representation, they provide reasoning and decision making skills about semantic formations and spatial configurations (Worboys, 2011).

At the conceptual level the semantic space models provide different types, observational meanings, semantic properties, and mutual relationships of indoor space objects. These concepts are captured from the real indoor environments through observation of the abstract concepts of indoor objects. Therefore, these concepts can be validated from the real indoor environment. However, the formation of conceptual models from real objects leads to the complex challenge of object interpretation because semantic information of indoor objects may vary due to different conceptual views, their meanings, and their levels of detail. This challenge can be overcome with the concept of forming ontologies at the high-level, domain level, and task level for indoor spaces (Yang and Worboys, 2011).

Hybrid Space Models

Geometric space models have metric attributes to provide distance information and accurate location, whereas symbolic space models which contain an abstract view of space, provide understandable information for humans about locations. However, these models lack metric information of space. Therefore, both approaches are not suitable to deal with the different requirements of indoor navigation. Similarly, a semantic space model alone can only provide semantic information. However, to have accurate location information and to deal with metric queries, the integration of a geometric space model is needed. Hence, integration of different space models enrich models to consider qualitative and quantitative points of view to deal with requirements of users (Kuipers, 2000). Several researchers have presented numerous approaches of combining different space models with the main objective of combining the various advantages of the different space models (Buschka, 2005; Leonhardt, 1998; Wallgrün, 2005).

Hybrid space models can be developed through distinct ways: Parallel models, patchwork-based approaches, and hierarchical models (Kuipers, 2000). Parallel or overlay models use integrated, different space models that cover the entire indoor space. Patchwork-based models consist of several local models which are combined together to develop a global space model (usually geometrical models are used at the local level and symbolic models are used at the global level. Hierarchical models enclose several layers with many abstraction levels (Fernández and Gonzalez, 2002; Jiang and Steenkiste, 2002)).



(a) Hierarchical space tree

(b) Specific space has its own coordinate system

(c) Hybrid geometric space tree

Fig. 2.4 Integration of different spaces in hybrid location model (Jiang and Steenkiste, 2002).

Jiang and Steenkiste (2002) have presented a hybrid space model which deals with location-based queries. The model is integrated using a hierarchical, symbolic, and geometric space model which contains the representation of objects of interest, sensor coverage ranges, and places. The model combines the strengths of all the integrated space models to deal with location-based queries. Unfortunately, the model lacks the capability to consider contextual dimensions in dealing with location-based queries. Another hybrid model has been presented by Stirbu (2009), which combines different location models representing different activities of the users. The foundation layer is constructed by a quadtree, while taking account some points of interest. Moreover, several topological models are considered based on users' activities. A simple graph model is used in combination with a lattice model to perform location-based queries (e.g., path queries, location).

A framework for mobile navigation has been presented by Fernández and Gonzalez (2002), which contains an annotated hierarchical graph model and consists of integrated multiple topological layers representing nodes and arcs at various levels of abstraction. Information is attached to arcs and nodes through a function at each level of abstraction. The model also supports basic queries (e.g., path searching). The model was further improved to include semantic hierarchy for human-robot communication (Galindo et al., 2005).

Bhatt et al. (2009) proposed a framework for a sound formalization of the integration of different space dimensions through modular ontologies which include quality, quantity, conceptual space. The conceptual space module represents the entities of space according to their properties without considering the context in which they operate. The quality space module specifies qualitative spatial characteristics of entities and the quantity space module defines metrical and geometric information of entities. The instances in each module are formally integrated based on the E-connection theory for ontologies. The main idea of E-connection is the interpretation of 'link relations' between disjoint domains (Kutz et al., 2004).

2.1.2 Three-dimensional Building Models

Differentiation based on Modeling Aspects

3-dimensional building models can be classified based on various modeling aspects: geometry models, topological models, semantic models, appearance-based models, and geo-referenced models. Geometry models represent 3-dimensional environments with geometric entities (e.g., triangles, lines, curved surfaces). These models are widely used in the field of 3-dimensional graphics, in the gaming industry, and in architecture. The usage of geometry models for the indoor navigation of autonomous robots through robotic mapping (e.g., grid maps, voxels) is very common. They provide metric information and are considered to be highly quantitatively accurate for indoor navigation activities (Gutmann et al., 2008; Wurm et al., 2010; Yuan and Schneider, 2010). Furthermore, these 3-dimensional environment models facilitate robot navigation with a high level of detail but on the other hand it increases processing costs and the usage of resources. Therefore, to avoid processing cost, many users prefer to represent the environment at some level of abstracted form with topological models. Topological models provide connectivity and adjacency information of each object relative to its neighborhood in an indoor environment, making it easier for the user to navigate (Lee and Kwan, 2005; Remolina and Kuipers, 2004). The main advantages of topological models are: the provision of topological information of the relevant entities, the representation of 3-dimensional environments in the easiest possible way to understand for the user, and abstraction (to avoid unnecessary processing time and resources). Apart from geometric and topological information, there is always the need for formal semantic representation of an indoor 3-dimensional building model's objects which support semantic queries and making 3-dimensional building model applications in different areas, for example, emergency, environmental, and energy planning (Iftikhar et al., 2014; Kolbe et al., 2008, 2005). These semantic models have several indoor navigation applications. For instance, the guidance of exit routes in rescue operations from indoor space (Rueppel and Stuebbe, 2008; Schilling and Goetz, 2010). Aside from semantic 3-dimensional building models, there are various building modeling approaches which focus only on visualization. For example, COLLADA formatted 3-dimensional building models. These approaches are frequently used in indoor virtual reality models for visualization purposes (Liu et al., 2010).

Differentiation based on Modeling Paradigms

Three-dimensional building models basically use two types of modeling paradigms for the representation of 3D geometry: Computer Solid Geometry (CSG) and Boundary representation (B-rep). The basic difference between these modeling approaches is that the former uses Boolean constructions or combinations to create complex surfaces or objects and the latter models the boundaries of building objects with a sequence of primitive geometries, such as points, lines, and surfaces. The CSG approach allows a user to create complex surfaces or solids by using Boolean operations (e.g., set operations: intersection, difference, and union) to merge or divide an object(s). An object representation is formed by ordered binary trees in which non-terminal nodes depict either rigid transformations or sets of operations. CSG representations are widely used in design focus operations where capturing the design of an object in the form of primitives is important (e.g., the addition or removal of material of an object represents primitives). The main advantages of CSG modeling are its accuracy, its guaranteed validity of primitives, and its natural formation of objects from sub-objects. On the other hand, Boundary representation models objects from its user's surface observational point of view. These models hold two types of information: geometric and topological. Topological information represents the relationship among points, edges, and faces. Geometric information provides details about the geometry of objects which include vertices, curves, and surfaces. These models are typically constructed either using extracted from sensor data or designed by CAD (Computer Aided Design) systems.

Indoor space models can be are represented through both approaches CSG and B-rep. For example, CityGML building models use B-rep and IFC can use a CSG model to represent indoor building models. Both approaches have strengths and limitations depending on the specific application. Apart from these two types there are grammar-based models where city building models are developed based on grammar-based systems considering the regulations and requirements for an urban proposals (Jacobi et al., 2009). In addition, there are scene graphs where hierarchical structure of shapes, groups of shapes, and groups of groups that collectively represent the details of the scene (Nadeau, 2000). The details of the scene further represent an environment or urban model.

Three-dimensional Building Modeling Standards

International standards, such as CityGML and IFC, provide standardized formats to represent, store, and exchange 3-dimensional city and building models. These standards generally target building models and to some extent focus on indoor building environments. Nevertheless, they are used for indoor building models and act as a main source of geo-information for indoor navigation applications. An overview of the two main building modeling standards which have different scopes is given below.

Building Information Modeling (BIM)

Building Information Modeling (BIM) is the process of using and creating a 3-dimensional building model during the project life-cycle of buildings for construction, design, planning, and operation. It is used as a base of accurate information for knowledge sharing among different domains of a project (e.g., facility management, construction, design engineering, etc). The Building Information Model is based on semantically enriched object oriented model which can be used to make decisions according to views and data appropriate to different users. Hence, a BIM model contains all information of a building, from different aspects including design, construction, operation, and maintenance procedures (Bazjanac, 2004). BIM has several applications. Some of them include: visualization, fabrication/shop drawings, facility management, cost estimating, conflict, interference, and collision detection between construction objects. The usage of BIM for different projects has enormous benefits and CIFE (2007) has summarized some of them; a 40 percent abolition of unbudgeted changes, accuracy in cost estimation within 3 percent, an up to 80 percent decrease in time taken to produce costs estimates, and an up to 7 percent decrease in project time (Azhar, 2011; CIFE, 2007).

The International Alliance for Interoperability (IAI), a non-profit, international alliance of construction industries with 550 organizations in 24 countries, was formed in 1995 with the objective to develop innovative concepts that can improve methods of sharing information over the life cycle of construction projects. The IAI has defined a specification for sharing data, globally, across disciplines, and applications known as Industry Foundation Classes (IFC). The IFC data model is an object-oriented data model representing the objects, their properties, and interrelationships. The IFC specification is maintained and further developed by the non-profit organization buildingSMART[1]. The IFC format is also registered by ISO[2] as an official standard ISO/PAS 16739. The latest official version of IFC is IFC4, released in March, 2013. The IFC schema architecture defines a core data layer which provides basic structure, relationships, and common concepts for all specialized models. Furthermore, the shared element data schemas specify a common element layer which provides more specific relationships and objects that are shared by several domains. There are also domain specific data schemas which organize definitions according to specific industry areas. The elements related with the built environment are assembled in shared building elements (*SharedBldgElements*). This element provides a conceptual model of indoor space for a building model. The whole building (*ifcBuilding*) is divided into floors (*ifcBuildingStorey*) which may consists of many spaces (*ifcSpace*). The building's indoor space is structured with spatial elements (*ifcSpatialStructureElement*), which are populated with building elements (*ifcBuildingElement*). The building elements include walls (*ifcWall*), doors (*ifcDoor*), windows (*ifcWindow*), slabs (*ifcSlab*), roofs (*ifcRoof*), columns (*ifcColumn*), and stairs (*ifcStair*). Each building element can have explicit geometric and topological representations. Geometry is normally represented in a local Cartesian Coordinate System (*ifcLocalPlacement*). Relationships between building entities, construction materials, and thematic properties can also be represented.

The IFC data model can be classified as a hybrid space model (classification scheme presented in section 2.1.1). It provides symbolic, semantic, topological, and geometrical information of indoor spaces. However, this data model does not provide any method or concept through which a graph can directly be developed for indoor space. Also, it lacks the subdivision of space according to different locomotion types. One of the important aspects that also needs to be considered is that the IFC geometries are modeled through a volumetric approach which focuses on the construction of an object. However, for the consideration of the context in indoor navigation when user considers different types of locomotion then they typically interact with boundary surfaces of indoor space. Therefore, indoor representation model which is based on boundary representation will get more preference in this case. In this sense, the BIM models act as a key source of information for the applications of indoor navigation because they are enriched with all indoor space information. However, the automatic subdivision of indoor space representations according to different locomotion

[1]buildingSMART is a non-profit organization to develop international standards for built environments. www.buildingsmart.org

[2]ISO (International Organization for Standardization) is a private, non-governmental membership organization, and one of the world's leading developer of International Standards. www.iso.org

types and the derivation of graphs with all spatio-semantic information are still needs to be investigated.

Topographic Information Models (TIM)

Topographic Information Models (TIM) model buildings, cities, and regions with the objective of developing a digital geoinformation resource for representing the natural and man-made features which can be used for decision making in several applications such as city and telecommunication planning, disaster management, real-time simulations for training, indoor navigation, and local or national or continental cadastral modeling. The main parts of TIM models are digital surface and terrain models, building environments, and the natural outdoor environment (e.g., vegetation). TIM models objects are represented with spatial, semantic, and topological information as well as with their functional information. In addition, they contain their decomposition hierarchies and relationships which are replicated from the real world (Kolbe, 2009; Kolbe et al., 2005). The geoinformation of a TIM is gathered through different approaches such as remote sensing, photogrammetry, and engineering surveying. The name TIM stands for topography gathers information as it is observed, in other terms, it stores geometries in boundary representations because boundary representation approach constructs geometry objects based on the user observation of the environment. All of the objects of TIM model are usually geo-referenced with a specific local or national or global coordinate system so the objects can be visualized through different visualization tools in real position on the surface of the Earth.

A 3-dimensional city model refers to a 3-dimensional modeling of a city and its objects in which geoinformation knowledge can be used in different applications for decisions at the city or regional level. In recent years, there has been a general trend to establish 3-dimensional city models with the objective to provide useful applications for its citizens (e.g., disaster management) (Iftikhar et al., 2014; Kolbe et al., 2008). This trend further accelerated with the modeling of cities at the national and regional level (e.g., a national 3-dimensional city model in the Netherlands and the European INSPIRE program [3] have targeted making a spatial data infrastructure for the whole European countries (Stoter et al., 2013)).

CityGML was initiated by the Special Interest Group (SIG 3D) in 2002 under the supervision of Thomas Heinrich Kolbe. Since then, it is currently being developed further by the SIG 3D. In 2008 CityGML became an international standard of the OGC (Open Geospatial Consortium)[4], an international standards organization of more than 450 companies, universities, government bodies, and research organizations. CityGML's current version 2.0 was adopted in March 2012. CityGML's main focus is on the semantic definitions of city objects including buildings and their parts, terrain, furniture, water bodies, and transportation objects. These thematic definitions address the issues of semantic heterogeneity and the support of data integration. Geometrical and topological representation uses the Geography Markup Language (GML) standard which is based on the markup language XML. This in turn provides support for data integration and minimizes heterogeneity.

For 3-dimensional city modeling, CityGML covers all relevant city objects. For each of these objects, semantic attributes, hierarchical relationships, and spatial representations are presented. The objects of city are constructed based on the concept of modules (e.g.,

[3]The European Union's initiative to develop an infrastructure for spatial information in Europe to assist environmental policies. www.inspire.ec.europa.eu

[4]The Open Geospatial Consortium is an international organization of 472 government agencies, companies, and universities to establish publicly available interface standards. www.opengeospatial.org

vegetation module). The core module presents the base classes for all objects in CityGML which share attributes. One of the most attractive features of CityGML is the provision of multi-scale representations of city objects in five levels of detail (LoD), regarding geometric granularity of the object modeling and semantic differentiation from LoD0 to the finest LoD4.

The city's building objects are represented using the building module. This module represents buildings and their parts with respect to geometry and semantics. At LoD4 of the conceptual building model, the indoor building environment is represented. The main conceptual building model class is *_AbstractBuilding* which is a subset of class *_CityObject* and which can be specialized into either Building or *BuildingPart*. Both classes inherit the attributes of the superclass. The building can be refined from LoD1 to LoD4. An object can be represented in distinct LODs by providing different geometries with respect to relevant LODs. In LOD1, a building model is represented by a building volume or block model using solid geometry. This building volume or block model is refined in LOD2 by providing *MultiCurve* and *MultiSurface* geometries, to represent architectural details of a building (e.g., columns or chimney). The outer facade of a building can be distinguished in LOD2, and higher LODs,semantically by the classes *BuildingInstallation* and *_BoundarySurface*. In LOD3, openings can be represented as components of *_BoundarySurface*. In LOD4, the building's interior can be represented by the class *Room*. The observable surface of a room is reflected geometrically as *MultiSurface* and volumetric room object is reflected as a *Solid*. The surface can be semantically classified into floor (FloorSurface), ceiling *(CeilingSurface)*, and interior walls *(InteriorWallSurface)*. The interior objects like lamps, pillars, chairs, and tables can be represented by the classes *BuildingInstallations* and *BuildingFurniture*. Furthermore, at all LODs, a building model can have individual or generic *TexturedSurfaces*, which play a very important role for visualization. The detailed specification can be accessed from OGC (2014a).

CityGML can be used for indoor navigation tasks because it provides most of the required information (semantic, geometrical, and topological information) for indoor navigation. It provides the semantic information about obstacles in indoor space but also their geometric representation, which makes CityGML most feasible for context aware indoor navigation. However, CityGML does not provide support for subspacing of indoor space based on different locomotion types, and explicit representation and conceptualization of connectivity and adjacency information of building objects.

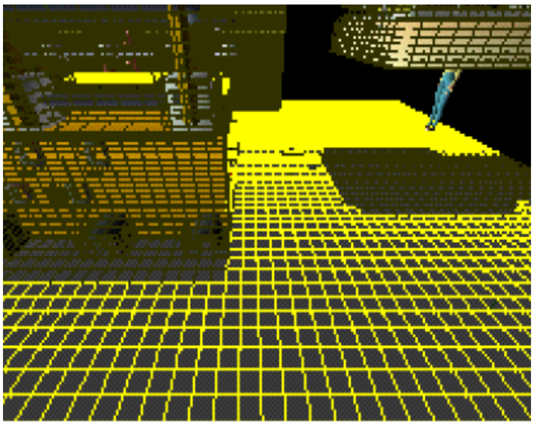
2.1.3 Space Abstractions from Three-dimensional Building Models for Indoor Navigation

Space representation of 3-dimensional environments is being intensively studied in the fields of robotics and 3-dimensional GIS. Commonly, the space representations are abstracted (e.g., represented by graph models) to carry out indoor navigation activities (e.g., route planning). The physical abstraction methods are highly linked with the environment representations because the abstractions (network models) are generated from these environments. The abstraction approaches differ in the focus they put on the particular aspect of space. For instance, some approaches define and use only geometric models for abstraction, whereas others use semantic information as a complement to geometric models for abstraction purposes. In the following, different approaches of abstraction from 3-dimensional environments or building models are reviewed.

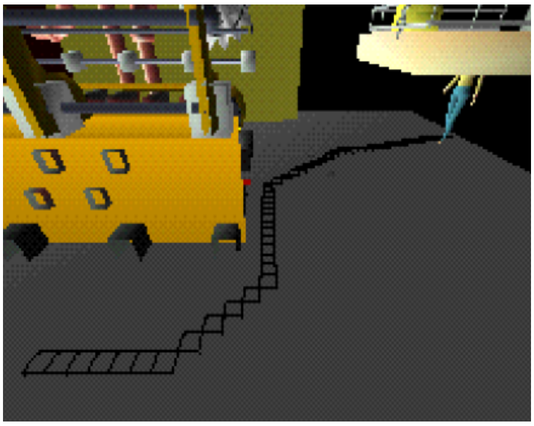
Grid-based Abstraction

The concept of representing a 3-dimensional environment discretized into equal-sized cells was first presented by Moravec (1988). In general, in the first step, sensor returns an indication that an object is or is not in its field of view. If sensor reports existence of an object then certainty grid 'Cx' is updated with a formula Cx:= Cx + Px- Cx x Px. Where Px contains set of numbers representing probability of certainty of object's existence in field of view which should be scaled so their sum is 1.In case there is no object in its field of view then formula might be Cx:= Cx x(1-Px), where Px represents only the chance that an object has been overlooked. Elfes (1989) also presented the same approach to represent 2 or 3-dimensional environments by tessellation of space into cells, and each cell is given a probabilistic estimate of its state as occupied, empty, or unknown. The author used these occupancy grids for mobile robot mapping in indoor navigation. Based on 2-dimensional grid maps, which contain accurate metric maps, the proposal to create topological maps is presented by Thrun and Bücken (1996). Topological maps are built by decomposing the grid-based maps into regions separated by narrow passages, for instance, doorways. The regions are then mapped into a graph, where nodes and arcs represent regions and connectedness of regions respectively. The overall graph forms the topological map to use for navigation.

Bandi and Thalmann (1998) presented an approach to generate motion paths automatically in complex 2-dimensional or 3-dimensional environments using grid-based abstractions as shown in figure 2.5. They discretized the space into a 3-dimensional grid of uniform cells and treated the grid as a graph to compute discrete navigable cell paths between two points. Each cell in the grid map is marked as an obstacle or a non-obstacle. They further represent border cells (borders of obstacles) such as borders of walls, pillars etc. as non-navigable considering the safety of the navigating human. Based on a free map and an obstacle map, they compute the global navigable path for the person.



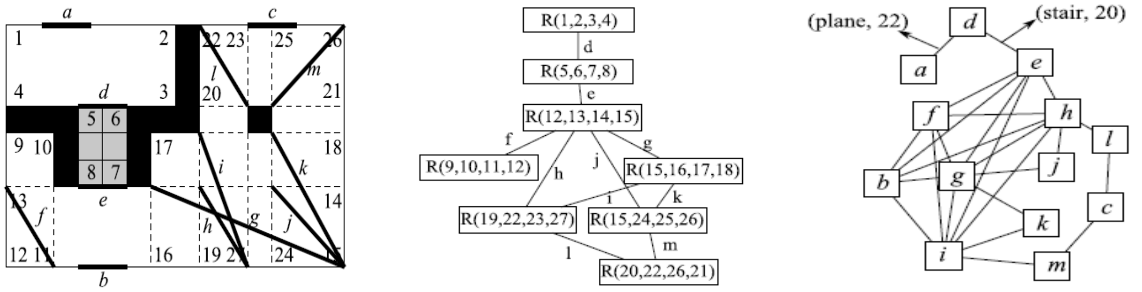
(a) Floor surface: floorfill for border cells



(b) Path generation

Fig. 2.5 Space discretization for human navigation and computation of navigable path (Bandi and Thalmann, 1998).

Yuan and Schneider (2010) presented a method in which a 3-dimensional indoor environment is decomposed into 3-dimensional cubes with the same base area and varying heights according to the object it represents. For instance, cubes representing a regular shape are different from cubes representing a pyramid-shaped cell. Each cube is judged against the properties of the navigating object to decide for its navigability. Hence, cubes are classified into obstacle and non-obstacle. The cubes are then merged into large blocks according to



(a) A floor surface with obstacles and stairs

(b) The graph representing the connectivity of the blocks

(c) Corresponding LEGO graph

Fig. 2.6 Extracting LEGO graph model from a floor plane (Yuan and Schneider, 2010).

the types of cubes and their navigability for the considered object. Then, these blocks are mapped into a graph representing each block as a node and their connectedness as an edge as shown in figure 2.6. The resulted graph reflects all navigable paths with various navigable widths and heights in a given indoor space situation.

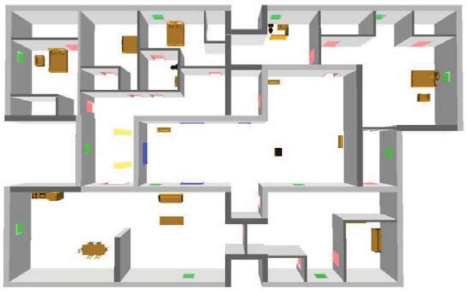
Lin et al. (2013) has presented a method to use semantic 3-dimensional building models for path planning on grid-based maps as shown in figure 2.7. This method has three main steps: in the first step, semantic and geometric information is extracted from building objects from an IFC file. In the second step, the floor surfaces are discretized into a planar grid. The last step extracts the topology graph for path planning. By using semantic information from the 3-dimensional model against the navigating subject's properties, it classifies each grid cell as being either an obstacle or navigable and then creates a hazard zone around obstacles to avoid for route planning. After having numerical values attributed to each grid cell which contain information about being navigable, non-navigable, and its risk level, the graph is generated from the grid. Furthermore, on this graph, various path planning queries may be applied (e.g., the shortest route between two points).

The main strengths of grid-based abstraction include high accuracy in representation of indoor space, having metric information, the simple application of geometric navigation constraints by associating numerical values with each cell, and easy process of reflection of the grid map into graph abstraction. However, these models also have some limitations, those are: in some cases due to rigidity of the grid, indoor space or objects cannot be represented accurately and, semantically decomposed objects of an indoor space are not parallel or adjustable with the grid resolution which results in not being represented in grid maps.

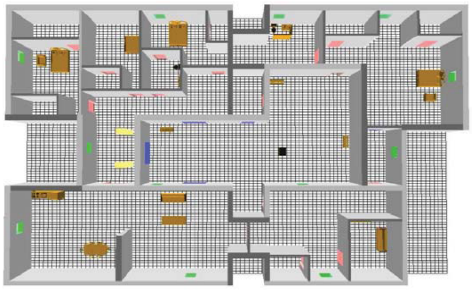
Cell Based Abstraction

Cell-based abstraction methods represent tessellations of indoor physical space. The resulting abstracted graph model from the physical indoor space captures the real building layout without caring about the shape and size of objects and with its natural relationships among its components. One of the early approaches to abstract the real world with graph models was presented by Remolina et al. (1999), in which places are grouped into regions and then regions are mapped into graphs where nodes and edges represent regions and relationships (connectedness) respectively as shown in figure 2.8. Some methods of cell-based abstraction from different researchers are presented in the following paragraphs.

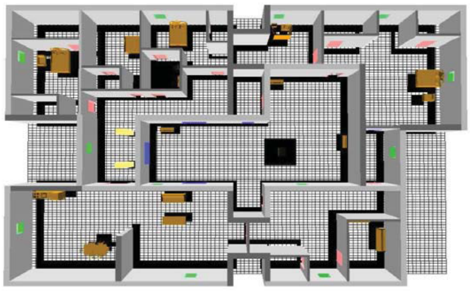
Gilliéron and Merminod (2003) presented a personal navigation system which uses a graph model of buildings extracted from CAD floor plans. The graph model represents building objects like rooms, stairs, corridors and their topological relationships. The graph model is called a node/link model and contains nodes representing long corridors or rooms



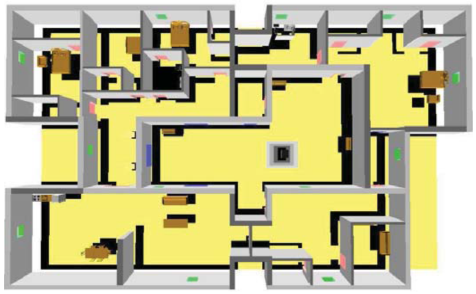
(a) The original IFC 3D building model.



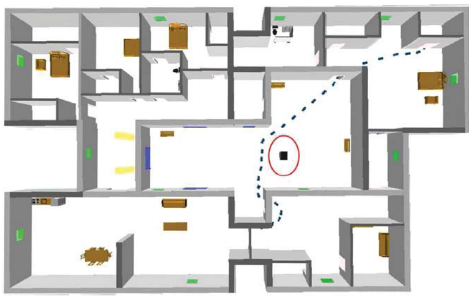
(b) Space discretization.



(c) IFC elements of the building model are represented as grid nodes: the grid nodes occupied by building elements are changed as 0 (unnavigable).

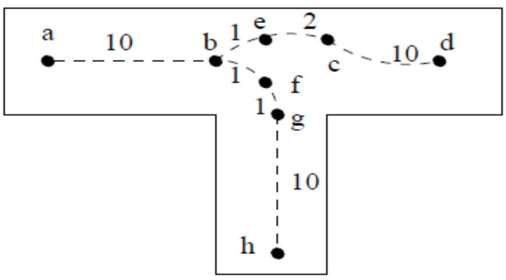


(d) Semantic information of building components is mapped into the grid nodes by providing relevant semantic information.

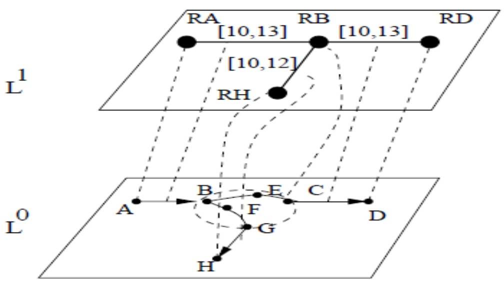


(e) Computation of the shortest path after taking into account the risky areas.

Fig. 2.7 Grid-based path planning using a 3-dimensional indoor model given in IFC (Lin et al., 2013).



(a) Places are grouped into regions.



(b) The resulting graph from the regions

Fig. 2.8 Formalizing regions and developing graph models from those regions (Remolina et al., 1999).

which can be further decomposed into more than one node. The elements of this graph are augmented with semantic information from building objects (e.g., access rights or the opening time of a room) which are necessary for the computation of routes in indoor navigation.

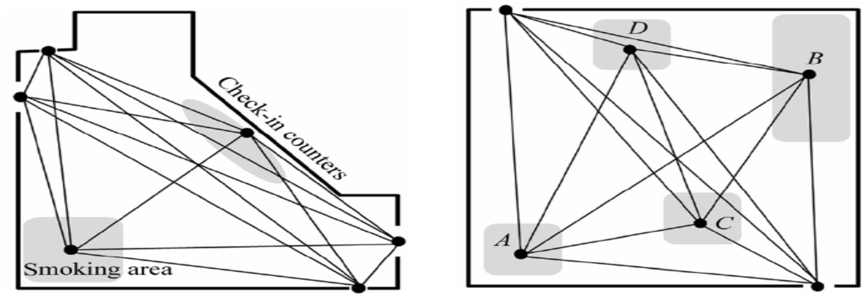
Meijers et al. (2005) developed a structure for evacuation from indoor spaces. The model is based on the subdivision of the building space into well-defined parts named sections, which are not overlapping and closed. Otherwise, virtual polygons are introduced to close the sections. Sections are classified into three types: end (exit or only one entrance), connector (exit or more than one entrance),or non-accessible (exit or no entrance) sections. The building model forms a graph model according to predefined rules, which include: an end section is always represented as a node, a granting space (passing, e.g., door) maps to an edge, and a connector section maps to a graph (nodes and edges). This model can be used for evacuation and visualization purposes as it contains semantic and geometrical information.

Lorenz et al. (2006) presented a spatial model for representing indoor environments. The model contains hierarchically structured graphs which consist of nodes and edges. Nodes of this graph represent rooms and corridors of a building floor plan, whereas edges represent pass-ways between rooms and corridors. The nodes of the graph can be enriched with semantic information of building spaces. Furthermore, to represent large free spaces like huge rooms or corridors, the space is divided into many further cells and each cell is represented as a node in the graph. This results in representing many nodes for a single large room containing many adjacent cells. The model also use hierarchical graphs to represent the hierarchical relationships of building parts. For example, each floor is represented by one node and the floor node contains further nodes to represent rooms on that floor. The nodes contain semantic information. Therefore, they support the generation of human understandable route plan instructions.

Using the concept of Lorenz et al. (2006), Stoffel et al. (2007) offered a graph based spatial model and algorithm which can be used for path planning in indoor environments. It provides a systematic approach to develop a network model from geometrical data of an indoor space. The algorithm takes as input floor plans of the building model in a vector-based format containing polygons representing regions or cells of building space. For indoor navigation, access points on the shared boundary of adjoining spatial polygons or regions are determined as boundary nodes. It also considers the hierarchical relations of the physical space of a building organized into floors, rooms, sections, etc., resulting in hierarchical graphs. Furthermore, the algorithm creates a partition of non-convex region into non-overlapping convex sub-regions. This stage includes linking concave corners or the next convex corners of polygons. Using this partitioning, the navigational graph for the physical space is developed, which can then be used for route planning between boundary nodes.

Goetz and Zipf (2011) presented a length optimal and user-adaptive routing graph model for complicated indoor environments. The model represents indoor spaces with semantic, topological, and metric information which supports routing in complex indoor building structures. The model partitions an indoor space into different areas according to special considerations. For example, a room can be further partitioned into different spaces based on a specific consideration (e.g., check-in counters or smoking areas). The partition areas are represented as nodes in the graph model and based on the accessibility paths between areas (the edges are created as shown in figure 2.9). Furthermore, different routes which consider the contextual requirements of different users can be computed.

Liu and Zlatanova (2013) have presented an approach which generates navigation models from existing 3-dimensional building models. Rooms are considered as nodes and openings or connections between rooms are considered as edges in a network model. This net-



(a) Routing graph for an airport entracne hall.

(b) Routing graph for an exhibition hall

Fig. 2.9 Developing graph models from several areas and obstacles in big rooms (Goetz and Zipf, 2011).

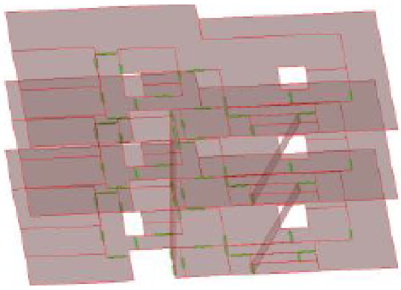
work model contains all the semantic information from the 3-dimensional building model stored in CityGML LoD4 format. Before creating the network model, a preprocessing step is done which includes creating virtual openings in the case of stairs and rooms. Furthermore, using floor plans of the 3-dimensional building model a network model is constructed also taking into account the semantics information of building (e.g., a door can always be open or only in emergency situations) for the accessibility representation. After generating a network model it is enriched with semantic information (as shown in figure 2.10). Logical based graph models are created from the main graph model of building.

Cell-based abstraction approaches for indoor navigation are typically prefered by common users over grid-based approaches as they are very abstract and may contain semantic information as well as can guide users in path planning in his/her understandable descriptions. They also depict complex indoor spaces in understandable way for users through graph models as they represent hierarchical relations of building and their parts. The abstraction of indoor space may be fruitful for some types of locomotion (e.g., human beings) but for other types of locomotion, detailed representation of indoor space my be needed for navigation. For example, the representation of navigable and non-navigable space within a room. In addition, most of the discussed methods represent only free spaces. This may restrict the flow of information about indoor space because in many emergency cases there may be a requirement to know about the obstacles in a specific indoor space (e.g., walls). Liu and Zlatanova (2013)'s method of constructing graph models from 3-dimensional semantic models using preprocessing steps is an encouraging development. However, there is a need of a standard procedure through which different existing semantic 3-dimensional building models can be converted into network models with their semantic information to use for various applications of indoor navigation. Moreover, the approaches discussed herein do not consider subdivision of indoor space according to different locomotion types.

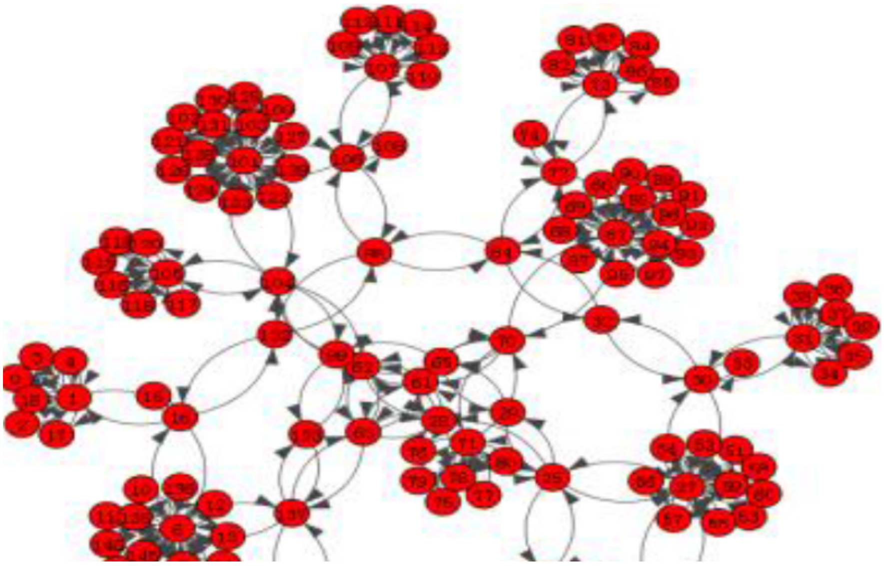
Graph Based Abstraction

Both grid and cell-based approaches use graph models to represent indoor space in abstracted form. Some of the graph-based abstraction approaches are discussed in the following paragraphs. Lee (2001) presented a 3-dimensional data model to reflect topological relations of urban objects. It depicts adjacency, topological relationships, and connectivity relationships between 3-dimensional objects in an indoor environment using Poincaré duality (as shown in figure 2.11). To model the complex relationships between 3-dimensional objects, the author utilizes the mathematical rules of Poincaré duality, in which objects in the real environment (primal space) are transformed into dual graph (in form of nodes and edges)

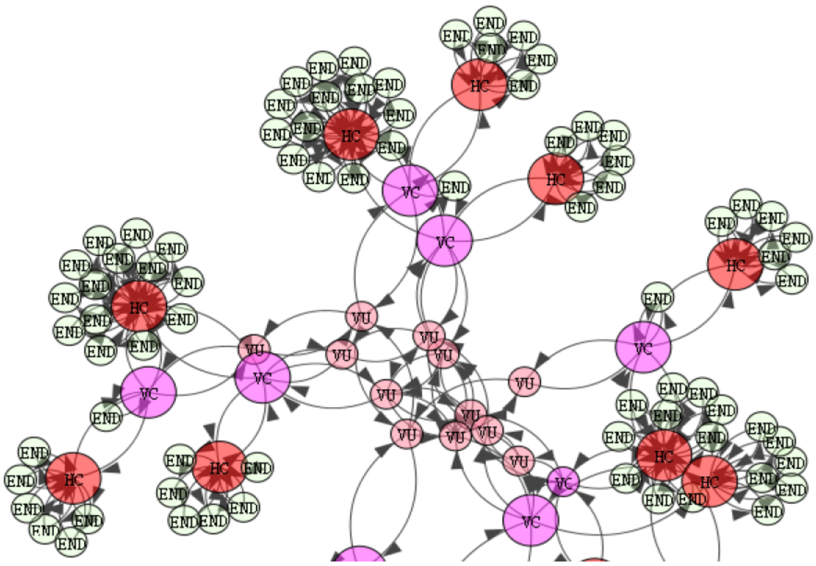
(a) Orginal floor plans of a building



(b) Recreated 2.5D building model



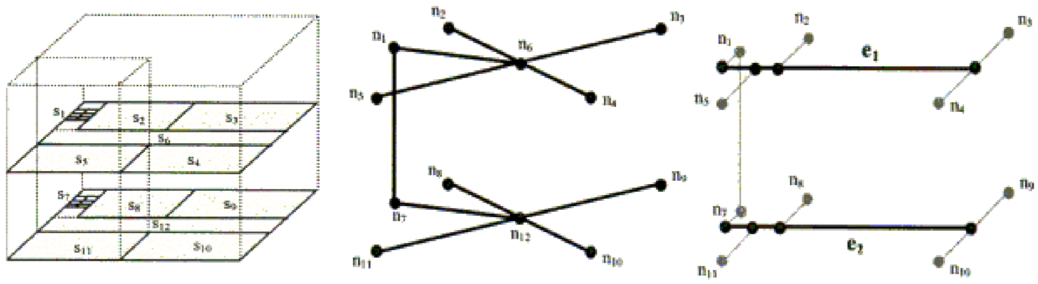
(c) Connectivity network. Red circles and arrow directions are representing room spaces with their room numbers and passage direction from one space to another respectively.



(d) Connectivity network enriched with semantic information (nodes are attached with space information, e.g, end space, hall, etc.).

Fig. 2.10 Producing navigation models from building models (Liu and Zlatanova, 2013).

in the dual space. The rules include transformation of 3-dimensional, 0-cells, 1-cells, and 2-cells in the primal space into 2-cells, 1-cells, and 0-cells respectively in the dual space. In simple words, solid 3-dimensional objects in the primal space are converted into vertices in the dual space and a common boundary shared by two 3-dimensional solid objects in the primal space are converted into an edge in the dual space. The major benefit of this formal transformation is that all topological characteristics will be preserved. The topological relationship between 3-dimensional objects can be depicted in dual space with nodes and edges and is called Node-Relation Structure (NRS). NRS is defined as a collection of nodes and edges. Once the NRS is refined according to the accessibility from one object to another of the 3-dimensional objects then it forms a network model refered as combinatorial network model which reflects the connectivity relationships between the 3-dimensional objects of the indoor space. The combinatorial network model which contains the abstraction of a node for a room or a corridor is combined with the central line or skeleton of the room or corridor through Medial Axis Transformation. Thus, distance queries can be dealt with easily and accurately. The model was implemented on real 3-dimensional data by Lee and Kwan (2005) to perform spatial queries and for visualization purposes. The same model was experimented by Lee (2004), Lee (2009), Lee and Zlatanova (2008) for the analysis of human activities and to provide navigation guidance for the rescue operations in 3-dimensional building models of indoor spaces.



(a) 3D building model (b) Combinatorial network (c) Geometric network

Fig. 2.11 The generation of a geometric network model from a 3D building model (Lee, 2001).

Jensen et al. (2009) proposed an indoor space model which uses Poincaré duality to translate 2-dimensional cells into dual space. The cells in the primal space represent spatial regions like rooms, corridors, or stairs. In this model, an adjacency graph in the first hand is developed and then refined into connectivity graph. The consideration of the movement permitted by doors is represented by a directed edge, which converts the connectivity graph into an accessibility graph. The authors also considered sensor cells to facilitate localization for indoor navigation. For sensor representation, they use so-called deployment graphs which reflect the topological relationships between sensor cells. The edges of deployment graphs are tagged with RFID readers' identifiers, which monitor the movements of subjects or objects between cells.

Boguslawski and Gold (2009) presented a data structure called dual-half edge (DHF) for the modeling and storage of primal and dual 3-dimensional cells of indoor space. The indoor building model is represented by non-overlapping polyhedral cells which are adjacent and connected. In dual space, these polyhedral cells are represented by nodes and edges which also represent topological adjacency relationships. The DHF stores only edges and nodes for the representation of a cell in primal space. An edge is divided into a pair of half-edges, each edge directing towards its related node and its paired half-edge to makes the opposite of the edge. Two pointers are created, one to the next half-edge around the vertex and one to the next half-edge. The authors used this data structure for route planning. This data structure is also used for the formal definition of a set of Euler operators that can construct and modify the cell complex of an indoor space (Boguslawski and Gold, 2010).

The main advantage of the discussed graph-based approaches is that they are based on a sound mathematical rules. However, these approaches do not discuss the usage of these models for the representation of navigable and non-navigable spaces. In addition, they also do not consider the subdivision of indoor space according to different types of locomotion.

Hybrid Models Based Abstraction

Hybrid models based abstraction approaches focus more on support of semantic and conceptual or symbolic modeling of geometric (grid and cell-based) and topological (graph-based) abstraction methods for indoor navigation. In other words, strengths are combined from semantic, topological, and geometrical approaches to abstract the space for indoor navigation. Some hybrid models are as follows.

Karimi and Ghafourian (2010) have presented a new technique for indoor planning for individuals with special requirements and preferences based on the standards of the American with Disabilities Act (ADA). Their technique works under the framework of Ontology and Algorithm for Indoor Routing (ONALIN), which is an indoor route planning ontology for different users with special requirements and preferences (Dudas et al., 2009). The route computation for the specific individual is based on a three-step process: “all”, “group”, and “individual”. In the first step, routes navigable for all persons without caring for their needs and preferences are determined. In the second step, routes are computed for a group with special needs. In the third step, a route is computed for the individual while taking into the account the preferences and special needs. Similarly, at the implementation level, in the first step, an adjacency matrix reflecting the topology of the building is created. In the second step, inaccessible links are removed based on the criteria of needs and preferences of the group. In the third step, inaccessible nodes are removed again based on the needs and preferences of the individual user. Once the final network is obtained, the algorithm computes the most feasible route accroding to the preferences of the user between two points.

Lyardet et al. (2008) have presented a context-aware indoor navigation system for indoor route planning. This system calculates indoor routes by considering the contextual information of users which includes user preferences, physical capabilities, and his/her location access rights. The system depends on a hybrid representation of an indoor environment which consists of a geometric, a symbolic building model, and a symbolic floor model as shown in figure 2.12. The geometric building model is a detailed geometric 3-dimensional model of the building and it is used for the localization used to transform coordinates to symbolic locations. The geometric floor model is a geometric 2-dimensional model of each single floor which is used for calculating a path and to provide guidance for the user. A symbolic floor model is a symbolic graph-based model of floors of a building which contains nodes and edges representing rooms or corridors and entrances or exits respectively. Furthermore, the system can be accessed through the web and has a dedicated module for user guidance through which users can obtain direction instructions. The main limitation of this system is that it works in 2D space only, which may simplify the routing task, but on the other hand, makes it difficult to deal with real world issues namely ’indoor navigation of a 3-dimensional object’ in route calculation using method of a 2-dimension space. In addition, there is no formal definition for the transformation from the geometric model to the symbolic model.

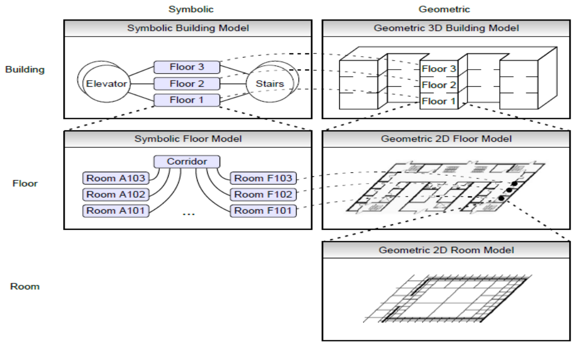


Fig. 2.12 Generation of a geometric network model from a 3-dimensional building model (Lyardet et al., 2008).

Zlatanova et al. (2013) developed a conceptual framework of indoor space subdivision for navigation. This framework focuses on the physical and conceptual subdivision of built environments and develops automatically network models from subdivided spaces to use for context aware indoor path planning for different users. The framework is depends on six general concepts or elements: agent, space, partition, resource, activity, and modifier. Partition is a subspacing procedure of a space in which subspaces are created according to their physical restrictions, design requirements, or the agent's spatial cognition. Agents are objects that perform a certain navigation task or use resources. Activity is the task under some specific navigation behavior an agent performs within a subspace. Resources are the equipment that an agent can use in a subspace and modifiers denote the final result generated by a specific event. The criteria of subspacing is based on the needs of the agent(s) in which activities of the agents are planned in subspaces. Resources are also considered and used for navigation. So, complete route planning is done using a combination of all the framework elements. Finally, based on partitions, a graph model is constructed for path planning according to the agent(s). The framework gives a general idea and some examples but does not explain in detail how a complex indoor space is automatically partitioned based on the needs of an agent. As in the framework the needs of agents are not elaborated. Because the needs and capabilities of agents can never be consistent as well as resources and modifiers of the environment.

The discussed hybrid models, which are a combination of geometric, topological, and semantic models and are used to facilitate indoor navigation for different users, compute route plans based on a network model representing the built environment without any formal definition of the transformation from a built environment to a network model. The discussed models also lack a formal or standardized method of integration among the different models that form the hybrid model (e.g., between a semantic model and a geometric model of building). In addition, almost all of the hybrid models presented compute a super-graph of the building at first, then subgraphs for the different users are constructed. The super-graph may be computed for a specific type of locomotion (e.g., wheelchair), which may restrict other locomotion types to use or create further subgraphs (e.g., unmanned aerial vehicle). Furthermore, most of the hybrid models lack methods of using semantic 3-dimensional building models (represented in international standards e.g., CityGML or IFC standards) for indoor navigation purposes. Nevertheless, hybrid models integrate heterogeneous models to facilitate users for localization and indoor navigation tasks using geometric models as well as by providing location based services in his understandable form based on semantic or symbolic building models.

2.1.4 Multilayered Space-Event Model (MLSEM) and IndoorGML

Multilayered Space-Event Model (MLSEM)

The Multilayered Space-Event Model (MLSEM) supports managing, storing, and representing different thematic spaces of indoor space. The purpose of a separate discussion on MLSEM is to understand its basic operating concepts so the framework can be used for representing and managing subspaces derived according to the different locomotion types. A short overview of MLSEM is provided in the following.

Becker et al. (2009a) have introduced a new conceptual framework, namely, the Multilayered Space-Event Model (MLSEM), for the modelling of indoor spaces to be used for indoor navigation systems. The model extends the work of Lee and Kwan (2005) to represent the indoor subspaces according to different thematic contexts. The topological relationships between 3-dimensional or 2-dimensional spatial objects are represented in topology space. The 3-dimensional spatial objects (Cells) in primal space are transformed into nodes (0-dimensional) in dual space using the Poincaré duality transformation. Similarly, the topological adjacency relationships between 3-dimensional objects, which form the boundary geometry in primal space are transformed into edges (1-dimensional) in dual space. Moreover, the nodes and edges of the Node Relationship Graph (NRG) are called states and transitions, respectively. An adjacency graph is formed in dual space representing a specific contextual primal space, e.g., topographic or sensor space. Furthermore, based on semantic information, the adjacency graph is transformed into a connectivity graph. The connectivity graph forms a unique space layer that consists of node and edge geometries. Indoor space can be thematically divided into different cellular spaces. For example, a corridor can be represented by a topographic area while it is also represented by a WiFi coverage area and Bluetooth sensor coverage area. Each thematic interpretation area will form a different space layer in dual space. This representation or the whole framework of multiple space layers is called the Multiple Space-Event Layered Model (MLSEM). Moreover, the multi-layers representing different thematic contexts of indoor space are integrated by means of joint-states. Thus, an n-partite graph representing joint-states is used to navigate a subject or an object as either can be in one cell (state) of each layer at a given time simultaneously.

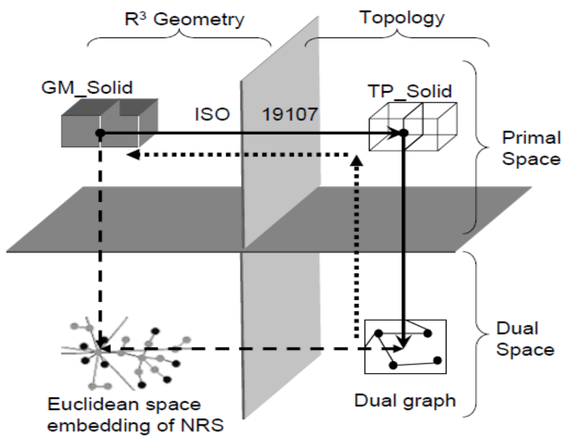


Fig. 2.13 Formation of the topographic space layer from a spatial decomposition based on building topography (Becker et al., 2009a).

A space layer (e.g. topographic space) can be subdivided hierarchically based on specific considerations. For example, navigable subspaces for the different types of locomotion can be subdivided. If there are different types of locomotion, this model allows the formation of a main layer (topographic layer) and then sub-layers to represent the subspacing for each type of locomotion (Becker et al., 2009b). The inter-space connection relation between main layer and sub-layers is represented by the topological relationships as *"contains"* or *"inside"* and *"equal"*. This concept allows for the hierarchical grouping of space in a specific layer.

This model facilitates the subdivision of a particular space into smaller spaces according to respective contexts without affecting the other space layers. The formation of a topographic layer from the topographic space and the modelling of 3-dimensional building spaces using an n-partite graph is shown in figures 2.13 and 2.14 respectively.

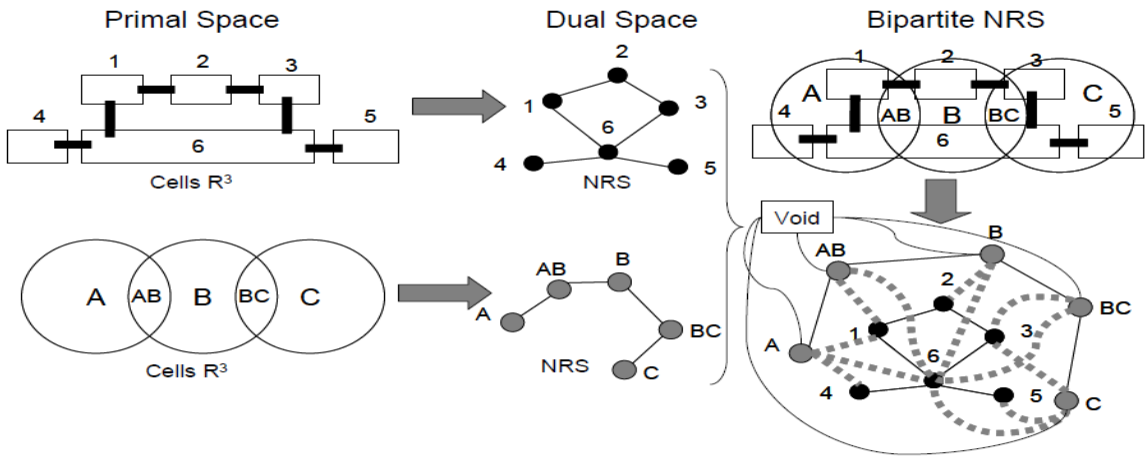


Fig. 2.14 Modelling 3D building spaces (topography and sensors) using a bipartite graph (Becker et al., 2009a).

Becker et al. (2009b) presented a data model for context handling and a modular framework based on ISO 19107[5] and 19109[6] standards by extending the previous work of Becker et al. (2009a). The proposed model can be mapped to a GML application schema so called *"IndoorGML"*. Thus, MLSEM has an application schema which is used for storage and as an exchange format for indoor spatial information. In addition, IndoorGML gives an opportunity to use semantically enriched 3-dimensional indoor environments for the navigation and determination of subspaces according to the given locomotion type. Additionally, MLSEM is based on sound mathematical rules (Nagel, 2014). Therefore, it is considered an appropriate framework to represent, integrate, store, and manage an indoor environment. Details about the IndoorGML are presented in the next section.

IndoorGML

IndoorGML, an international standard of the OGC, represents and allows for exchanging of geoinformation that is required to develop and implement indoor navigation systems. It is considered complementary to other 3-dimensional building modelling standards (e.g., CityGML and IFC) by providing indoor spatial information with a concentration on indoor navigation.

IndoorGML, an application schema of MLSEM, can be divided into two frameworks for the purpose of understanding. Those are the Structured Space Model and the Multi-Layered Space-Event Model (Li, 2014). The Structured Space Model (SSM) explains how each space layer evolved systematically within four segments. The SSM subdivides

[5]ISO 19107: Specifies conceptual schemas for expressing the spatial characteristics of geographic features. www.iso.org/iso/catalogue_detail.htm?csnumber=26012

[6]ISO 19109:Defines rules for developing and documenting application schemas in geographic information. www.iso.org/iso/catalogue_detail.htm?csnumber=39891

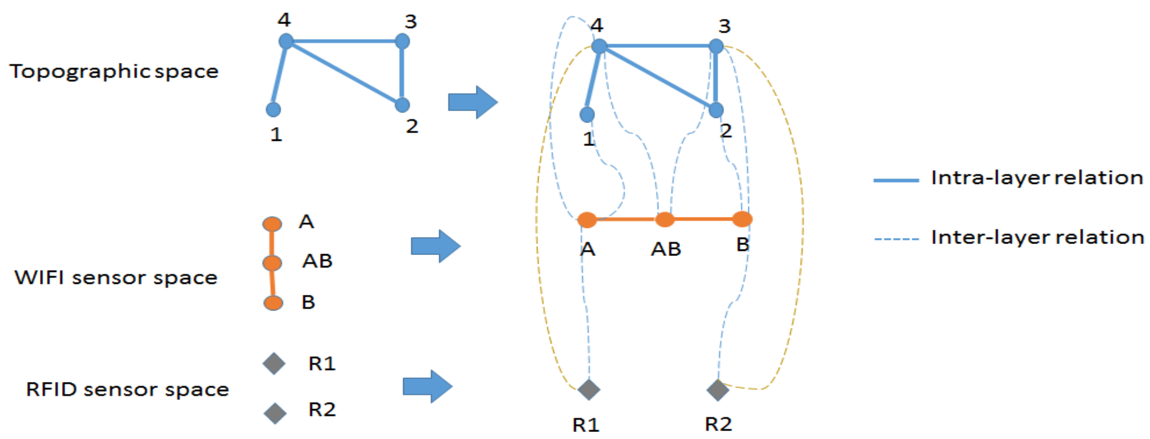


Fig. 2.15 Formation of different space layers (Li, 2014).

3-dimensional building models into four segments: primal space and dual space on the one hand, and geometry and topology on the other hand (shown in figure 2.13). Furthermore, the MLSEM provides a method for integrating multiple space layers to support indoor location and information services as shown in figure 2.15. IndoorGML also defines key concepts which include the reference to any object in external datasets such as CityGML or IFC, connection with outdoor spaces, subspacing, and modularization to define extensions of IndoorGML to cover a specific thematic field. The OGC's specifications (Li, 2014) provide details about each concept.

Furthermore, the authors (Li, 2014; Nagel, 2014; OGC, 2014b) have provided details and application examples of IndoorGML. They have further concluded that IndoorGML is a very flexible and provides a sound mathematical foundation to represent and manage different thematic contexts of indoor semantic 3-dimensional building models for indoor localization and information services required for indoor navigation systems.

2.2 Indoor Navigation according to different Types of Locomotion

In the past, locomotion types in the context of navigation have been discussed in detail in different fields like robotics, contact geometry, and indoor navigation systems. In the following sections, a short background of various types of locomotion used for indoor navigation, a treatment of their constraints, and the determination of navigable space are discussed. In the first section, different types of locomotion and the formation of their constraints as well as the computation of navigable space in different field of studies are elaborated. In the second section, different indoor navigation system approaches, which use different indoor space models and various representations of locomotion types to compute route plans in indoor space are discussed.

2.2.1 Different Types of Locomotion in Indoor Navigation

The idea of configuration space representation as a method of transforming and representing a moving robot among obstacles into a very simple problem of moving a point avoiding among obstacles was introduced by Lozano-Perez (1983). It computes the so-called obstacle space by determining forbidden configurations to the robot due to the presence of these obstacles. Using the configuration space methods in the robotics field, Sentis and Khatib (2006) presented a framework that deals with the whole body control framework for humanoid operating in a human environment in the context of self-collision, constraints, and obstacles. They define the constraints as the physical and movement related restrictions and categorized them into contacts, joint limits, collision avoidance, and balancing. The framework decomposes a whole-body's multi-contact behavior into low level tasks and integrates the handling of internal and external constraints while accomplishing the tasks. To avoid the robot's body colliding with obstacles, a repulsion field is applied to the robot's body which enforces a safety distance from the obstacle. The framework focuses on robot motion planning while considering internal and external constraints of the body which consist of mainly stresses on the body parts' movements. The focus of this thesis is on indoor locomotion types and issues generating from the whole physical body of the locomotion types in determining navigable and non-navigable space in built environments. Therefore, the scope of this thesis does not cover the constraints related to the movements of body-parts of robot or locomotion type.

Latombe (1991) discussed kinematic constraints for robot motion planning. He explained how the robot's body part movement and whole-body movement affects its path planning in configuration space. He further explained that geometric constraints are used to know about geometry connections and collision detection for robots motion planning in configuration space. Again, in this thesis, the focus will remain on constraints of whole body objects not on body parts.

Han et al. (2002) presented a method to determine an accessible route for a wheelchair considering geometric and behavioral constraints using motion planning methods. They used an approach called "performance-based" which evaluates the suitability of trajectories computed by simulating the behavior of a wheelchair in the configuration of a facility. The performance-based approach models the actual behaviors of a wheelchair which are related to the functional usage of a building and to the specification of a building code. The building code considered for this approach is the American Disabilities Act Accessibility Guidelines (ADAAG) that contain specifications for determining the navigable route for wheelchairs. In this approach, the motion planner determines a navigable route based on the criteria that the individual elements of indoor space are geometrically clear and contain accessible components (e.g., door). The geometrical clearance of an individual element is determined through verifying the existence of an adequate clearance width along the route. Then, considering the behavioral and geometric constraints (e.g., maximum turning capacity) of the wheelchair, the route is further evaluated. The authors concluded the approach with remarks that the method can be ambiguous, contradictory, and complex to realize as a computer application because of the possible many behaviors of the wheelchair. The presented method uses semantic and geometric constraints of the wheelchair but the authors did not use any semantic model for indoor space representation. Yet, they are using the ADAAG specifications for buildings, but without considering a formal representation of the building model, this approach will be too ambiguous to apply. In addition, the wheelchair is considered with its behavioral and geometric constraints but there is no formal representation of those constraints in their method which makes the approach very abstract. Furthermore, they argue that their method can be used for different artifacts but without using a formal representation of environment and locomotion types it will be impossible to generalize their approach to other types of locomotion (e.g., flying vehicle).

Mattikalli and Khosla (1992) described a method to determine constraints on translational and rotational motion of 2-dimensional and 3-dimensional objects from their contact geometry. Translations and rotations are represented by spatial vectors and axes of space respectively. Based on these the realization of geometric space of motion parameters is carried out. The constraint using a single mating surface element is achieved by determining the space that is not allowed. In this way, the constraint for the whole surface is obtained. They also computed the union of not-allowed space due to each contact surface element and the space of allowed motion parameters by taking the complement with whole space. The method presented can be used in the simulation of an objects' motion to determine constraints which will play an important role in determining allowed and not-allowed space for an object. The method is purely geometrically based and has useful applications in geometric environments and object representation.

Santana and Correia (2005) presented a constraint-based behavioral architecture called "Survival Kit" (SK) for robot navigation in an indoor environment. The kit provides immediate reactions to be implemented in a robot control system during navigation. The working architecture in SK relies on constraints, which are generated according to their properties by using different reflexes running in parallel. The SK semantics are particularly designed for secure navigation and assigning task-achieving requirements to upper-layers. To perform safe navigability, well-adapted semantics are defined as a solution to the problem at hand. The action feature space is the main component of this architecture, which describes all available actions to the robot allowed for a given sector of the environment. Hence, a set of all possible sectors, with their descriptor, and definitions (constraints and its temporal validity) is defined. The presented method will fail when applied to make generalizations or in use for other types of locomotion because of very specialized defined semantics, constraints, and sectors for a specific robot.

Lopez et al. (2012) presented an online path planning approach in dynamic environments for non-flying objects. The method represents objects while taking obstacles and navigable surfaces into consideration which will allow the system to compute temporal paths through disconnected and moving platforms. The method represents the navigating object as a cylinder bounding volume to simplify the approach and supported with transition, jump motion, and navigation on slopes with capabilities for indoor navigation. Each capability has a minimum and maximum limit for navigation, e.g., maximum vertical impulse speed. The 3-dimensional environment composed of geometric objects defines the workspace to navigate for the object. The whole workspace is represented in configuration space where interaction of the volumes are defined. According to the capability of the navigating object, three types of interaction volumes are determined: the navigable surface, the forbidden volume, and the accessibility volume. Forbidden volumes represent the set of configurations where the navigating object collides with the environmental objects. This volume is computed by extruding the object's shape along the z-axis based on the height of the cylinder and the shape is extended along (X, Y) based on the radius of cylinder. Navigable surfaces represent regions where the object can navigate freely and accessibility volumes contain regions which are reachable to navigate for the object using its capability skills (e.g., jump capability). The method further considers dynamic environments where objects move or change their position over time and constructs a topology graph of navigable objects. The method has some limitations, it uses a pure geometric environment, considers the navigating object with limited navigation capabilities, and the method is considered only valid for a single type of locomotion, i.e., walking. Furthermore, the method presented does not represent the properties or capabilities of the navigating object or environment in any formal semantic 3-dimensional representation format and it also completely ignores the 3-dimensional free space of the indoor environment to determine its navigability for the navigating object.

Grzonka et al. (2012) have presented a fully autonomous indoor flying vehicle that possesses a general navigation system. The authors presented a navigation solution that deals with different aspects of navigation which include path planning, control, localization, mapping, and height estimation. In addition, the navigation system can be adapted to various flying vehicles. For localization, it uses 2-dimensional grid maps which can be either built by itself or a different type of robot. The system also builds its own map through the hierarchical mapping method of Simultaneous Localization and Mapping (SLAM) approach. The authors also provide a stabilization system for the flying vehicle by independent controllers which include yaw control, altitude control, and x,y control. Furthermore, the navigation system computes path plans by avoiding obstacles based on potential fields. The purpose of discussing this paper is that in the robotics field, developing maps online through the SLAM approach and applying obstacle avoidance methods for the different locomotion types to compute navigable spaces has been in practice for long time. Nevertheless, these methods still lack the capability to use 3-dimensional semantic building models. In addition, there are very specialized robots for the specialized tasks in indoor navigation but they cannot be interchanged for their navigation tasks (e.g., guidance) or do not use a framework where different types of locomotion can be used. Online mapping, control navigation systems, and their usage for a specialized type of locomotion is outside the scope of this thesis. This thesis intends to compute navigable spaces for different locomotion types based on their specialized navigation constraints from semantic 3-dimensional building models.

2.2.2 Different Types of Locomotion using Indoor Space Models for Indoor Navigation Activities

In the following, different types of locomotion and their various approaches of representation as well as their usage of indoor space models presented by different authors are discussed.

Dudas et al. (2009) presented an indoor ontology and an algorithm (ONALIN) that facilitates routing for its users with different requirements and preferences (e.g., physical and sensory impaired). ONALIN takes into consideration the American Disability Act (ADA) standards which enforce requirements on indoor space of public buildings to ensure accessibility for disabled people, and calculates routes for the user considering his/her preferences. ONALIN is based on three main concepts: path elements, obstacles, and landmarks. PathElements are further classified into vertical and horizontal paths. Furthermore, it provides relationships among navigable spaces which are needed for developing network models to calculate routes according to requirements and preferences of the user.

Karimi and Ghafourian (2010)'s three-step approach for computing the navigable route according to the needs of an individual is the general practice most of the approaches of route planning adapt. The approach has some limitations: for the extraction of nodes from the 3-dimensional building model is not clearly defined whether they are based on a specific mathematical method or abstraction of symbolic parts of a building (e.g., floor surface) and details about the representation of locomotion types or users are not defined. In addition, in the first step of this method, to compute a route for an individual, the network model is determined from the floor surface of the building model which cannot be used for the flying vehicle in the second or in the third step. Therefore, this method does not support different types of locomotion.

(Kikiras et al., 2006; Tsetsos et al., 2006, 2005) proposed and implemented a semantically enriched navigation system called OntoNav for indoor environments. They consider environmental semantics and user capabilities in addition to geometric information. The system is human centric and defines user profiles based on attributes from his/her demographics, mental/cognitive, sensory, and motor abilities. The authors defined the so-called Indoor Navigation Ontology (INO) to design indoor environments for semantics-driven user navigation and explained definitions about indoor environment like obstacle, passage, etc. They also defined a User Navigation Ontology (UNO) that models the physical, mental capabilities, and preferences of the user. Conditional statements and reasoning processes are used to compute the navigable route for the particular user. Guidance for the user is implemented through user specific instructions. The OntoNav system does not explain the details about the abstraction of extracting the network model from indoor space and it generates a network model which is further used for computing routes or subgraphs for the specific user according to his profile. Unfortunately, the super-graph representing the building model cannot be replaced for different locomotion types. For instance, a network graph computed for a wheelchair (e.g., generated based on floor plans of building) cannot be used for the flying vehicle. In addition, the Kikiras et al. (2006)'s method has concentrated more on logical capabilities of the pedestrian user.

The MNISIKLIS : indoor location based service for 'all' proposed by Papataxiarhis et al. (2009), provides indoor location based services with the concept of a design for 'all' approach (accessible to different user groups, e.g., disabled persons). In the first step, the path elements (nodes and edges) which are incompatible with the user profile, of the building graph are removed. For example, for the wheelchair user, the elements of the graph representing stairway are removed. In the next step, based on route complexity and distance, the route plan for the user is determined. The indoor routing application is based on 2-dimensional GIS-layers which include floor maps, corridors, stairways, and room entrances. The system focuses on one type of locomotion, i.e., walking. Therefore, the system becomes restricted to specific type of locomotion (which is also against this thesis's objective to support for different types of locomotion).

Brown et al. (2013) presented a semantic topographic space and constraint model for indoor navigation. They proposed a constraint model that discusses the constraints generated and required for a 3-dimensional topographic space to assist all tasks of indoor navigation and their integration into the Multilayered Space-Event Model (MLSEM). The constraint model is specific to topographic space and it does not discuss the constraints that are required to be considered from locomotion types for their indoor navigation.

Liu and Zlatanova (2013) proposed an indoor data model called the Indoor Navigation Space Model (INSM) which is designed with the objective to automatically derive the connectivity graph of a 3-dimensional building model that can be used for indoor navigation for different users. They defined building spaces that include obstacle, opening, navigable space cell, vertical unit, horizontal unit, and end space where the Navigable Space Cell (NSC) plays a central role. Furthermore, the 3-dimensional semantic building models in CityGML or IFC format are used to extract path planning graphs for the purpose of conversion into INSM . Initially, they use the 2-dimensional floor plans to develop graph. The method presented automatically to derive graph models for navigation purposes for different types of locomotion has limitations because the graph derived from floor plans cannot be used for flying vehicles. In addition, the model classifies the space into navigable and obstacle in INSM during the conversion from the source building model but in general, during the decision process, to declare a building object as obstacle the program has to consider information of the locomotion type which is completely ignored in this transformation process.

Becker et al. (2009b) discusses the importance of "the consideration of the navigational context" in indoor navigation. They give an idea about the importance of the mode of locomotion and the issue of subspacing of indoor space considering the type of locomotion. They also provide a concept to represent subspaces within MLSEM and give details about how subspaces can be represented based on different considerations. However, the article lacks an explanation how those considerations can be made (e.g., different locomotion types according to their constraints) and also does not give details about the procedure to determine subspaces. Keeping in view the idea of subspacing, this work highlights the importance of the constraints of locomotion types.

Nagel (2014), in his PhD thesis, improved the navigation constraint model of (Brown et al., 2013) by extending and integrating with the MLSEM, which deals with the constraints generating from the topographic indoor space for the different users. The author presented a conceptual data model for the representation and realization of navigation constraints from indoor topographic space and also considered constraints generating from users through a *UserContext* module. The constraint model considers physical, logical, and temporal constraints of indoor space and realizes this through constraint conditions. The proposed model operates with explicit representation of information about navigation constraints from indoor space. The model works in-line with the graph-based and hybrid abstraction approaches where each cell or node in a building model or graph respectively can be enriched with the explicit constraint conditions to be fulfilled to navigate for a user. However, the author does not consider the constraint conditions based on the requirements of the different types of locomotion to navigate in indoor space (e.g, the wheelchair always needs floor surface to hold on besides free space to navigate). The nonnavigable indoor space computed through this approach will be in abstracted form or inaccurate. For example, after realizing a condition for a wheelchair, the whole room is determined as navigable but, in reality, there will be unsafe space in the room for the wheelchair making around the wall surfaces (obstacles). This thesis is not written to replace existing works in the field of indoor navigation but to give an alternative way to accurately determine navigable spaces for the different locomotion types, and to model constraints based on the requirements of the different locomotion types as well as to compute the navigable subspaces considering their implicit information from 3-dimensional semantic building models.

Chapter 3

The Constraints and Requirements of Locomotion Types

This chapter[1] proposes a conceptual constraint model for the different types of locomotion in indoor navigation which captures the information about the locomotion types' navigational requirements to be fulfilled and also support reasoning about this information during their navigation in indoor environments. Constraints of the locomotion types are restrictions or limitations enforced by locomotion types such as speed limitations, capability limitations, or time restrictions. Navigation constraints of the locomotion types play a very important role in indoor navigation because they contribute in decision making for the navigability of the indoor spaces to make them either inaccessible or accessible for the locomotion type.

In the previous chapter, one of the important challenges that was highlighted was that most of the previously presented approaches for indoor navigation do not provide support for different types of locomotion, i.e., flying, driving, and walking. To address this challenge, this chapter intends to define requirements for indoor navigation and further determine constraints from those requirements for their unconstrained indoor movement. In addition, this chapter presents a conceptual constraint model to represent information about various locomotion types that support to determine navigable indoor spaces according to each locomotion type. The scope of this chapter is to define requirements, classify constraints, and to develop a conceptual constraint model for different locomotion types which should be explicit enough to determine possible navigable and non-navigable spaces according to the constraints of each locomotion type.

3.1 Related Work

Human beings spend large portions of every day activity inside buildings (Jenkins et al., 1992). Therefore, the people's focus on geography has developed from the global level to the micro (indoor) level in a short span of time. As a result, many indoor navigation applications have been developed, and in each application it is always imperative to determine the navigable and non-navigable space for the locomotion types while also considering their requirements. Compared to outdoor navigation indoor navigation is more complex. This argument is based on the following reasons: the need for detailed information about enclosed space, dealing with multiple story buildings, ensuring each locomotion type's movement is non-constrained, and unstatic like outdoor road network space..

The consideration of the navigational context which includes the constraints of loco-

[1]The content of this chapter is partially based on Khan and Kolbe (2012).

motion type has been discussed in the literature for many decades. On the one hand, this literature supports capturing information about the locomotion type and, on the other hand, provides the opportunity for the computation of navigable space based on rules and reasoning processes. Many authors proposed to model navigation constraints as a part of indoor space models (Brown et al., 2013; Dudas et al., 2009; Meijers et al., 2005; Nagel, 2014; Stoffel et al., 2007; Tsetsos et al., 2006; Yuan and Schneider, 2010). These approaches aim at an explicit representation of information about indoor navigation constraints. Therefore, constraints are modeled and associated with the objects of the indoor space with the purpose of providing extra information for putting rules or restrictions on the movement of navigating objects. However, in semantic indoor space models, information concerning movement restrictions information is available implicitly. For example, whether a user can navigate through a door can be determined from the geometric information of the door or the geometric information of a navigating object. In this research work the implicit derivation of navigation constraints is followed. Nevertheless, it fully supports the explicit representation of constraints through semantic information and subspaces.

In contrast to an explicit approach, several authors have developed profiles for the different locomotion types, users, and user groups which contain their requirements for indoor navigation and, based on those profiles and preferences of users, they compute navigable structures (Goetz and Zipf, 2011; Karimi and Ghafourian, 2010; Kikiras et al., 2006; Liu and Zlatanova, 2013; Papataxiarhis et al., 2009; Tsetsos et al., 2006, 2005). Most of these approaches focus on a single type of locomotion (e.g. walking or driving) as some of them extract network models from floor plans, making these graphs only navigable for the locomotion types dependent on the floor surface of the building. Aditionally, some of the authors are dealing with different types of locomotion as they are computing navigable subspaces based on graph models of buildings where subgraphs are determined from a super-graph.

Furthermore, the profiles for users are developed again through an explicit approach where each user is given extra information, preferences, requirements, and limitations. In this chapter, the approach to use implicit information on the user or locomotion type (different locomotion types' profiles can be developed based on their unique constraints which are evolved from their requirements, properties, and behaviors) is used to develop constraints for different locomotion types with the intention to compute navigable subspaces at the geometric level which can later be reflected in graph models. Therefore, this approach is adapted with the intention of fully supporting different types of locomotion for indoor navigation while also using implicit information of existing semantic 3-dimensional indoor building models. In other approaches (Goetz and Zipf, 2011; Han et al., 2002; Karimi and Ghafourian, 2010; Kikiras et al., 2006; Liu and Zlatanova, 2013; Lopez et al., 2012; Papataxiarhis et al., 2009; Tsetsos et al., 2006, 2005), authors consider logical and physical constraints. In this chapter, the focus remains only on physical constraints of the locomotion types because physical constraints always take precedence over logical ones.

Aside from these two different approaches of developing navigation constraints, there are several methods in robotics and computer geometry fields where they consider only geometric constraints of the navigating object (Han et al., 2002; Latombe, 1991; Lopez et al., 2012; Santana and Correia, 2005). In the field of robotics in particular, authors consider micro body parts' movements of the object for navigation. In this research work, the constraints for the whole body of the locomotion types are considered with the semantics, geometry, and topology information of the locomotion type.

In the following sections, the modes of locomotion and locomotion types considered for this study are discussed. Furthermore, how the requirements and constraints of the different locomotion types for indoor navigation are developed is explained. In addition, based on constraints of the different locomotion types, a conceptual constraints model, along with example usages, is proposed.

3.2 Modes of Locomotion

The term locomotion refers to the way a body moves from one place to another. There are several ways for different types of locomotion to move in a free environment, and the selection of the locomotion type's movement is an important aspect to consider for the design and computation of navigable space. The common locomotion types of nature are crawl, fly, jump, walk, run, and slide. Most robotic locomotion is inspired by nature's locomotion types; except wheel-based locomotion which is a human invention to achieve high efficiency on flat ground.

In the robotics field, locomotion is the complement of manipulation (Siegwart et al., 2011). In manipulation, the body part of a robot remains fixed while the objects in workspace move by putting force on them. In the case of locomotion, the operating environment of a robot remains stable and, instead, a robot move by putting force on the environment. In both cases, the focus of study are actuators which generate interaction forces and mechanisms. Furthermore, they share the challenges of stability, contact characteristics, and environment type. Commonly, the analysis of locomotion starts with mechanics and physics. However, this thesis focuses on the computation of navigable subspaces for the different locomotion types. Nevertheless, different locomotion types which are commonly used in indoor environments are discussed in this chapter along with the whole body's physical requirements to navigate smoothly in a static semantically enriched 3-dimensional environment.

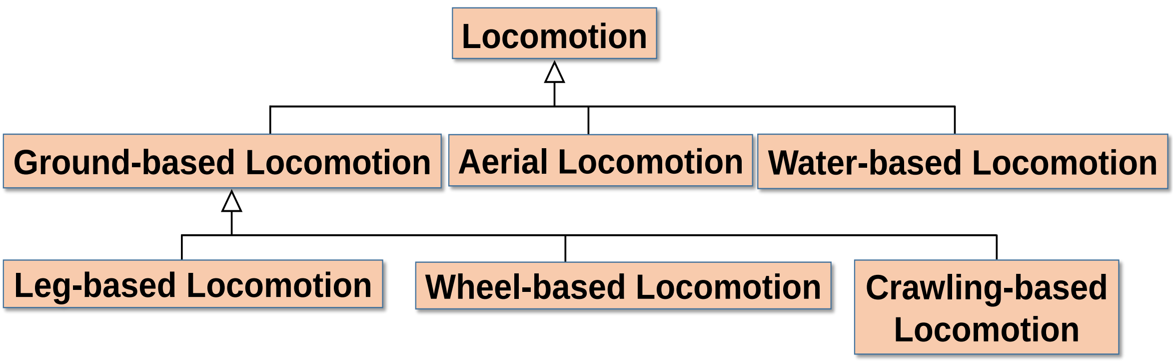


Fig. 3.1 The types of locomotion distinguished based on the type of environment in which they operate and on the mobility type of each mechanism.

Robot locomotion can be categorized based on the environment the robot operates in, e.g., ground, aerial, and underwater. The ground locomotion can be further classified into into wheel, leg (s), and crawling based locomotion (shown in figure 3.1). In the following section, the different types of locomotion considered for this study are discussed.

3.2.1 Locomotion Types

Based on the criteria of mobility mechanism indoor environment locomotions are categorized as either walking, driving, or flying. Walking refers using leg(s) for movement and driving refers to wheel based locomotion types. The flying locomotion type for its movement flys, maintains stability, and maneuvers in the air.

In an indoor environment, an example of each type of locomotion is considered which represents the distinguished type of locomotion and determines their requirements and constraints for indoor navigation. For example, driving or wheel based movement is represented by a wheelchair. Similarly, leg(s) based locomotion (that is the most common type and can be replicated as a bipedal walking system in indoor environment) is represented by a walking person. Besides these two locomotion types, micro Unmanned Aerial Vehicle (UAV) (Grzonka et al., 2009) are a new technology used in built environments. A UAV is considered as an example for flying locomotion.

1. Flying, e.g., Unmanned Aerial Vehicle: In recent years, there has been an increased interest in the research of Unmanned Aerial Vehicles (UAV) because of their decreasing manufacturing costs and their small-sized flying platforms with many basic useful applications in complex indoor environments, for instance, rescue operations. This raises directly the question of how to determine safe navigable spaces using already existing semantic 3-dimensional indoor building models. Most of the other approaches concentrate on outdoor operations or vehicles that can autonomously operate by developing their own indoor mapping (e.g., Simultaneous Localization and Mapping technique) for navigable route planning.

   Flying: An aerial vehicle that can fly and sustain stability in the air is referred to as a flying vehicle. Recent developments in aerial vehicle experimation has resulted in without onboard crew in outdoors and even in indoor environments (Grzonka et al., 2012). In this work, micro the Unmanned Aerial Vehicle (UAV) is considered an example for flying locomotion.

   Unmanned Aerial Vehicle (UAV): UAVs are defined as powered aerial vehicles sustained in flight by aerodynamic lift over most of their flight path, and guided without an onboard crew. In this study, the author is considering Micro UAVs, which can fly inside buildings. Different aviation authorities have different standards for the flying activities of UAVs. Here, a typically micro UAV with its physical properties is considered for this study.

2. Driving, e.g., Wheelchair: Built environments are developed and designed while taking into account the needs of mobile people, architectural choices, and construction costs. However, it is important to note that these considerations form hindrances for those with mobility disabilities. Wheelchair users always need accurate and detailed navigable routes to navigate in indoor environments (Menkens et al., 2011). The availability of semantic 3-dimensional city models particularly for public buildings, highlights the importance to compute navigable routes for driving locomotion, i.e., wheelchair.

   Wheelchair: A wheelchair is a chair with wheels that is designed to be used for the conveyance of a disabled or injured person. According to the International Standards Organization (ISO)'s standards, the average dimensions of a wheelchair are 28 inches wide, 51 inches long, and 43 inches high (ISO, 2014a). The average obstacle an electric wheelchair can climb is 8 inches high and static stability measures are defined in static stability document ISO/CD 7176-1. The overall determination of dimensions, mass, and turning space requirements for the wheelchairs are defined in ISO 7176-5 (ISO, 2014b). In this study, a wheelchair that is only moving on the floor is considered.

3. Walking, e.g., Person: In last the few years, humanoid robotics has become an interesting area of research in the robotics field as it has provided new avenues for exploration compared to driving locomotions (Hornung et al., 2010). However, humanoid robots

also need detailed and accurate information about navigable spaces to navigate in indoor environments considering their specialized needs. Similarly, persons in indoor environments, particularly in huge public buildings like airports and hospitals need indoor route plans to reach to their destinations.

Walking: A locomotion, which uses leg(s) for its mobility, is referred to as walking. In indoor environments, the commonnly used leg-based locomotion are humans, animals, or robots. In this thesis, the author is considering a human (a walking person) as an example for the walking type of locomotion.

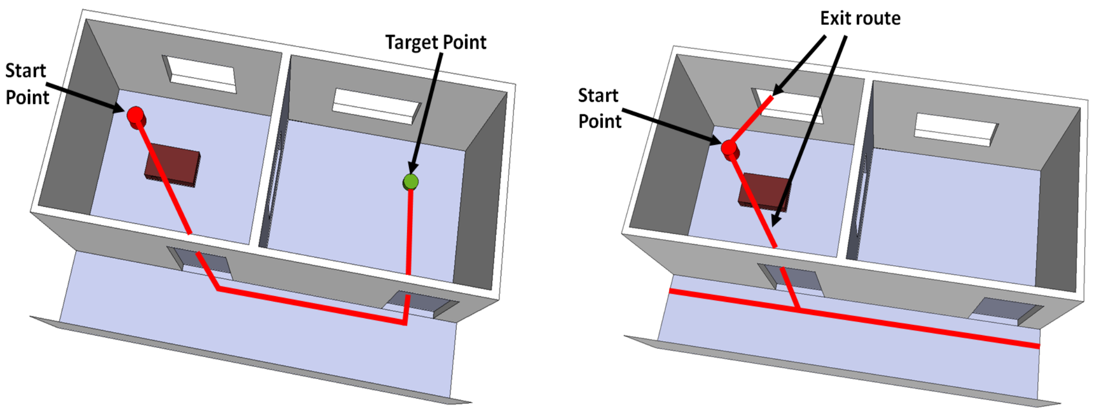
Walking Person: any individual who is a self-conscious or rational being and uses leg(s) for walking is considered a walking person. In normal cases, a human being moves on the floor and crosses less than 3 feet high obstacles. In this research, a physically fit, not injured or non-disabled person is considered.

3.2.2 Role of Locomotion Type for Constraining Indoor Movement

3.2.3 Use Case 1

The role of constraints of locomotion types can be abstracted considering the use case of determining the shortest route plan between two points. In this use case, rooms are adjacent and connected through a corridor and an open window. There is a box laid on the floor in one of the rooms. The route plans for the shortest path from start to target point and exit route in the given static indoor environment will be very different for the different locomotion types as shown in figures 3.2- 3.4.

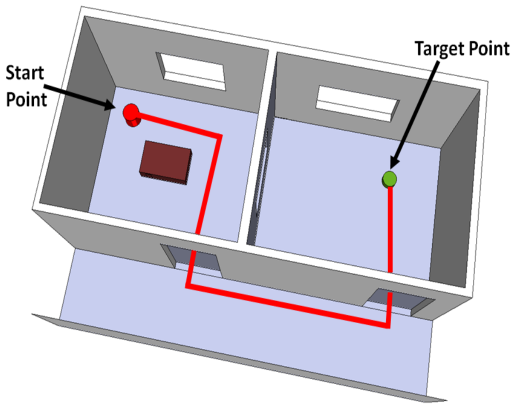
In the normal situation, the shortest route for a person to reach the target from the starting point is by passing over the box as shown in figure 3.2a , whereas the wheelchair or driving robot has to drive around the box to reach the target. The flying vehicle will reach the target through an open window. So, it can be noticed that in a normal situation the route plans for the different locomotion types are completely different. Similarly, in an emergency evacuation from the building, there are only two possible exit routes for the person (exit through door and exit through window) shown in figure 3.2b. The exit route (only through the door) for the wheelchair is shown in figure 3.3b and for the flying vehicle is shown in figure 3.3b. It can be observed that the shortest routes are different because of their unique navigating requirements and capabilities.



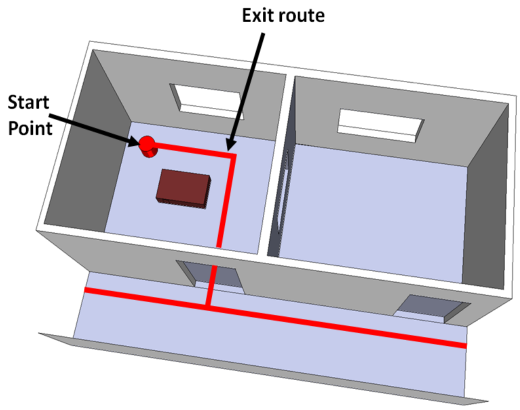
(a) The shortest route to reach a target for a person in a normal situation is by passing over the box

(b) In an emergency situation, a person can exit through a door or a window.

Fig. 3.2 Possible route plans for a person

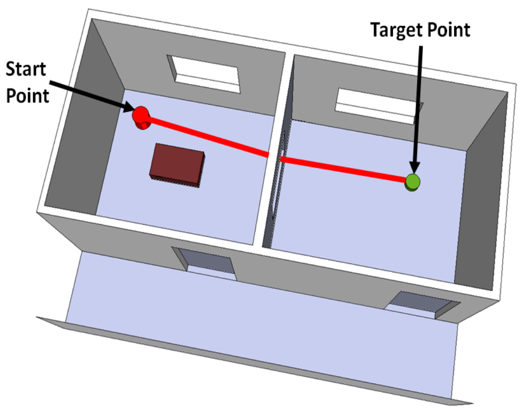


(a) A wheelchair or a driving robot has to avoid the box to reach the target.

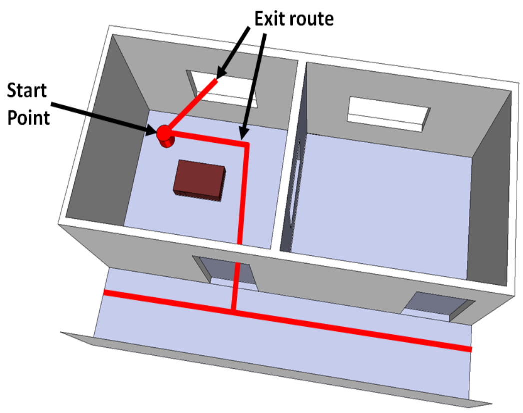


(b) In an emergency situation, a wheelchair has only one option to exit from a room, i.e, by the door.

Fig. 3.3 Possible route plans for a wheelchair.



(a) The shortest route for the flying vehicle is through an open window.



(b) In an emergency situation, a flying vehicle has more options to exit, e.g., by doors and windows

Fig. 3.4 Possible route plans for a flying vehicle

3.2.4 Use Case 2

Consider a slightly modified use case, in which two rooms are adjacent and connected through a corridor and an open window. The corridor and right room now contain a step (shown in figure 3.5). When the actual navigable space (free space) for the walking person is considered, it can be observed (in green in figure 3.6) after deducing the non-navigable space around the wall surfaces. In comparison, the navigable space for the wheelchair for the same two rooms is different (shown in figure 3.7) because the wheelchair cannot drive on steps and creates more non-navigable space around the wall surfaces of rooms. Similarly, the navigable space for the flying vehicle is also unique (shown in figure 3.8) because it creates non-navigable space directly above the floor surface of the two rooms due to non-navigability of flying vehicle through the floor surface.

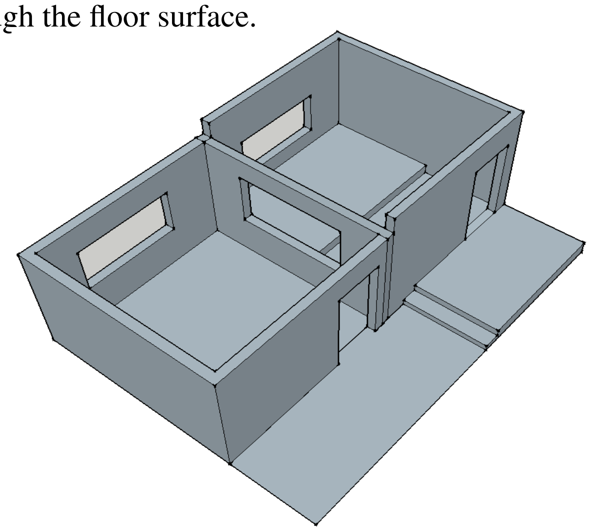


Fig. 3.5 Two rooms connected through an open window and a corridor. The corridor and right room each contain a step.

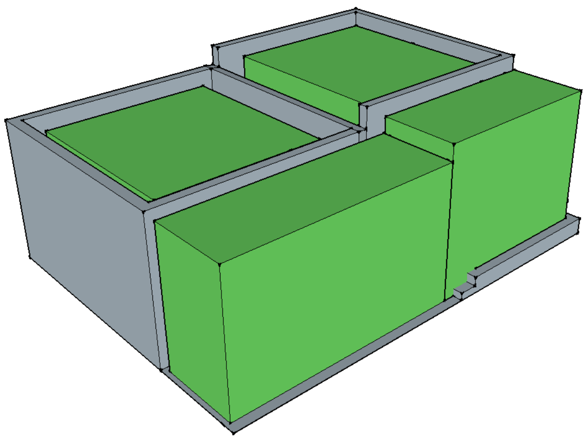


Fig. 3.6 Navigable space for a walking person.

Use case 2 shows that the navigable spaces for the different locomotion types in a given static indoor space (shown in figure 3.5) are different in a normal situation (as shown in figures 3.6, 3.7, and 3.8) (Navigable spaces are shown in green).

When the network models or the topology information (space adjacency) is extracted from navigable spaces (depicted (top view) in figures 3.9a, 3.10a, and 3.11a) for the purpose of route queries and abstracted representation of navigable spaces, then the network models for each locomotion type are different as shown in figures 3.9b, 3.10b, and 3.11b.

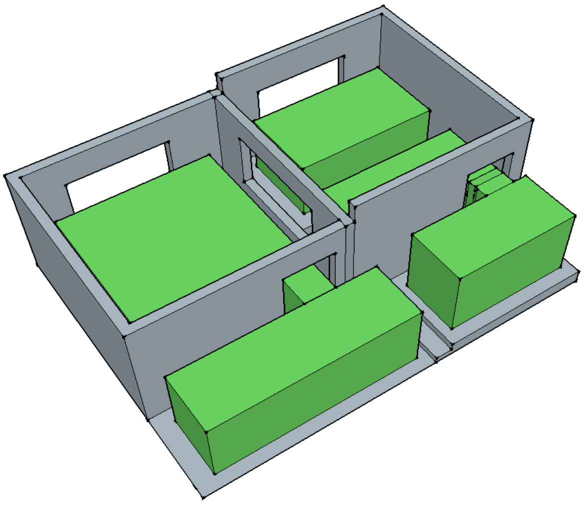


Fig. 3.7 Navigable space for a wheelchair.

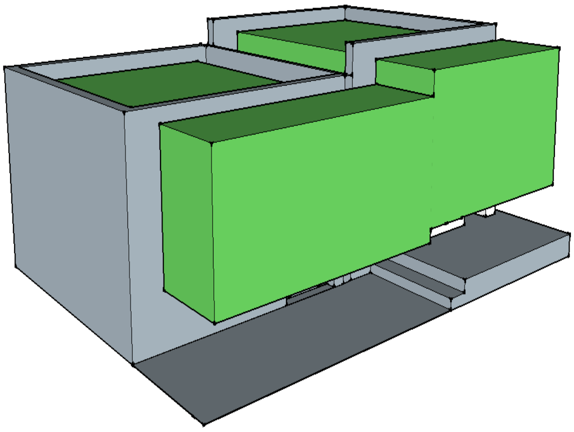
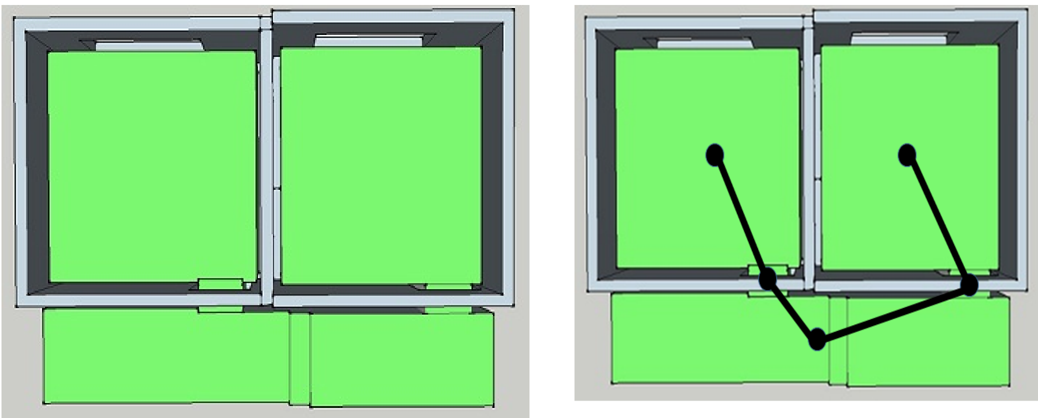


Fig. 3.8 Navigable space for a flying vehicle.

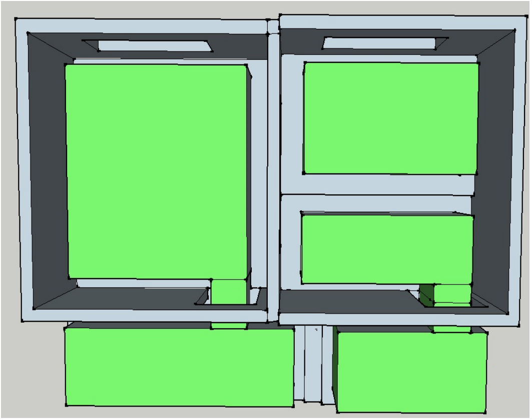


(a) Navigable space

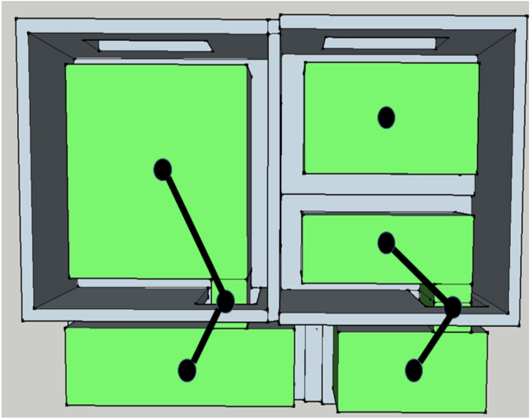
(b) Navigable space with network model.

Fig. 3.9 Navigable space and corresponding network model for a walking person.

For example, in figure 3.9b, the network model representing the navigable space for the walking person consists of five nodes representing five navigable independent spaces and edges representing the connection between two navigable spaces. Therefore, the network model shows that a person can walk from one room to the other navigating through the doors and the corridor. However, the network model representing the navigable spaces for the

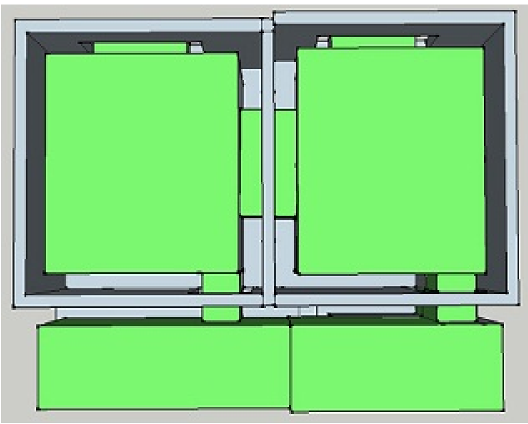


(a) Navigable spaces for the wheelchair.

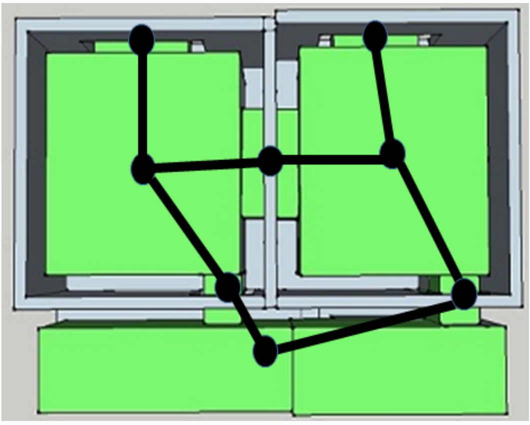


(b) Navigable space with network model.

Fig. 3.10 Navigable spaces and the corresponding network model for a wheelchair.



(a) Navigable spaces for the flying vehicle.



(b) Navigable space with a network model.

Fig. 3.11 Navigable spaces and the corresponding network model for a flying vehicle.

wheelchair (shown in figure 3.10b) shows that there are two independent navigable spaces within a room and that they are not accessible from each other because a wheelchair cannot drive on the step located in the room. Similarly, the two rooms are also inaccessible from each other due to the steps in the corridor. Hence, the network models for the different locomotion types are different because they are representing unique navigable spaces for different locomotion types based on their navigating requirements.

3.3 Requirements for the Different Locomotion Types to Navigate in Indoor Spaces

By observing the use cases discussed in sections 3.2.3 and 3.2.3, it can be determined that different locomotion types generate or have different requirements to navigate in indoor space. They require those requirements to be satisfied in order to navigate in an indoor environment. The identification of these requirements leads to the determination of constraints for the indoor navigation of a specific locomotion type. The requirements for the different locomotion types to navigate in indoor spaces are listed in the following:

1. All types of locomotion share properties and behaviors at the generalized level 'locomotion' as shown in figure 3.1. Those properties and behaviors need to be defined. Some of those properties of each locomotion type emphasize the need of requirements

to be addressed in order to navigate in indoor space. Some examples are given in table 3.1.

Table 3.1 Requirements at the generalized level

Property of Locomotion type	Requirement to fulfill for indoor navigation
Volume	Need 3-dimensional space in indoor space equal or more than the volume of the locomotion type.
Navigability in a specific space	Cannot navigate through blocked space, need free/empty space to navigate.
Spatial extent of locomotion type in horizontal direction	Indoor space must be more than the spatial extent of the locomotion type in horizontal direction.
Spatial extent of locomotion type in vertical direction	Indoor space must be more than the spatial extent of the locomotion type in vertical direction.

2. The types of locomotion are defined based on mode of mobility and on common uses in indoor space. These properties of each locomotion type have specialized requirements and need specialized treatment to navigate in indoor space, e.g., driving, walking, and flying defined in section 3.2.1. Examples are given in table 3.2.

Table 3.2 Requirements at the specialized level

Locomotion type	Property of Locomotion type	Requirement to fulfill for indoor navigation
Driving	Ground surface connectivity	The ground surface of locomotion apparatus (e.g. wheels) needs to be connected with the surface of indoor space to be navigated.
Walking	Ground surface connectivity	The ground surface of locomotion apparatus (e.g. feet) needs to be connected with the ground surface. In some cases, there is no need to enforce this requirement, e.g., during walking a person's one leg may not be intact with the ground surface.
Flying	Ground surface connectivity	No need to be connected with ground surface of indoor space during flight.

3. The requirements generated from properties and behaviors of locomotion types that need to be addressed to navigate in indoor space are categorized into the following types:

(a) Real physical requirements: The real physical requirements are those requirements which are related to a locomotion type's actual physical properties. For example, the volume of a locomotion type must be less than the operating indoor space to navigate in that space. The physical requirements are further distinguished as follows.

   i. Geometric related requirements: All the requirements related to the geometry of the locomotion apparatus of a specific locomotion type are referred to as geometry related requirements. For example, the spatial extent of a locomotion apparatus in horizontal direction must be less than the navigating free space. Geometry related requirements are further categorized into scale, topology and directional requirements. Scale requirements are those requirements, which are related to the physical extent of the locomotion apparatus (e.g. spatial extent in horizontal direction). Scale requirements put an emphasis on the importance of a locomotion apparatus's physical extents. Topology requirements include topological relations required to be fulfilled between locomotion apparatus and indoor space for its smooth navigation. For example, a locomotion apparatus must be able to be *'within'* free indoor space to navigate. 'Directional requirements' contain requirements which need to be addressed during the navigation of the locomotion type in indoor space. For instance, a wheelchair must always be *'in'* the floor surface in order to successfully navigate that surface.

   ii. Capability related requirements: Each locomotion apparatus has capability properties. For example, a wheelchair has a limited capability to drive on a slope. A wheelchair can drive on a ramp if its capability to drive on the ramp is within its limit. It has further specialized requirement types; 'Pass On', 'Cross Through', and 'Maneuver'. 'Pass On' requirements include locomotion apparatus should have the capability to pass on a specific indoor space. For example, on a step, hole, slope, etc. The locomotion type should have the capacity to 'Cross Through' some specific indoor spaces which may include smoky, water filled, or crowded indoor spaces. The maneuvering requirements demand maneuverability skills capacity of a locomotion apparatus that may include jumping, crawling, etc. in specific indoor spaces. For example, in order to overcome the gap between two floors.

   iii. Unconsidered-list requirements: Based on the preknowledge and semantics of the locomotion apparatus, there are parts or areas of indoor environments that do not need to be considered for its movement. For example, in normal situations, a wheelchair does not need to consider the ceiling or windows for its movement trajectory.

   iv. Status requirements: There are many additional requirements that need to be considered for the locomotion apparatus. This includes the physical working condition of the indoor space that may be categorized as normal, above normal, or below normal conditions. For example, a wheelchair has the capability to drive on a glass floor but the status of that glass floor should be normal otherwise it cannot drive.

(b) Safe physical requirements: These requirements highlight the importance of all the requirements which are not physically present but must be considered as physically existing for the safety or other purposes, e.g., security. For example, the spatial extent of the locomotion apparatus in horizontal direction is 3 meters but is considered as 4 meters for safety reasons.

4. There is also the requirement of taking into account the parameters of a situation, (e.g., exceptional or normal) in determining the navigable space for a locomotion apparatus. For instance, a person does not navigate through an open window in normal situations but he will exit through a window in exceptional situations.

5. There is a requirement of taking the parameter of time into account when determining the navigable space for a locomotion apparatus in an indoor environment. For example, a room can be smoky in a fixed period of time which cannot be navigate by a locomotion apparatus.

3.4 Constraints resulting from Different Locomotion Types

3.4.1 Types of Constraints for Locomotion Types

The requirements that have to be fulfilled for a locomotion apparatus to navigate define specific constraints. The definitions and formation of the constraints from requirements of the locomotion apparatus to navigate in indoor space are given in the following:

Constraints: The term constraint here refers to as an obstacle or hurdle in the smooth movement of a locomotion apparatus. For example, a person cannot walk through a wall. In this example, the incapacity to walk through a wall is a constraint for a person. The purpose of defining and formalizing constraints is to address the requirements of different locomotion types in indoor navigation in an organized manner. Through a constraint, a locomotion apparatus expresses a condition or a rule from its property or behavior and fulfillment of that condition becomes a prerequisite for the smooth movement of the locomotion apparatus. The application of the fulfillment of a constraint of a locomotion apparatus may be individual or may be the combination of different constraints which may result in its smooth movement in indoor space.

Each locomotion type discussed in section 3.2.1 has different constraints which are determined from requirements of the locomotion apparatus for its navigation in indoor space. The constraints are categorized into real physical and safe physical constraints.

1. Real Physical Constraints: are those constraints that may arise due to the real physical requirements of the locomotion apparatus. Physical constraints are classified into two types:

   (a) Static Constraints: Constraints that are static and do not change over time. For example, the spatial extent of locomotion apparatus in horizontal direction and slope required for its stability. The static constraints are categorized into specialized types.

      i. Geometry Related Constraints: These constraints result from geometric requirements of the locomotion apparatus. For the smooth movement of the locomotion apparatus, these constraints need to be addressed. Geometry related constraints have specialized constraints which include scale, direction, and topology constraints related to the locomotion apparatus.

      ii. Capability Constraints: Constraints that expresses capacity of the locomotion apparatus in a specific area. For example, the highest speed of a locomotion apparatus is 10 m/s. This capacity limit enforces a condition on the locomotion type to have less speed for its smooth movement. Similarly, when the locomotion apparatus is in its initial position or in its final position or during its movement, it always requires stability for stable movement. Therefore, capability constraints addresses the capacity requirements of the locomotion apparatus.

iii. Unconsidered-list-Constraints: Constraints which are formed to fulfill the requirements of the unconsidered-list requirements are mentioned in section 3.3.

iv. Status Constraints: The fulfillment of status requirements imply status constraints which define physical conditions of indoor space for the smooth movement of the locomotion type. The main difference with the capability constraints is that the status constraints are generated from the indoor environment whereas capability constaints are related or generated from the locomotion apparatus.

(b) Dynamic Constraints: Constraints that change with the time period are called dynamic constraints. These constraints may include movements of the body of the locomotion apparatus and its kinetics constraints which may change with the time period and result in different requirements. For example, spatail extent of a locomotion apparatus in horizontal direction may change over time.

2. Safe Physical Constraints: These constraints are not actually physical but act like physical constraints and arise due to organizational or security rules/ policies. The safe physical constraints are categorized into following types:

   (a) Static Constraints: Safe physical constraints which are static and do not change over time are called static constrains. For example, the spatial extent of a wheelchair in horizontal direction which may be more than its original extent for the safety reasons. These are categorized into the following specialized types of constraints:

   The specifics of these constraints are almost the same as of physical constraints except these are safe physical ones.

   i. Geometry-related Constraints
   ii. Capability Constraints
   iii. Unconsidered List Constraints
   iv. Status Constraints

   (b) Dynamic Constraints: Constraints that change with the time period are called dynamic constraints. For example, at airports during the collection of trolleys, the individual trolley gets bigger with the combination of other trolleys and this process increases its length constraint over time. Dynamic constraints are also categorized into specialized types like geometry related constraints, capacity constraints, unconsidered-list constraints, and status constraints.

The following conceptual constraints model for different locomotion types is proposed which addresses all types of constraints discussed in the previous paragraphs.

3.4.2 Conceptual Constraint Model for the Locomotion Type

The proposed conceptual constraint model for different locomotion types is shown in figure 3.12. The model is formally expressed using Unified Modeling Language (UML)[2].

Each locomotion type, which can be flying, walking, or driving, can have one or more complex locomotion constraint. Each complex locomotion constraint may consist of a combination of one or more locomotion constraint. Two or more locomotion type's constraints are combined using Boolean operators. Furthermore, each locomotion constraint can be real physical or safe physical. Real physical describes all those requirements that need to be fulfilled which are related to real requirements of the locomotion type (e.g., volume of the locomotion apparatus that enforces the requirement for the locomotion apparatus to have equal or more than its volume of free space to navigate). Safe physical constraint enforces the requirement to be fulfilled for safety reasons, (e.g., the actual volume of the locomotion apparatus is 3 cubic meters but for safety reasons, the safe physical constraint is considered 4 cubic meters). Both real and safe physical constraints depend on the condition or situation (e.g., normal or exceptional) of the environment in which they are realized. In addition, the constraint type plays a very important role whether it is a foundation constraint or an advanced constraint (more information is provided in the next chapter). Besides the constraint type, there is also the need to consider the temporal restriction of a constraint because there are constraints for a locomotion apparatus which vary depending on time duration. Real or Safe physical constraints have specialized constraints which are: Geometry Related constraints, Capability constraints, Status Constraints, and Unconsidered List constraints. The Geometry Related constraints have specialized constraints which describe the constraints of scale, direction, and topology of the locomotion apparatus. Capability constraints define the conditions needed to be fulfilled related to the capability of the locomotion apparatus to navigate in indoor space. For instance, a walking person has the capability to cross through a thin glass with a diameter less than of 0.01 meter in emergency situations. Therefore, the walking person has the capability constraint and cannot break through glass with thickness of more than 0.01 meter in an emergency situation. Capability constraints are further specialized into *PassOn, CrossThrough,* and *Maneuver* constraints which deal with passing on a space, crossing through indoor objects or space, and different maneuverability skills of locomotion types, e.g., jumping, crawling, etc., respectively. A Status constraint is a specialized constraint of a physical constraint which describes the condition to be fulfilled with the operating environment of the locomotion type, e.g., a smoky environment. Moreover, an Unconsidered-list-constraint considers the type of locomotion apparatus and puts conditions on the locomotion apparatus in its navigability. For example, a wheelchair always drives through doors, so the windows are designated as non-navigable for the wheelchair in normal conditions.

3.4.3 Example Usage of the Locomotion type Constraint Model

The following examples demonstrate the modelling of different types of constraints based on the conceptual model introduced in the previous section. Each example is supported by a UML instance diagram that reflects on the objects, their attributes, and associations which are mandatory to describe the individual constraint.

[2]The Unified Modeling Language (UML) is a general purpose modeling language in the field of software engineering that is used as a standard approach to visualize the design of a system.

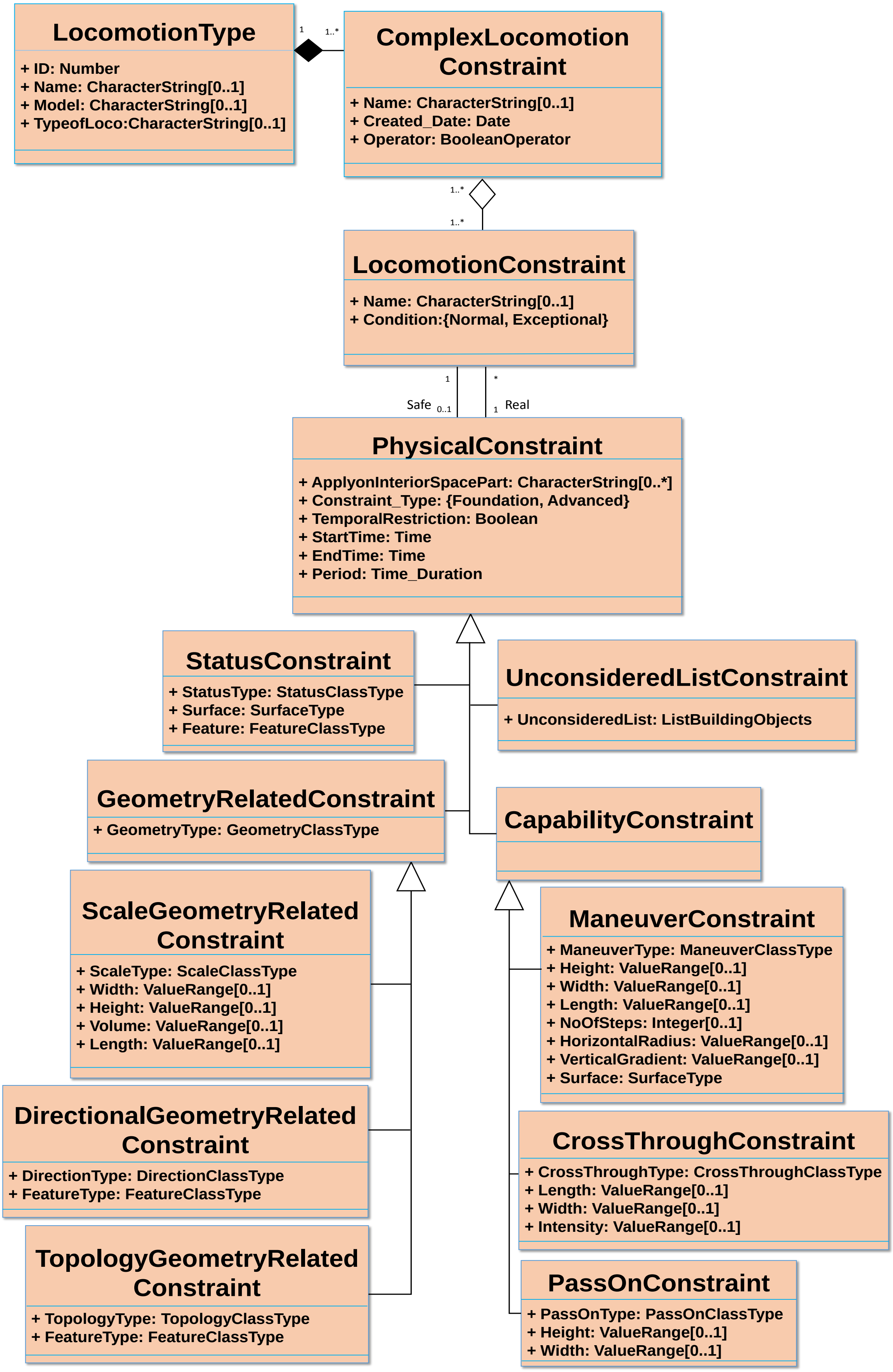


Fig. 3.12 Conceptual constraint model for the different locomotion types. The class types are given in the next figure.

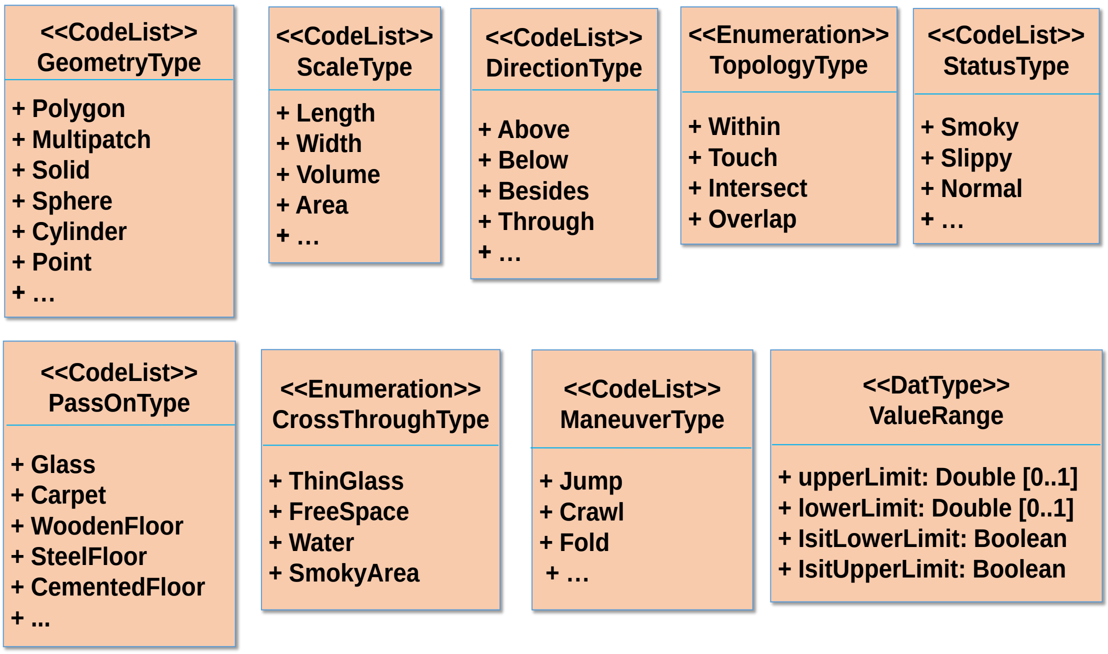


Fig. 3.13 Class types for the constraint model.

Example 3.1:

The example shows how to explicitly describe the locomotion type with its constraints generated from its physical properties and behavior. In figure 3.14, a simple sketch of a walking person in a cylinder (mean to simplify) is sketched. The walking person assuming some attributes like name, type, height, width, and volume. The attributes of the locomotion type show specific values which define constraints for the locomotion type to navigate in indoor space. These attributes include the type of locomotion that is locomotion apparatus is a walking person. This locomotion apparatus, (i.e., walking) will automatically inherit many constraints to explicitly define navigation in indoor space. For example, *DirectionalGeometryRelatedConstraints* need to be defined as: the walking person can only walk or navigate in an indoor environment above the floor surface, below the ceiling surface, and without touching wall surfaces. Thus, these constraints make the conditions on the locomotion apparatus that it can only navigate on floor surfaces and other surfaces of 3-dimensional environments are non-navigable(e.g., water surface, etc.). Similarly, the values of the attributes height, width, and volume put conditions on the locomotion apparatus that it can only navigate once these conditions are fulfilled. For example, *ScaleGeometryRelatedConstraints* require that the height, width, and volume of indoor space must be more than 1.5 meters, 0.5 meters, and 1.18 cubic meters respectively in order to navigate that space smoothly. Furthermore, there are *TopologyGeometryRelatedConstraints* which define conditions of topology on a locomotion apparatus's body geometry to be fulfilled for the navigation of an indoor environment. For instance, to navigate in an indoor space cell it is obligatory for the locomotion apparatus that its body must be able to manage to arrange itself within the free space cell otherwise that space cell will be non-navigable. In addition, it makes the condition that the walking person's body geometry can only touch the floor surface and wall surface during navigation. Therefore, they cannot be overlapped or intersected. These selected examples can be expanded to attributes of the different locomotion types for the several types of constraints modeled in figure 3.12.

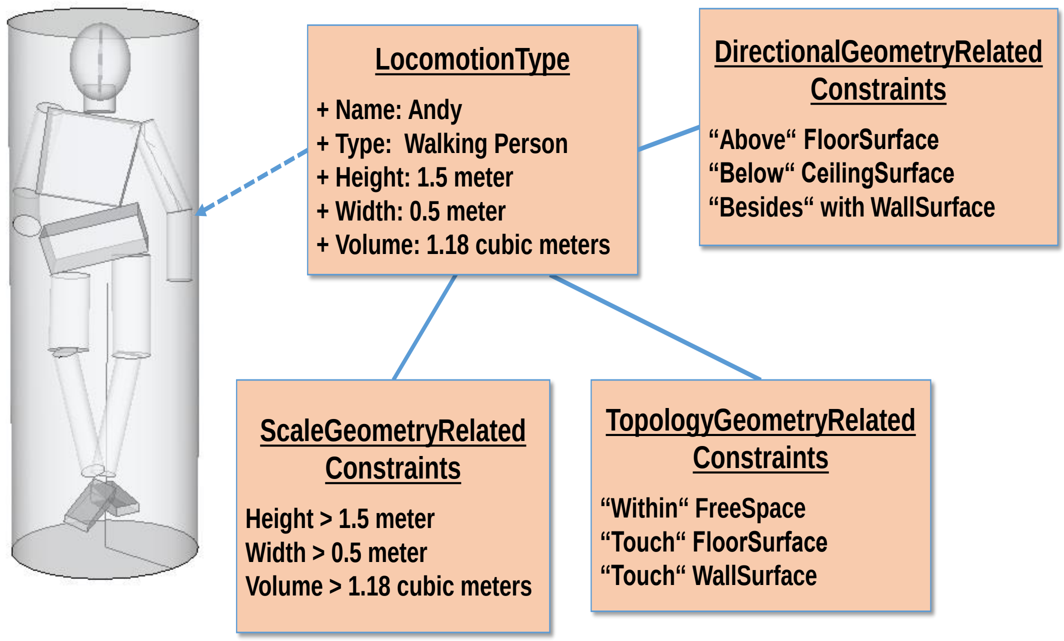


Fig. 3.14 An example usage of geometry related constraints of the locomotion type.

Example 3.2:

Figure 3.15 shows the usage of capability constraints of the locomotion types. The simple sketched walking person has properties: can walk on a glass floor, his type of movement is steps, he can cross through free space only, and he has maneuver skills of jumping. These properties contribute to form various types of constraints for the locomotion apparatus. For example, *PassOnCapabilityConstraints* defines its movement type, which is step, and that it cannot move over obstacles with a height of more than 0.3 meters. This constraint further implies the only floor type on which it can move is glass floor and that it cannot navigate on steel or other types of floors. The *CrossThroughCapabilityConstraints* make a condition that it can only cross through free space. Therefore, other types of objects cannot be navigated due to this constraint. The *ManeuverCapabilityConstraints* put a condition on this locomotion type, indicating that it can jump up to the height of 0.5 meters or length of 1 meter, while any more than that length of gap or hole or other objects in indoor environment cannot be navigated. The detailed definition of constraints for this locomotion type also gives the opportunity to represent it more explicitly and, to deal with and define indoor space navigability. This can be observed from the example of locomotion apparatus maneuver type attribute, which expresses it can only jump while *ManeuverCapabilityConstraints* defines in detail how much it can jump in length and height.

Example 3.3:

Figure 3.16 illustrates an example of the definition of status and unconsidered-list-constraints for the locomotion type based on the explicit attributes and preknowledge of the locomotion type. The attributes describe the locomotion type for a walking person and he can only walk in indoor space in a normal condition (e.g. uncrowded, unsmoky, etc.). Once it is determined that he is a walking person, then, based on preknowledge, it can be concluded that in a normal situation he will prefer to walk through doors. Whereas many areas including wall surfaces, ceiling surfaces, windows, and chimneys are considered non-navigable. The *StatusConstraints* imply that a walking person can only move through normally conditioned spaces. Therefore, it creates the condition that crowded or smoky areas cannot be

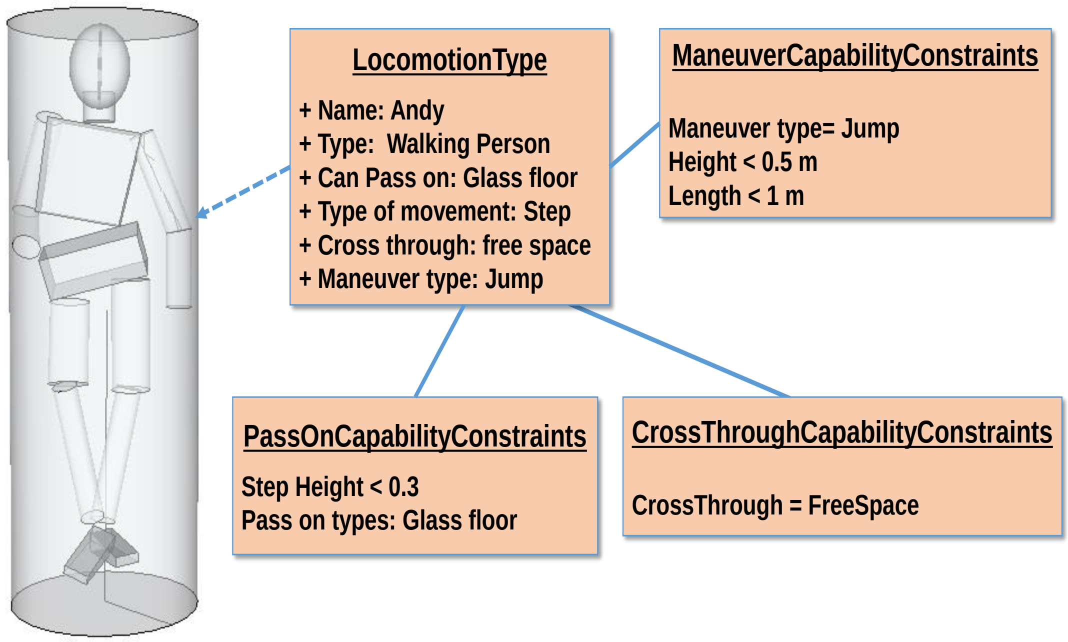


Fig. 3.15 An example usage of capability constraints of the locomotion type.

navigated.

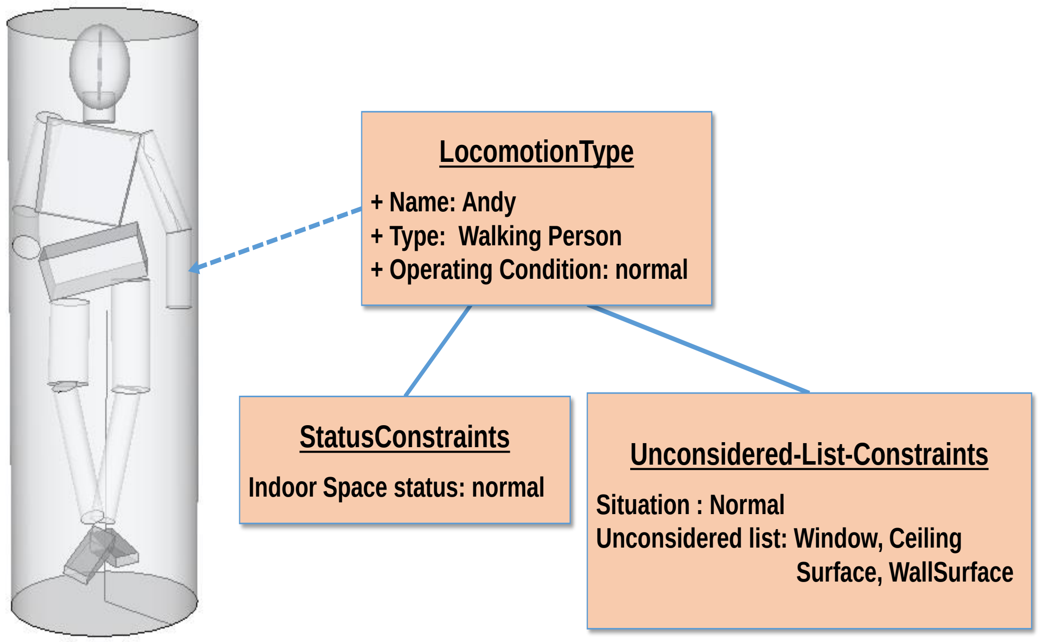


Fig. 3.16 An example usage of status and unconsidered list constraints of the locomotion type.

Chapter 4

Subspacing of Indoor Space according to different Locomotion Types

This chapter[1] defines requirements for a subspacing framework and a procedure for subspacing according to the various types of locomotion. The requirements of a subspacing framework describe the importance and issues of computing navigable subspaces for various types of locomotion. In the following sections, those highlighted requirements are addressed which pave the way towards a subspacing step and support for different types of locomotion in indoor space. The prime objective of subspacing is supporting indoor navigation for different locomotion types while also considering their distinguished indoor navigating constraints using existing semantic or geometric 3-dimensional building models.

4.1 Related Work

A great deal of research has been carried out about creating subspaces for different locomotion types from 3-dimensional building models. Many researchers have done subspacing for various reasons. Some of those reasons and methods along with their objectives, are discussed in the following:

Meijers et al. (2005) have represented more nodes for a single corridor or long space to achieve better route performance. For example, by taking the central node of a corridor, making an adjusting line at the center and creating nodes next to the doors‘ points allows for better route performance as compared to only representing nodes of doors and corridors. Goetz and Zipf (2011) presented a method in which huge rooms or halls can be represented with their obstacles or particular important spaces by reflecting nodes from each space in order to represent the real situation of indoor space to the maximum extent. In contrast, (BuildingSMART, 2014; OGC, 2014a; Stoffel et al., 2007) represent indoor space with the objective of make it more understandable and manageable, (i.e., hierarchically, semantically or geometrically) for its users. Similarly, Zlatanova et al. (2013) presented a framework to create subspaces based on different criteria including physical, conceptual, and functional. Six general concepts are used: space, partitions, agents, activity, resources, and modifiers. The criteria of subspacing is based on the needs of the agent(s) in which activities of the agents are planned within subspaces and with the support of the resources. The main purpose of this framework is to create automatic navigation structures (graph models) from existing 3-dimensional semantic models but the framework still lacks to explain the real implementation of the needs of the agent(s).

[1]The content of this chapter is partially based on Khan and Kolbe (2013).

Most of the past work on subspacing focuses on a single type of locomotion, e.g., walking or driving. In several methods, the network graphs extracted from floor plans of the buildings make these graphs only navigable for the locomotion types which are dependent on floor surfaces of the building. However, the process of indoor route planning for different types of locomotion depends on a network graph that is supposed to be extracted from the 3-dimensional building model. For example, many methods (Dudas et al., 2009; Goetz and Zipf, 2011; Haile, 2010; Lertlakkhanakul et al., 2009; Lin et al., 2013; Steuer, 2013; Stoffel et al., 2007; Tsetsos et al., 2005) do not consider the free space in an indoor environment to derive the navigation structures or graph models. Three-dimensional free space has the same importance as floor surfaces representing the navigable space for a specific locomotion type. For example, for a flying vehicle, the floor surface can be non-navigable but importantly the free space is navigable for its navigation. This shows that a navigable floor surface of a room does not define the whole room as navigable for flying objects like Unmanned Aerial Vehicles. Therefore, there is a need to represent and extract the navigation structures or network graphs from the free space and other parts of interior environment separately to decide about their navigability. Few researchers (Dudas et al., 2009; Goetz and Zipf, 2011) consider users or user groups for their indoor navigation and they define a profile for each user by defining his/her physical capabilities and preferences. Furthermore, the network model extracted from the main topographic model of the building is filtered (subgraphed) based on the user's profile. These approaches do not represent the actual geometric navigable space for the user because the subgraphs representing navigable space for the user are computed from a supergraph. In this thesis, the author is interested in the computation of the actual geometric navigable spaces for the different locomotion types considering their physical constraints. The actual geometrical navigable spaces are further reflected in subgraphs. In this chapter, the author considered the conceptual constraint model presented in the previous chapter for each locomotion type. In addition, most of the previous research papers give the same preference to physical and temporal constraints of locomotion type but in this work, the author considered physical constraints to be the base, taking precedence on temporal requirements.

4.2 Requirement of a Framework for Indoor Subspacing

Subspacing refers to a process of subdividing a space based on different considerations which can be logical or physical. For example, a building can be divided into various parts in order to represent sensor covering areas as well as it can be differentiated into several areas based on security reasons or accessibility. In this thesis, the author is interested in subdividing the indoor topographic space based on physical considerations of the different locomotion types. From the use cases defined in sections 3.2.3 and 3.2.4, a list of requirements is defined, which emphasizes a need of a framework to address the indoor subspacing based on different types of locomotion. The requirements are as given in the following:

1. From the related work discussed for the determination of navigable spaces for different locomotion types, it is apparent that most of the authors and their methods focus on single types of locomotion and this selection of a single type of locomotion restricts other types of locomotion for indoor navigation. Therefore, there is a need of a method that should provide support for different types of locomotion to determine navigable spaces in indoor environments.

2. Based on section 3.3 and section 3.4, it becomes clear that different locomotion types have different requirements for indoor navigation and that they determine different constraints that must addressed. These different constraints determine various

indoor subspacings for different locomotion types. Thus, distinguishable subspace for a specific locomotion type needs to be determined.

3. Once constraints (limits and strengths) of a locomotion type are known, then there is a need to describe in detail; how they are realized or applied in an indoor environment. Whether there is a need of further categorization or not, this will be helpful in dealing with the locomotion type in different indoor environments and situations (e.g., emergency evacuation).

4. There is a need to define how the properties and behaviors of the locomotion type are utilized to determine navigable and non-navigable space in a semantically enriched 3-dimensional indoor environment. For example, if a CityGML formatted 3-dimensional indoor building model is given, then how the wheelchair's properties are utilized to know its navigability in a unit space area becomes important.

5. There is a need of a framework to use semantic, geometric, and topological information to determine the details about navigable and non-navigable space for a locomotion type in indoor space. The geometric or semantic information alone can handle the situation to some extent but to avoid complex calculations, to get the fast, and accurate results there is a need to use an aggregate of information from different domains. For example, each step of a stair can be checked geometrically for a wheelchair to drive but if the subspacing system has semantic information about stairs then it can easily skip the stairs in a navigable route of a wheelchair.

6. There is a need of a procedure to implement and address the constraints of the locomotion type to navigate in indoor space which will result in the computation of navigable space from indoor space for a specific locomotion type.

7. A unit of indoor space needs to be distinguished into navigable and non-navigable based on the constraints of the locomotion type that will result in the overall determination of navigable and non-navigable spaces for the locomotion type.

   A set of measures has been established towards this framework to address these requirements which are explained in the following sections.

4.2.1 Categorization of Constraint Types

The requirements and different constraint types for the specific locomotion type are discussed in section 3.3 and section 3.4 respectively. In this section, all the constraint types are categorized into two types, namely foundation and advanced (to address requirement 3) to deal with the requirement of how the constraints types can be realized to determine navigability of indoor space. Foundation constraints are the basic constraints that expresses what are the essential entities require and requirements from entities of indoor space for the smooth movement of the locomotion type. For example, geometry related constraints and topological constraints. Foundation constraints are the prerequisite for advanced constraints. In other words, foundation constraints are those constraints which are derived from the properties of the locomotion type at the generalized level (locomotion type level) shown in figure 3.1 and advanced constraints are derived from the specialized properties of the locomotion types, for example, flying.

The following table 4.1 shows the constraints type category and entities required from navigational space to address the requirements of the constraint. Detailed constraint types and entities required from navigational space for different locomotion types are given in appendix H.

Table 4.1 Categorization of constraint types and entities required from an indoor environment for the safe navigation of a wheelchair.

Property of Locomotion Apparatus	Value	Constraint Type	Requirement for the smooth passage of locomotion Apparatus	Constraint type category	Entity of navigational space
Height	1.5 meter	Fixed Constraint; Geometry Related Constraint	Height of passage must be greater than the height of the locomotion apparatus.	Foundation Constraints	Height
Width	1 meter	Fixed Constraint; Geometry Related Constraint	Width of passage must be greater than the width of the locomotion apparatus.	Foundation Constraint	Width
Length	1 meter	Fixed Constraint; Geometry Related Constraint	Length of passage must be greater than the length of the locomotion apparatus.	Foundation Constraint	Length
Position	On horizontal Surface	Fixed Constraint; Capacity Constraint	Passage must contain a horizontal surface to support the locomotion apparatus.	Advanced Constraint	Horizontal Floor Surface
Maximum Speed	40 km/h	Fixed Constraint; Capacity Constraint	Speed must be less than the maximum speed of the locomotion apparatus.	Advanced Constraint	

4.2.2 Partition of Indoor Space

Considering requirements 3 and 7, each indoor environment's unit space needs to be defined whether it is navigable or non-navigable based on the constraints of the locomotion type.

An indoor environment consists of indoor space cells. The considered indoor space has physical existence and is determined navigable or non-navigable based on the physical constraints of the locomotion type. When a semantically enriched 3-dimensional building model is considered for different types of locomotion then for a particular type of locomotion a specific indoor space becomes more relevant. For example, a window is more relevant for a UAV's route planning while it is less relevant for a wheelchair in a normal condition. Considering this argument the semantic parts of a 3-dimensional building model are categorized into two types for route planning of each locomotion type as “consider” and “unconsidered”. “Consider” are those parts of a building model that are essential and “unconsidered” parts are those parts which are not important during the route planning of a specific locomotion type. Categorization is based on two situations: normal and extra-ordinary situations. The requirements of “consider” and “unconsidered” of a specific space of an indoor environment are realized through unconsidered-list constraints presented in a conceptual constraint model in the previous chapter.

Simultaneously, the indoor space cell is distinguished based on foundational constraints of the locomotion type. The indoor space cell which fulfills the requirements of the foundation constraints is described as considered/free or temporarily blocked space for navigation, while not fulfilling the requirements of the foundation constraints is considered as non-navigable.

Considered indoor space part of a building is further distinguished into navigable, permanently non-navigable, and dynamic space based on advanced constraints. Navigable space is a free space available for movement of the locomotion apparatus after fulfilling its constraints. Non-navigable space is a restricted space where the locomotion apparatus cannot move due to its constraints. A dynamic space is navigable and non-navigable in specific periods of time. In the same way, an indoor space part is represented as considered and unconsidered space based on safe physical constraints and further differentiated into navigable, permanently non-navigable, and dynamic space.

The indoor space partition for the locomotion type considering its constraints is shown in figure 4.1.

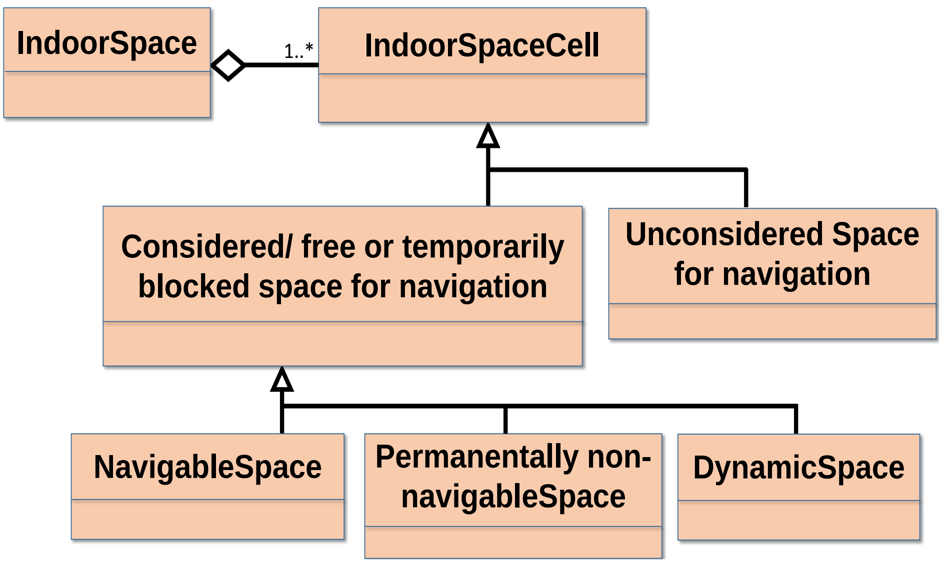


Fig. 4.1 Partition of indoor space based on the constraints of the different locomotion types.

4.2.3 Navigational Cells

The concept of navigational cells is discussed to address requirements 4 and 7.

After determining whether an indoor space is either navigable or non-navigable based on the constraints of locomotion types, the questions arise how these constraints are applied on specific parts of an indoor environment, and what methods do exist that partition the indoor space semantically or geometrically? The answer is affirmative and there are different methods to partition indoor environments. Some of the methods are discussed in the following:

Meijers et al. (2005) presented a graph based model that is geometrically embedded for precise results for evacuation from building interiors. The graph is extracted from a semantic model of interior spaces, and these interior spaces are well-defined parts called sections from a building model based on functionality, building structure, and accessibility. To be able to have accurate and useful indoor route plans, the spaces of navigation and exit routes (e.g., doors, exits) are explicitly modeled. Each section is ensured to be closed, even if not closed in reality, virtual polygons are introduced (e.g., stairs' open spaces) and enforced to be unique as well as not overlapping. In the context of navigational cells of indoor space, this method partitions space into small units of sections which are regarded as navigational cells and reflected into network graphs for navigation purposes.

Stoffel et al. (2007) provided a graph based spatial model and algorithm disscussed in detail in section 2.1.3. The algorithm develops a navigational graph for the physical space, as well as the paths between boundary nodes. The sub-regions and regions formed considering the geometrical and physical aspects of a building function as navigational cells to derive graph models for indoor route plans.

(Choi et al., 2007; Lertlakkhanakul et al., 2009) described a new way-finding method for complex buildings which contains non-navigable areas detached to space boundaries and space boundaries containing non-convex shapes. The method uses topological way-finding methods to generate paths by means of integration of Building Information Model (BIM). In this method, a building model was created by a BIM based modeler (so called "GongTown") and parts of the building are treated based on a structure-floor plan model. The space topology was generated by representing a node for each building component such as space, door, and window whereas a link is representing a connection between two connected spaces. Furthermore, way finding is performed by developing the topological graph and considering distance and other attributes such as door type and space type. This method also discusses how to deal with obstacles and non-convex spaces by a subdivision of space. The steps include searching for concave space that contains any concave obstacles. If a concave space is found, it is then subdivided into a minimal set of convex subspaces. In the next step, it constructs a network graph by representing one node for each subspace and one for the middle of each edge between subspaces. At the end, all doors are connected to the nearest subspace node and paths are determined for navigation. In this method, the composed subspaces constitute the navigational cells in and are, thus reflected in graph model for indoor route queries.

Apart from the discussed methods of representing indoor spaces, IFC (BuildingSMART, 2014) and CityGML (Kolbe, 2009; Kolbe et al., 2005; OGC, 2014a) standards for three dimensional semantic building models are well-known international standards which support for semantic, topological, and geometrical representations of buildings. These standards partition the topographic spaces of buildings into well-defined parts. Each part of the building (in both standards) provides implicit information which can be utilized for indoor navigation for the different locomotion types. Few authors (Gröger and Plümer, 2010) have developed methods to derive graph models from these semantic models for indoor navigation.

The physical constraints of the locomotion apparatus are applied to each convex subspace or semantically distinguished part of an indoor environment. The sub-regions, subsections or subspaces generated through the above discussed methods are used to determine the navigable and non-navigable space for each locomotion type. The resulting navigable space for the locomotion apparatus will contain one or a collection of navigable sub-regions. Those small functional divisions or sub-regions are called navigable cells which are referred to by different names in different methods of indoor space representation (Nagel et al., 2010). For example, Stoffel et al. (2007) called these unit spaces boundary nodes and spatial regions.

During the application of locomotion apparatus's constraints, those constraints are ignored which are applied only to semantic based indoor models. On the other hand, constraints based on semantics are applied if the indoor representation model is based on a semantic model (e.g., CityGML).

4.3 MLSEM and Subspacing based on the Type of Locomotion

In this thesis the author intends to use the MLSEM framework, which was discussed in section 2.1.4, for managing and storing subspaces for the different types of locomotion. A brief discussion about the subspacing concept in MLSEM and its advantages for use with the different locomotion types is described in the following.

MLSEM is a framework that integrates and represents different network graphs representing different thematic structures of indoor space for navigation and localization of a subject or object. It was presented by Becker et al. (2009a). MLSEM not only facilitates an efficient way to manage and represent the indoor environment but also provides an application schema (IndoorGML) to store, localize, and navigate a subject or object in an indoor environment. Becker et al. (2009b) have presented a method to create subspaces within MLSEM framework based on different contextual considerations in indoor space. According to this method, all contextual configurations can be managed as unique space layers and they are connected through the inter-space connection relation. The relevant and required data for indoor route planning is selected from the set of layers. The selection depends on logical and thematic considerations while localization infrastructure also plays important role. In figure 4.2, an example of the selection of different considerations is shown. Examples of the several contexts can be modes of locomotion and disaster areas. Once the selection of space layers based on contextual considerations is made, then connections are detected to determine the association of incident nodes via all possible joint states among the different space layers. The computation of joint states and their intersecting geometries results in a 3-dimensional volume in which the navigating subject or object will be.

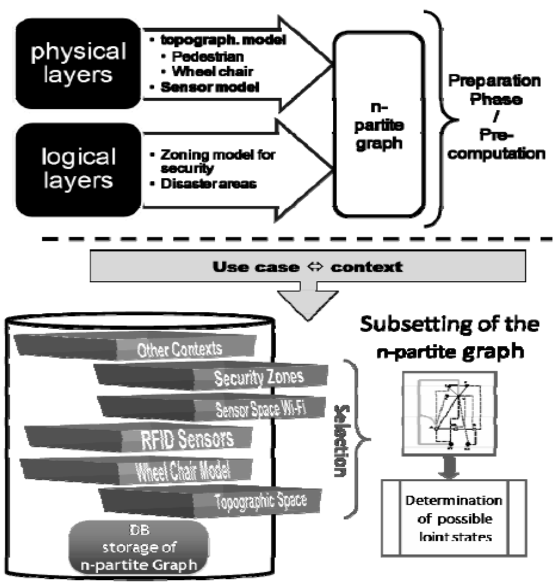


Fig. 4.2 Selection of contextual considerations in MLSEM (Becker et al., 2009b).

Furthermore, the space cells within a specific space layer (e.g., topographic space) may be subdivided according to specific contextual considerations. For example, the mode of

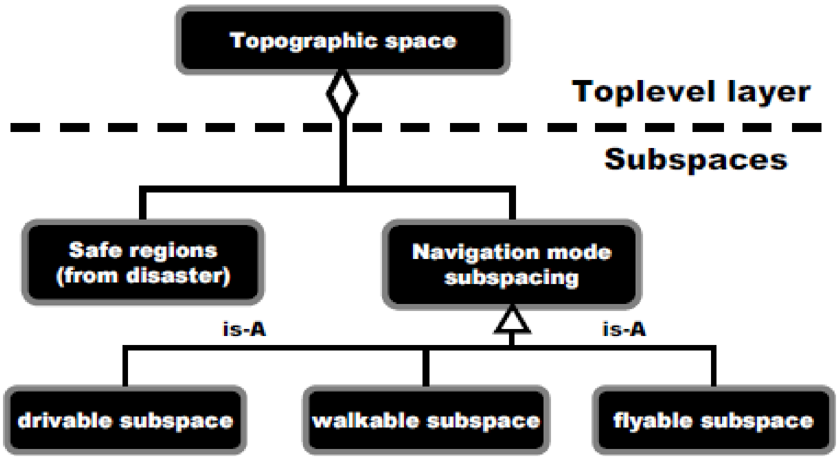


Fig. 4.3 Subspacing of topographic space based on modes of locomotion (Becker et al., 2009b).

locomotions, shown in figure 4.3. Context dependent layers are created from the main space layer to accommodate different smaller compositions from the whole. These sub-layers are dependent on the main layer as they only represent the specific portions of the whole space. Therefore, the inter-space connection between the super-layer and its sub-layers are described as *"contains"/"inside"* and *equal*. This method has provided an idea about how subspacing can be done on the basis of different contextual considerations within the framework of MLSEM. However, the paper lacks an explanation how those considerations can be made (e.g., how different locomotion types can be distinguished) and also does not explain how those subspaces are created at the geometric level which are reflected in graph models as subspaces or sub-layers.

There are multiple reasons to use the MLSEM framework for subspacing approach within this thesis. The major consideration is that the MLSEM has been mapped to a GML application schema called IndoorGML (based on the data model provided by Becker et al. (2009b)) which provides the opportunity to use semantic 3-dimensional building models for indoor navigation and localization purposes (Li, 2014). Another main reason is the possibility to create and manage subspaces or sub-layers due to contextual considerations for different types of locomotion. Furthermore, MLSEM accommodates each space layer to integrate with other thematic layers of indoor space. This ability can be utilized for various indoor space queries. For example, the navigable space layer of a wheelchair can be integrated with a sensor space layer of indoor space to facilitate location based services (e.g., which navigable areas of wheelchair support wifi sensor coverage?). In addition, IndoorGML supports a standard approach to deal with different themes and activities of indoor space through the initiation of packages. For example, the provision of an indoor routing package that, with the advancement in indoor space technologies and approaches, allows to flexibly add more packages as required.

In this thesis, the author intends to create subspaces or sub-layers of the topographic space for different types of locomotion while considering their physical constraints. Topographic space can be represented using well-established 3-dimensional building model standards (e.g., CityGML or IFC). The procedure and subspacing processes are defined in the next sections and result in subspaces for different types of locomotion from semantic 3-dimensional indoor building models within the framework of MLSEM.

4.4 Procedure for Subspacing

To address requirements 5 and 6 from section 4.2 , a procedure with a framework is presented for the subspacing of indoor environments according to the constraints of the locomotion type.

The subspacing procedure is divided into the following steps. In the first step, physical constraints of the locomotion types are realized on physically available unit spaces of a 3-dimensional building model. The unconsidered-list constraints of the locomotion type decide on the particular parts of indoor space whether to consider them navigable or non-navigable for a specific locomotion type. For example, a chimney of a building is not required to be checked for the wheelchair as it is considered non-navigable in a normal situation. Actually, any unconsidered part of the building is determined as non-navigable space by the subspacing system based on preknowledge about the locomotion apparatus and its constraints. This step reduces the complex calculations and procedures to know about navigable and non-navigable regions of indoor space.

In the second step, considered space is categorized into three types navigable, non-navigable, and dynamic space based on foundation and advanced physical constraints of the locomotion type. A navigable area is an obstacle free area where a locomotion apparatus can move freely. A Non-navigable area, (i.e., permanently non-navigable) is a restricted area or obstacle where locomotion apparatus cannot move freely. A dynamic space is an area that is navigable for a fixed period of time.

Figure 4.4 shows the procedure to distinguish indoor spaces based on the physical constraints of the locomotion type.

The discussed procedure which results in a navigable subspace layer for the considered locomotion type in Multilayered Space-Event Model (MLSEM) is formalized as follows:

An Indoor Space (IS) consists of indoor elements or indoor navigational cells.
IS= {ground floor, door, object, ..., table, roof, space}
Each element in an indoor environment may has properties (e.g., length, width, volume, type of material, etc.).
Ground floor= {p_1, p_2, p_3, p_4, .., p_n}
A set of locomotion types M = {L_1, L_2, L_3,. . . , L_n}
Each locomotion type L_1 in M is associated with a finite set of properties L_1= {hm_1, hm_2, hm_3, . . . , hm_n}
Some properties of locomotion type L_1 take part in exploring navigable space. Those properties, e.g., hm_1 and hm_2 that take part and need to be addressed for smooth movement of L_1 in indoor environment are called constraints of L_1.
hm_1 and hm_2 are referred to as constraints C_1 and C_2 respectively of L_1. C_1 and C_2 represent requirements to be addressed for the smooth movement of L_1 in indoor navigation. Each constraint, e.g., C_1 contains instances and procedures to fulfill its requirements. For each locomotion type, (L_1) there is procedure Prc() which considers indoor environments and starts from the constraints, performs extensive geometry, semantic, and topology checking with the properties of the elements (p_1, p_2, and etc.). After performing a constraints check, it decides about the element of indoor space whether it is unconsidered, navigable, non-navigable, or dynamic space for the locomotion type L_1.
This procedure is elaborated further as follows: When the locomotion type (L_1) is selected from a set of locomotion types (M) then considering its particular physical and safe physical properties some elements of indoor environment are skipped as non-navigable or not-allowed.

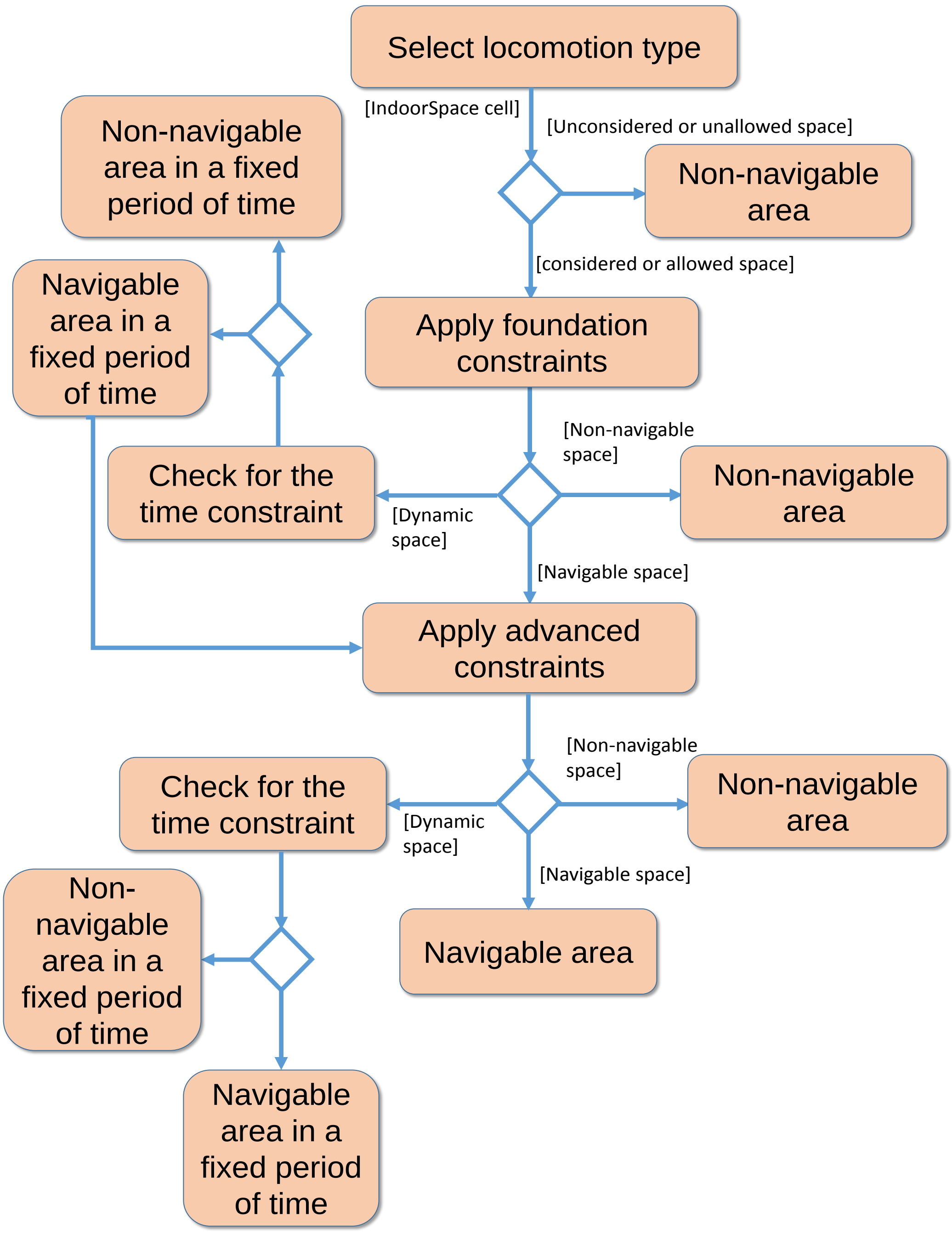


Fig. 4.4 The procedure to distinguished indoor space based on the physical constraints of the locomotion type.

In the next step, considered or allowed elements of indoor environments are checked to fulfill the primary physical constraints of L_1. During this step, the elements of an indoor environment are categorized into navigable, non-navigable or dynamic space. Those elements of an indoor environment which are categorized navigable and navigable in a specific time period are further checked for the advanced physical constraints of (L_1). The elements of an indoor environment are again categorized into three types: navigable, non-navigable, and dynamic space. The collection of elements of an indoor environment which are distinguished as navigable and navigable in a specific time period are collectively called navigable space or a disjoint union of navigable cells for (L_1). The whole procedure is summarized in figure 4.5.
Each navigable space cell in primal space is converted into a node in dual space. If the primal space cell is in connection with its adjacent navigable cell, then it is represented with an edge in dual space depicting a transition between the two cells. At the end, a navigable space layer representing a navigable subspace model for the selected locomotion type L_1 is computed.

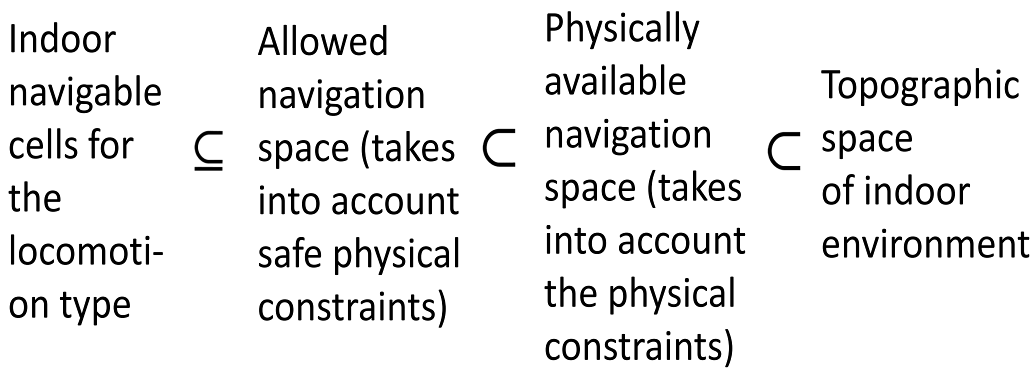


Fig. 4.5 The summary of determining navigable cells for the locomotion type.

The subspace layer determined in the previous step is integrated with the main topographic space layer of a 3-dimensional environment using the connections inter and intra-space connections of the MLSEM.

The whole scenario of subspacing of indoor space according to a locomotion type considering its constraints and getting navigable cells is shown in figure 4.6.

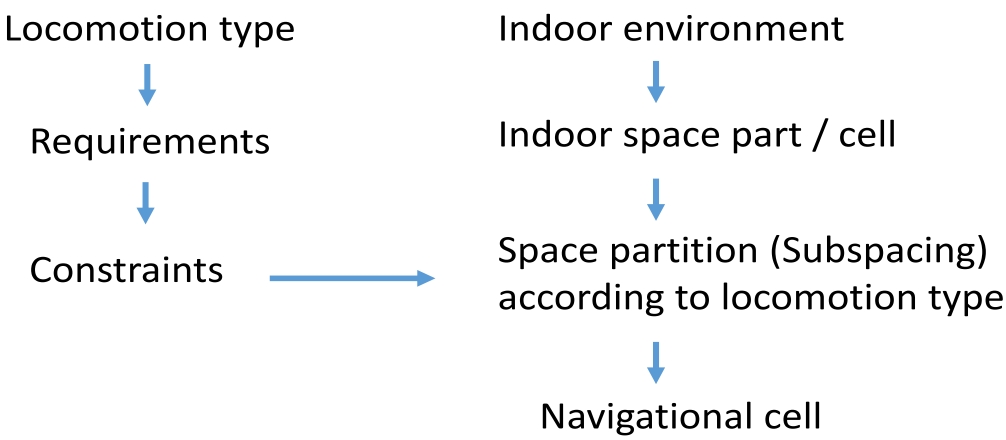


Fig. 4.6 The overview of indoor subspacing according to the locomotion type.

4.5 Subspacing of Indoor Space based on the different Locomotion Types

Each type of locomotion apparatus determines navigation requirements for its smooth movement in an indoor environment. Once these navigation requirements are formalized, they form constraints required to be fulfilled for the locomotion apparatus. A locomotion apparatus consists of at least one or many complex locomotion constraints that may form from a single or combination of many physical constraints. The physical constraints of the locomotion type are categorized into two main types; real physical constraints and safe physical constraints. Real physical constraints define actual physical requirements of the locomotion type to be satisfied to navigate in indoor space and safe physical constraints are those requirements that need to be fulfilled for safety or security reasons.
The process of determining navigable and non-navigable space for the specific locomotion type starts with the assumption that there is a geometry, topology, and semantic description of the objects in the workspace. There is also spatial information related to the locomotion apparatus available. Unlike with many basic path planning problems, there are no explicit obstacles for the locomotion apparatus. The decision of labeling an obstacle has to be decided for each individual object or space cell and based on the constraints of the locomotion apparatus. A cell is considered an obstacle, if and only if the constraints of the locomotion apparatus are not fulfilled. For example, stairs are an obstacle for a wheelchair if it does not have the capacity to drive on stairs.
The locomotion apparatus navigates in a 3-dimensional environment thus configuration space is 3-dimensional. The indoor environment *'CL'* represented into a 3-dimensional space solid cells. Each 3-dimensional solid cell contains a set of attributes *'C_a'*.
$CL = X_1, X_2, X_3, ..., X_n$, n shows number of cells
$X_1 = X_1.C_a$
Where C_a defines the cell attributes.
The attributes of each space cell contain semantics, topology or geometric information related to the cell, e.g., feature type, width, volume, etc.
To improve and simplify the representation of navigable and non-navigable space for the specific locomotion type, geometric representations of the moving body of each locomotion type is simplified. Unmanned aerial vehicles are represented by a 3-dimensional sphere whereas a walking person and a wheelchair are represented by 3-dimensional cylinders with their heights.
One might think of this method to approximate locomotion apparatuses and space cells as over simplifying the work space. While this seems to be true, one of the contributions of this work is to demonstrate the ability of such systems to determine navigable and non-navigable subspaces using geometric methods for the specific locomotion type considering its constraints and using semantic 3-dimensional building models.
In robotics motion planning, the crucial task of determining free space for the subject or object is known as global path planning or the collision checking problem. In this work, the author is interested to determine the collision free or navigable space for each type of locomotion. As earlier assumed, the geometries of the locomotion apparatuses are represented as a 3-dimensional sphere for a UAV, and 3-dimensional cylinders with variations of height for a human being and a wheelchair. Spherical and cylindrical representations of locomotion apparatuses allow to determine obstacle spaces around obstacles in a simplify way by only knowing the distance to the nearest object. Based on configuration space approach the distance to the nearest object is computed by simply compared to the radius of the cylinder or

sphere Lozano-Perez (1983).
The following assumptions are made about the workspace and the locomotion apparatus for collision detection. The author assumed that locomotion apparatus:

1. Does not bend its body to pass an obstacle.
2. must (particularly humanoid and wheelchair) always be in a stable position vertically, making always constant distance with the horizontal surface.
3. Whenever moving or driving on an inclined obstacle. For example, a ramp must always make constant unsafe trajectory curve (arc of circle) whose distance will the remain same as that of the radius of cylinder or sphere.
4. Can compute the accessibility between two navigable spaces to determine the obstruction or unsafe region of an obstacle.

Each locomotion apparatus *'L'* contains physical properties *'P'* with specific values (e.g,. height is 2 meter, length is 3 meter, etc.).
Locomotion apparatus: $L \rightarrow P = \{ p_1, p_2, p_3, p_4, ..., p_n \}$ n shows number of properties
Some of these properties of locomotion apparatus take part in decision making about 3-dimensional space cells for their navigability. Those properties, which take part in exerting requirements to be fulfilled become constraints 'S' of the locomotion apparatus.
Constraints of locomotion apparatus: $L \rightarrow S = \{C_1, C_2, C_3, C_4, ..., C_n\}$ *n shows number of constraints*
In indoor environment 'CL', the space cell 'X_1' will be determined as navigable for locomotion apparatus 'L' if only if its constraints 'S' are fulfilled.

$$CL(X_1) = \begin{cases} Navigable & \text{if L's constraints 'S' are fulfilled} \\ Nonnavigable & \text{if L's constraints 'S' are unfulfilled} \end{cases}$$

Consider an example where there is an attribute of a locomotion apparatus 'hc' representing its height. This attribute height 'hc' exert requirememt to be less than the height of space cell (forming a constraint 'C_1') to determine that space cell as navigable for the locomotion apparatus.
$hc \in P$
hc= Height of locomotion apparatus

$C_1 = \{ \text{height of space cell} > hc \}$
If the constraint 'C_1' is fulfilled then the considered space cell will be determined as navigable otherwise non-navigable. Assume two space cells 'C_i' and 'C_j'.

$$C_1(fulfilled) = \begin{cases} fulfilled & hc \leq \text{height of 3-dimensional space cell} \\ Unfulfilled & hc > \text{height of 3-dimensional space cell} \end{cases}$$

Space cell C_i is declared obstacle for locomotion apparatus L because C_1 is unfulfilled, On the other hand, C_j is declared navigable for L because the constraint *'C_1'* are fulfilled. The relation between the two space cell boundaries are checked if their boundaries are in touch. In that case, the boundary space geometry of both geometries is computed.
Boundary space geometry $G_1 = C_i \cap C_j$
In this case, the boundary space geometry of a 3-dimensional polygon is computed from two

geometries: C_i and C_j are 3-dimensional solids. This boundary space geometry G_1 represents the surface of obstacles interfacing with the navigable space cell C_i.
The clearance *d (Cell)* of cell C_i is defined as the minimum distance to boundary space geometry G_1 or the obstacle cell C_j. The value of *d (cell)* is the euclidean distance equivalent to radii or heights of the cylinders or sphere representing the locomotion apparatus *L*. The computation of this value is implemented by obstacle expansion of obstacles until a distance *d* is reached. This computation is also achieved using the Minkowski sum (Lee et al., 1998) of the geometry representing the locomotion apparatus *(L)* and the boundary space geometry G_1.
Further, the definition of the free configuration space is as follows:
$C_{free} = \{ (x,y,z) \in C \mid C_i - \textit{Minkowski sum (geometry of L, } G_1)\}$
Once the free space is determined, then the author is interested in determining the dual representation of the whole navigable space for the specific locomotion type. Each navigable space cell is represented by a node. Two space cells, if they are connected and accessible from one cell to the other for the locomotion type, are represented by an edge.
In free space cell C_i, applications of some constraints C_2 of the locomotion apparatus create obstruction (non-navigable space) and the decision to create that obstruction from the obstacle area depends on accessibility between two navigable spaces. If and only if the constraints of the locomotion apparatus are fulfilled to access from one space cell to another or overcome the obstacle space then it will not create obstructions, otherwise it will. The obstruction space is subtracted from the free space cell and then the dual space representation of the free space cells for the specific locomotion type is built.
The growing region of non-navigable space of the 3-dimensional environment based on Minkowski sum's method is computed. Furthermore, the dual representation of whole navigable space, which reflects the impact of the type and constraints of the locomotion on navigable space of a 3-dimensional environment is determined. At the end, each subspace will form a unique layer for the specific locomotion type in the MLSEM.
The flow chart of subspacing is presented in figure 4.7 and explained in the following:

1. Decision whether an indoor cell is navigable or non-navigable (obstacles); application of foundation constraints of the locomotion type: Each space cell (a semantic unit cell of CityGML or IFC is considered as a space cell) of indoor space is taken into consideration for constraints of locomotion apparatus; fulfillment of the constraint will decide about the cell as navigable or non-navigable. Initially, foundation constraints of the locomotion apparatus are considered to apply on each space cell, e.g., volume of the locomotion apparatus is checked with the volume of each air space cell, whether it is less than or greater than. If the volume of an indoor space cell is greater, then it is considered as navigable otherwise non-navigable (Sometimes this decision is taken at individual cell level and sometimes at the combination of the nearest cells). Similarly, each primary scale, capacity, and topology constraint types are checked. Some of them are checked based on semantics rules and some at geometric levels. For example, the knowledge of the capacity constraint of a wheelchair that it cannot drive through walls and preknowledge about all the walls available in our 3-dimensional semantic building model, this constraint categorizes all the walls of a building as non-navigable and they are determined as obstacles for the wheelchair.

   Obstacle expansion: Lozano-Pérez and Wesley (1979)'s concept of using configuration space for robot motion planning represents the robot as a point, maps the contact-free configuration space, and represents the configuration-obstacle space that is non-

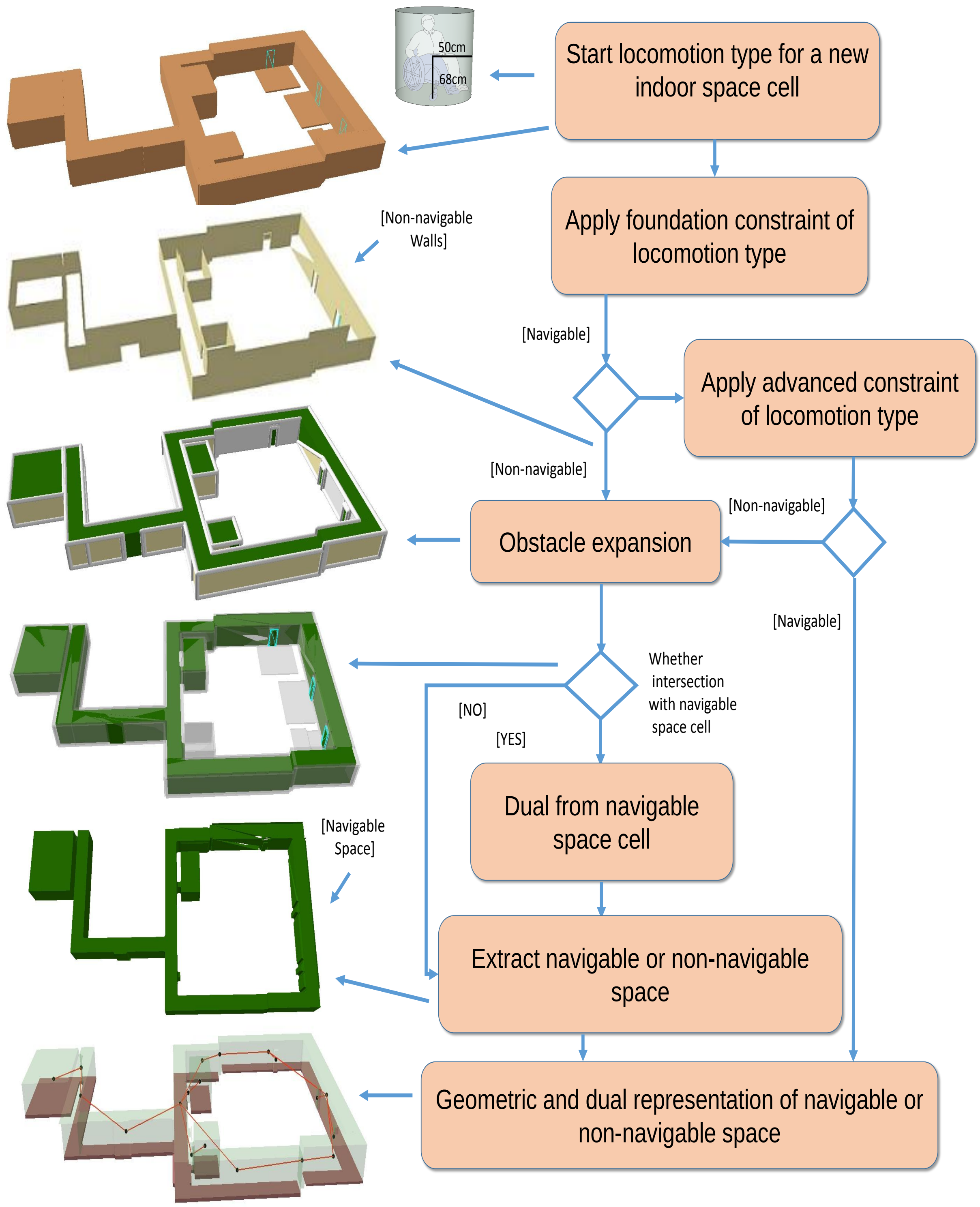


Fig. 4.7 The subspacing of indoor space based on the type of locomotion.(Note: for the illustrations a wheelchair is considered with its constraints for a small building.)

navigable or unsafe for the robot. This concept is used to determine unsafe regions around obstacles for each type of locomotion. The considered 3-dimensional building environment composed of geometric elements, defines the navigation workspace in which the configuration space represents all the possible configurations between the locomotion type and the environment. In configuration space, a popular simplification of the path planning problem is to grow the obstacles in order to reduce the locomotion type down to a point. This step of obstacle growing is very important as it distinguishes the navigable and non-navigable space for the locomotion type. The method used to expand the obstacles and shrink the locomotion is described here in detail. In determining the unsafe (non-navigable) space around the obstacle, the user has to check the collision for the locomotion type and obstacle cell. For this purpose, using the method of Lozano-Pérez and Wesley (1979) locomotion apparatus's body is shrunk to a point, while the obstacle cell is grown by the size of the body. This grown cell will be helpful to determine collision detection between the locomotion type and space cell simply by determining whether the shrunk point is inside or outside of the grown cell. The grown cell is the Minkowski sum of the convex hull of the work space obstacle cell and the locomotion type's geometry (Bajaj and Kim, 1988). In graphics and robotics fields, different methods have been used to determine the Minkowski sum of two objects. In this thesis, the author is using a simple geometric method given in the sources (Bajaj and Kim, 1988; Diktas and Sahiner, 2006; Schøler et al., 2014; Wise and Bowyer, 2000) to compute the Minkowski sum of locomotion apparatus's body geometry and obstacle cell. Based on this method, the Minkowski sum is obtained by replacing a work space obstacle's convex hull vertices with the locomotion apparatus' geometry. For example, replacing edges with cylinders and replacing facets with translated facets (translated along their normal). In case of the geometric representation of locomotion apparatus as sphere, the radius of sphere and translation of facets is equal to the locomotion apparatus's bounding sphere.

2. Navigable geometries after subtracting non-navigable (unsafe) geometries: After getting the grown geometries as 3-dimensional solids from obstacles, in the next step, they are subtracted from the navigable space in which they are occupied to get the actual navigable space.

3. Decision for indoor space cell as navigable or non-navigable (obstacles); application of advanced constraints of the locomotion type: The navigable space extracted after applying primary constraints is elevated for advanced constraints. For example, in a wheelchair case, in the first step, the floor surface and empty air space of a building are extracted as navigable space, in the second step, the floor surface is checked to see if it fulfills the advanced constraints of the wheelchair or not. In this thesis case, wheelchair requires smooth (no stairs, no gap or objects with height more than 0.152 meter) surface floor to navigate. To check the smoothness of the floor surface, the height distance between the current polygon and its next connected polygon is considered. If the distance is zero, it is connected and there is no gap. After confirming its connectivity, in the next step, the other surfaces making angle with the current polygon are checked. If it is 180 or 0 degree then it is completely smooth otherwise it has to be compared with the capacity constraint of the wheelchair. If the angle is less than 35 degrees, then have to check for the slope of the polygon, whether it is within the range of the capacity constraint of the wheelchair. When these constraints are satisfied, then we have to declare those areas as non-navigable, which do not fulfill constraint con-

ditions and they become obstacles for the wheelchair. These newly declared obstacles have to grow and again the procedure described in step-3 is carried out to extract the actual navigable space for the locomotion type.

4. Extracting navigable space: After applying the advanced constraints of the locomotion apparatus, the non-navigable space (grown obstacles) are subtracted from the navigable space. At the end, the navigable space is computed for the locomotion type.

5. Obstructions: There are indoor space cells that make obstructions in navigable space based on constraints of the specific locomotion type. To obtain accurate indoor navigable space, there is the need to consider connected navigable spaces of the non-navigable space and whether they fulfill the accessibility constraints of the locomotion type or not. If they are fulfilled, the non-navigable space does not create an obstruction in navigable space. Otherwise, we have to exclude the obstruction space as non-navigable from the navigable space for the locomotion apparatus. For example, a small gap in the floor surface that is non-navigable space for the wheelchair, when the accessibility between two connected navigable spaces is checked including the gap, then it is determined that the gap capacity of a wheelchair can overcome this obstacle and can drive on the gap. This gap space is an obstacle but does not create an obstruction in the air space above the gap for the wheelchair.

6. Dual representation of navigable space: Dual representation of navigable space was created based on Poincaré's method within the framework of the MLSEM. The overall network model for the whole environment represents the navigable space for the locomotion apparatus. If the network model for the same environment is unconnected this means that the navigable space is subdivided into separate sections that cannot reached from each other.

4.5.1 Subspacing using a 3-dimensional Semantic or Geometric Model

The procedure and process of subspacing is discussed in section 4.4 to determine navigable subspaces for the different types of locomotion based on the assumption that the indoor space has all the required and explicit information within the 3-dimensional semantic building model. Contextual information about the subject's navigation environment is collected from 3-dimensional semantically enriched virtual models in the form of information or rules from each navigational cell provided by its data models. For example, 3-dimensional building models represented in CityGML or Industry Foundation Classes (IFC). In this thesis case, the information about properties and behaviors of locomotion types are explicitly provided. Furthermore, navigation requirements are defined based on the information of the locomotion type that is gathered from its properties and behavior. These requirements are further formalized into distinctive constraints which need to be fulfilled for smooth navigation.

There are different international standards to store, exchange, and represent 3-dimensional building models. The prominent ones are IFC and CityGML as well as a new standard, i.e., IndoorGML. They have different approaches and have various data models (discussed in chapter 2) for the representation of buildings. Now the issue arises which building model standard is compatible with this subspacing procedure or is there a method to integrate different semantic 3-dimensional building models to achieve subspaces from any of the exiting data models for different types of locomotion. The issue and its solution are discussed in the next chapter.

Apart from existing 3-dimensional semantic models, there are many representations which model buildings only geometrically. For instance, building models extracted from laser scanning, e.g., point clouds. These examples do not have implicit or explicit semantic information. To deal with these types of building models, this subspacing procedure and explicit representation of constraints of each type of locomotion can play an important role in defining their semantics as well as determining navigable subspaces. For example, due to the availability of semantic information and its constraints with the locomotion type (e.g., walking person), many parts of buildings can be characterized (e.g., walking accessible geometric areas can be determined as floor surfaces and areas above the person can be classified as ceiling surface. Furthermore, their navigability can be determined based on constraints of the walking person). However, this approach and method still needs to be explored as in this thesis subspacing procedure is only implemented on semantically enriched 3-dimensional building models. Nevertheless, some initial experimentation with point clouds 3-dimensional model was carried out to assess the idea and it remains successful to distinguished a simple 3-dimensional box's parts into semantic partitions and to decide about their navigability (e.g., a square box modeled in point clouds is partitioned into floor surface, wall surfaces, and ceiling surface based on the information of the locomotion type, i.e., walking person). The explanation and a some initial results are given in appendix G.

4.6 Subspacing of Connected Open Spaces

A navigating subject or object in indoor space always needs air/free space to perform navigation. Therefore, free space becomes one of the important parts of a 3-dimensional indoor environment to be considered for navigation. Free space needs to be subspaced at graph and geometric level to represent the real situation to the maximum extent. This can improve the performance and accuracy of 3-dimensional route plan queries in indoor space. For example, if a room is represented with one node in dual space then it is very abstract and for a route plan within a room, the user only has one option for a central node. This could make the situation difficult and result in inefficient outcomes in route planning. In another example, consider two long rooms A and B, adjacent to each other and connected through a door D1 as shown in figure 4.8. When these two rooms and door are represented in dual space as a network model, then it can be noticed that the network model extracted from the primal space is not representing the real situation because edges are crossing outside of the topography of rooms depicted in figure 4.8 which can produce inaccurate results for route planning.

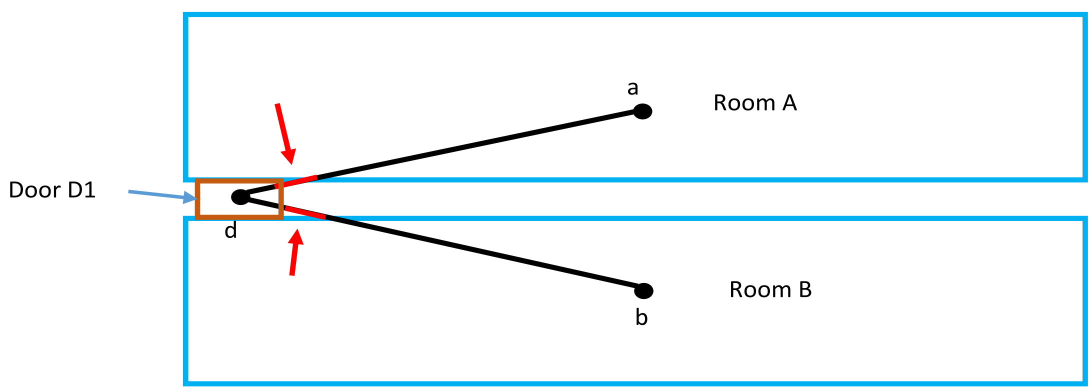


Fig. 4.8 The two rooms (connected by a door) and their corresponding network model before subspacing based on the connected open spaces.

Considering the problem of inefficient results of route planning, there is the need to subspace the air/free space further. When the air space within a room or corridor is observed, then it can be noticed that during route planning a user always searches for the exit/entry point within a room. Therefore, it supports the argument that the free space in the room adjacent to the connected open space has always some importance when compared to the other indoor space in a room. Thus, the author subdivided indoor free/air space based on connected open space objects. Figure 4.9 shows the free space *'Bb'* and *'Aa'* of both rooms connected with a door. Once the rooms *A* and *B* are subspaced into room *Aa* and room *Bb* , and the network model is extracted, then it can be noticed that the network model represents the real situation better as compared to the network model shown in figure 4.9. The open objects connected with the free space of a room may be hole, air, and so on.

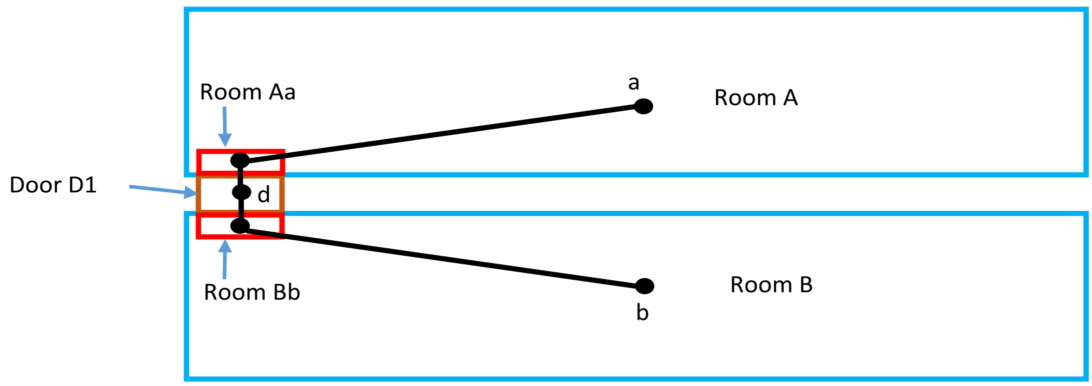


Fig. 4.9 The two rooms (connected by a door) and their corresponding network model after subspacing of the connected open spaces (in this case open space is door).

Figures 4.8 and 4.9 are illustrated in a 2-dimensional situation. In a 3-dimensional indoor environment, the situation will be the same: only the subspaces adjacent to the open space are computed through extruding the 3-dimensional boundary surface of the open space and adjacent room, the length of the extrusion can be the unsafe length of the navigating subject or it can be object making with the obstacle space (e.g., in a generalized representation case, a 3-dimensional sphere representing a UAV can make the unsafe length around obstacles equivalent to its radius.) or depending on the user specific cases, for example, a user can decide the length by considering the area of the room to be subspaced. This method is realized on a small part of a 3-dimensional building model which is illustrated in chapter 6.

Chapter 5

Derivation of Locomotion Subspaces using Semantic 3D Building Model Standards

This chapter[1] describes a multi-step transformation process executed to automatically generate IndoorGML datasets from existing indoor building model data given in either Industry Foundation Classes (IFC) or City Geography Markup Language (CityGML) Level-of-Detail (LoD) 4. Moreover, it addresses semantic transformations, geometric transformations, topological analyses, and spatial reasoning in order to derive navigational structures for the different types of locomotion.

IndoorGML, a standard of the Open Geospatial Consortium (OGC), defines an information model for indoor space based on the requirements of indoor navigation (Kim et al., 2014; Li, 2014; OGC, 2014b). IndoorGML allows users to represent, manage, and store different infrastructures of the indoor environment in primal (volumetric and boundary geometries) and dual (graph model) spaces along with semantic information. Furthermore, it provides a sound mathematical framework to derive, use, and manage parallel and hierarchical graph structures (layers) based on the different contextual considerations for the purpose of indoor navigation and information services. IndoorGML is not tightly coupled with a specific type of semantic 3-dimensional building model. Instead, existing standards for semantic 3-dimensional building models from the Building Information Modeling (BIM) and Topography Information Modeling (TIM) domains, namely the Industry Foundation Classes (IFC) and the City Geography Markup Language (CityGML), can be used in combination with IndoorGML. IndoorGML provides a unique platform for existing 3-dimensional semantic building models to integrate, manage, and to extend their horizon of applications along with the other indoor thematic context spaces (e.g., sensor space). Therefore, there is a need to investigate the potential of integrating these different semantic building models with the IndoorGML model. This investigation goes beyond the conversion from one schema to the other. It also includes the concept of automatically deriving correct navigation structures for indoor navigation with different types of locomotion.

Both types of semantic 3-dimensional building models represent and manage semantic, geometric, and topological information through different approaches. For example, CityGML uses the boundary representation to represent building geometry, while IFC mainly uses volumetric and parametric approaches. In recent years, many researchers have tried to integrate both models to take benefit from the respective other area of specialization. Most

[1] The content of this chapter is based on Khan et al. (2014a).

of these integrations or transformations aim at translating a dataset from one schema to the other (El-Mekawy et al., 2012; Isikdag and Zlatanova, 2009).

In order to be able to use existing semantic 3-dimensional building models (either modeled according to IFC or CityGML for the representation of topographic space in IndoorGML), the 3-dimensional building models need to be both abstracted to graph models and transformed into volumetric and boundary geometries including their semantic information. This transformation requires to take care of the correct topology as well as other transformation requirements, such that the correct navigation structures can be derived. Therefore, unlike the traditional works which translate from one information model to the other, in our case, there is a need to investigate semantic transformations, geometric transformations, topological analysis and spatial reasoning with the objective of deriving correct navigation structures for indoor navigation. As an integral part of these transformations, there is a need to apply algorithms for creating subspaces of topographic space, while taking into account different locomotion types, namely walking, driving and flying.

In order to fulfill these requirements, and in order to achieve a high level of automation in the transformation process, the author has designed a multi-step transformation process to automatically generate IndoorGML datasets from indoor building models.The details are presented in the following sections.

5.1 Related Work

5.1.1 From IFC to CityGML LoD4

Many researchers address interoperability and interaction between IFC and CityGML models, which are two prominent semantic models in the thematic areas of Building Information Modeling (BIM) and Topographic Information Modeling (TIM)[2] respectively. IFC is an international standard for AEC data exchange and representation. It is designed with the prime objective of representing building objects with geometrical and semantic information (BuildingSMART, 2014). On the other hand, CityGML is an OGC standard for the representation and exchange of 3-dimensional urban objects, including buildings (Kolbe, 2009). A number of publications and projects have focused on the integration of IFC and CityGML (De Laat and Van Berlo, 2011; Isikdag and Zlatanova, 2009). Some researchers have given attention to the transformation of data from IFC to CityGML (De Laat and Van Berlo, 2011), whereas others have focused on extending CityGML with regard to conceptual requirements for converting CityGML to IFC models (Nagel et al., 2009). There is also work that has been done on bidirectional transformation between CityGML and IFC using a unified building model (El-Mekawy et al., 2011). Most of the work on transformation of datasets from IFC to CityGML focuses on transformation of geometry and semantics from one representation to the other data model. However, in this thesis, the author is interested in deriving detailed navigable graph structures according to the different locomotion types. Therefore, the focus of this chapter will remain on a detailed representation of a building model and the use of an elementary approach to convert 3-dimensional building models represented in IFC with semantic, topological, and geometric information into CityGML, and then to IndoorGML, in order to achieve correct navigation structures (graphs).

5.1.2 From CityGML LoD4 or IFC to IndoorGML

CityGML, (discussed in section 2.3), is a well-known OGC standard which is used to store, exchange, and represent urban objects. The main features of CityGML include: multi-scale

[2] The semantic 3D modeling of cities and landscape according to topographic criteria.

modeling, i.e., five Levels of Detail (LoDs) to represent a city from the regional level down to the interior building level, modules those contain semantic modelling for different thematic areas, and definitions of classes and relations for the relevant topographic objects in cities. CityGML LoD4 models are specially interesting for indoor navigation since they represent interior structures of building (e.g., rooms, lamps, tables, pillars, stairs, etc.), openings, building furniture, and building installation classes.

While CityGML defines a detailed representation of the semantic, geometric, and topological information of indoor 3-dimensional buildings at LoD4, Becker et al. (2009a,b) address the requirements and key concepts related to indoor navigation in indoor space. A proposal was forwarded by Nagel et al. (2010) to have a new standard, i.e., IndoorGML, for indoor space representation based on the requirements and concepts they mentioned in their paper. IndoorGML allows users to represent and exchange indoor space information that is essential to develop and implement indoor navigation systems. IndoorGML represents geometric and semantic properties of indoor space but they differ in the space representation from CityGML and IFC. Normally, it is recommended to use IndoorGML in combination with other standards, particularly for the representation of indoor subdivisions, where a subspace represented in a subgraph externally references a common indoor building model represented in any other standard, e.g., CityGML (Li, 2014; OGC, 2014b). Therefore, it is considered a complementary standard to both CityGML and IFC to support indoor navigation services.

In this thesis, the author intends to subdivide indoor space according to different locomotion types. Based on the physical constraints of the different locomotion types the navigable spaces can differ. These different geometric navigable models representing navigable spaces for different locomotion types cannot be represented in same data model using external reference feature of IndoorGML. Thus, there is requirement to create the indoor subspace models of buildings in IndoorGML. The subspace models in IndoorGML are sublayers of the main topographic layer (representing the building model). Furthermore, to make these subspaces coherent with the main topographic layer we consider it important to convert the building model represented in CityGML to IndoorGML. In the following, a detailed transformation of each feature type of a public building represented in CityGML LoD4 into IndoorGML is presented for the purpose of computing subspaces.

5.1.3 Deriving Subspaces according to different Locomotion Types

In chapter 3 the author has discussed the fact that many researchers have focused on a single type of locomotion for indoor navigation, e.g., walking or driving. In contrast to these various methods, this work will focus on support to different types of locomotion using existing semantic 3-dimensional building models either CityGML or IFC. For this purpose, in the first step, the semantic building model given either in CityGML or IFC is converted into an indoor space representation model, i.e. IndoorGML, which provides a whole framework to represent, integrate, and manage indoor subspace as well as to deal with indoor space queries. In the second step, based on the conceptual constraint model for the different locomotion types shown in figure 3.12, subspaces are generated for each type of locomotion. Those subspaces are further reflected in navigable graph models within IndoorGML to address route planning queries.

5.2 Transformation from 3D Building model standards to an IndoorGML data model

The general concept of generating IndoorGML datasets from different semantic 3D building models either represented in IFC or CityGML LoD4. Furthermore, determining navigation structures according to different locomotion types based on their specific navigation constraints is illustrated in figure 5.1.

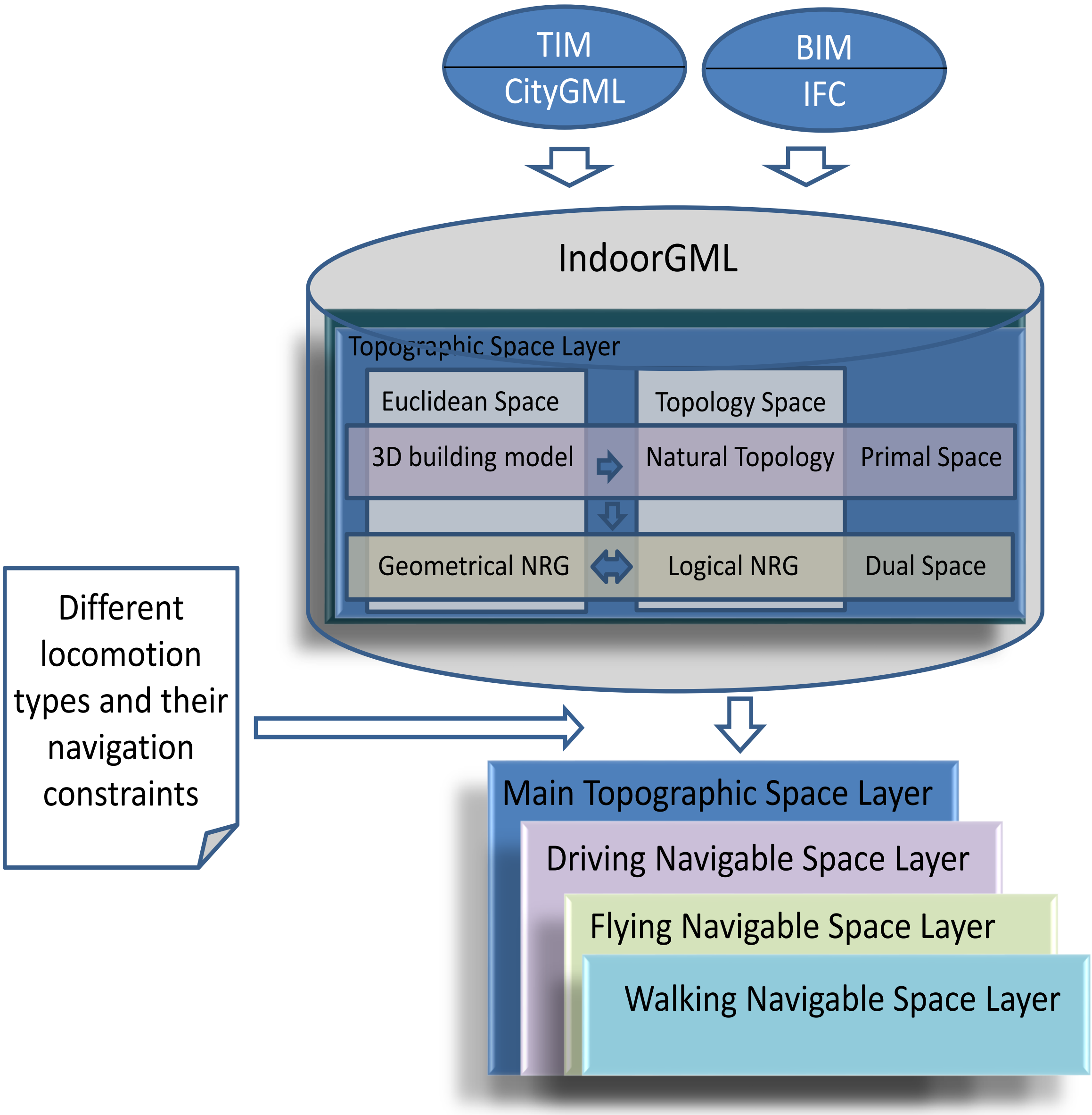


Fig. 5.1 Generating IndoorGML datasets from TIM and BIM sources and determining navigation structures according to different locomotion types in IndoorGML.

The Multilayered Space-Event Model (MLSEM) is a framework presented by Becker et al. (2009a) provides not only the method to abstract or to form graph geometries Node Relation Graph (NRG) (Lee, 2004) from primal space (volumetric objects e.g. representing topographic space) but also defines a link between those graph models with other graph models representing different contextual thematic spaces of indoor environment for use in indoor applications, e.g., linking an indoor topographic layer with an another layer representing sensor covering area for route planning. IndoorGML, which is the application schema of the MLSEM concepts, is not tightly coupled with a specific type of semantic 3-dimensional building model. Instead, existing standards for semantic 3-dimensional building models from the Building Information Modeling (BIM) and Topographic Information Modeling (TIM) domains, namely the Industry Foundation Classes (IFC) and the City Geography Markup Language (CityGML) can be used in combination with IndoorGML. In a simple case, transforming IFC or CityGML to IndoorGML just means to create references between nodes of the (manually created) Network Relation Graph (NRG) (Lee, 2004) representing the topographic indoor space and the corresponding IFC *IFCSpace* or CityGML *Room* objects. As our intention is to automatically create subspaces of the indoor space described by the IFC or CityGML data and to automatically derive the NRG from these subspaces while taking into account the constraints defined by different types of locomotion.

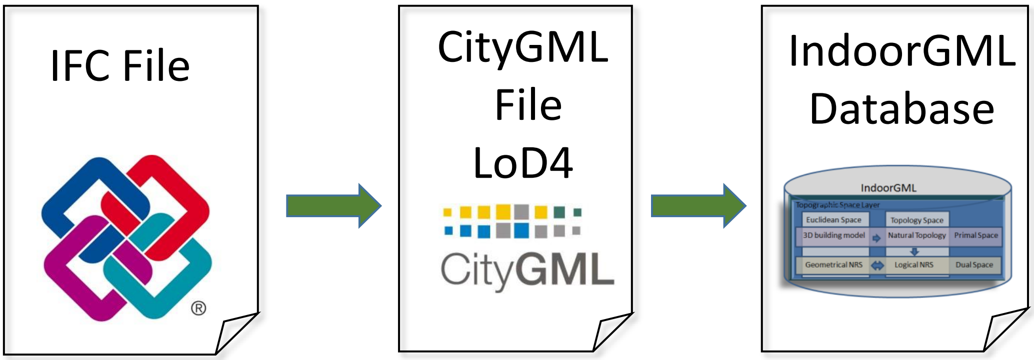


Fig. 5.2 Transformation of a 3-dimensional building model from IFC to CityGML LoD4 and then to IndoorGML

In order to reduce complexity and to allow the existing semantic 3-dimensional building models to be represented both according to IFC and to CityGML, this transformation task is divided into multiple subtasks which are grouped into two main steps as shown in figure 5.2. In step 1, IFC data is semantically and geometrically transformed to CityGML LoD4 and the topology is analyzed. In step 2, CityGML LoD4 data is semantically, and geometrically transformed to IndoorGML. The transformation process from a parametric geometry representation to Boundary Representation (BRep) as required both by CityGML and IndoorGML, is investigated. In the semantic transformation, the focus remains on transforming the maximum amount of the semantic information related with each indoor object following the schema rules of the IFC source and the CityGML target object. Whereas in topology analyses, the requirements for having correct topological relations between an indoor building model's objects and their connected geometries (e.g., connected door and room geometries must correctly touch each other, there must be no overlap and that they must determine boundary geometry) are investigated. As IFC allows a user to model a semantic 3-dimensional building in many different ways (Nagel et al., 2009), flexibility in the transformation to CityGML is required. This requirement is taken into account by using a standard spatial ETL tool, a FME workbench[3], for the implementation of a sub-step in the second step. The transformation from CityGML to IndoorGML has fixed rules for the semantic and geometric transformation. Here, the focus of investigation is to transform boundary geometries from CityGML to volumetric space objects in IndoorGML including their semantic information, e.g., a multisurface room feature is translated into a room solid with its boundary geometries, i.e., interior wall surfaces, etc. Besides the transformation

[3]FME Desktop is an application for translating and transforming data. www.safe.com

from CityGML to IndoorGML, the third step of the overall transformation procedure deals with the subspacing of topographic space and deriving the NRG for different locomotion types.

5.2.1 Transformation from IFC to CityGML LoD4

The basic concepts and related work required to transform from IFC to CityGML are discussed in detail in Isikdag and Zlatanova (2009). In addition to these concepts, there is the requirement to consider the basic requirements on structure and context of the IFC model for a successful IFC to CityGML transformation with the objective of deriving navigable graphs.

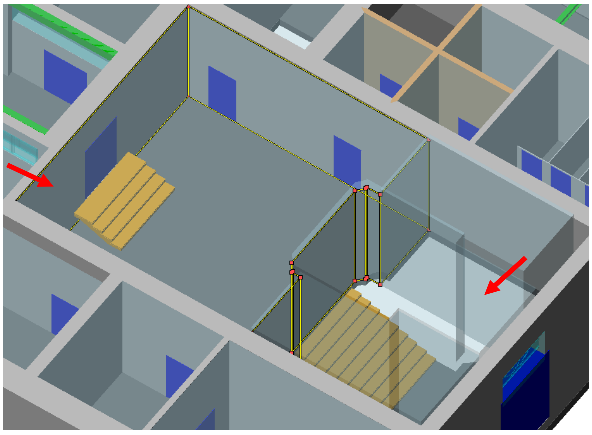


Fig. 5.3 *IFCSpace* representation of a room and a porch.

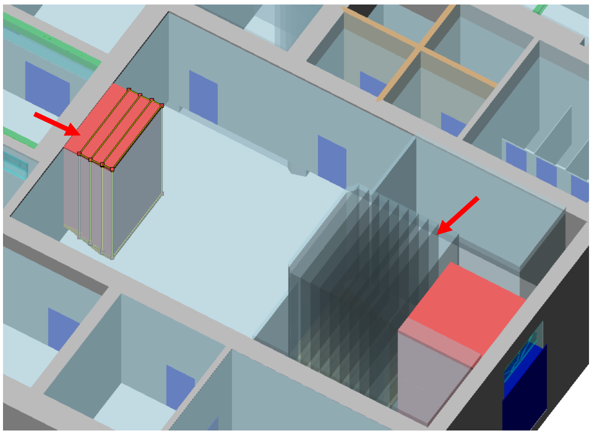
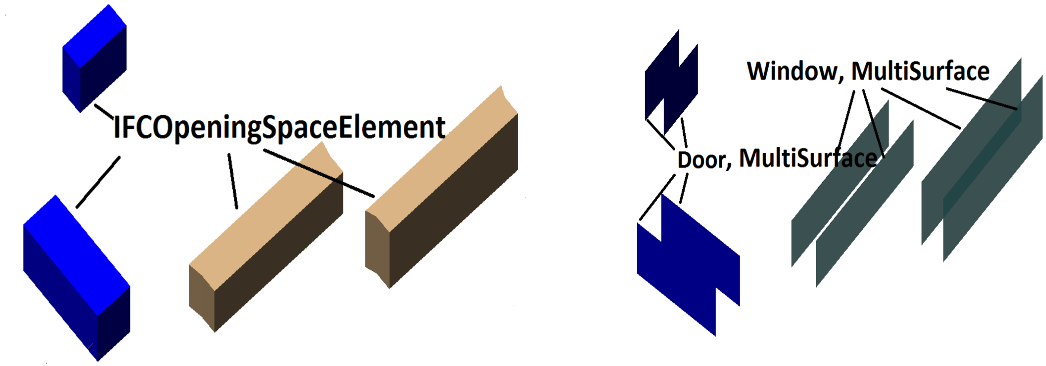


Fig. 5.4 Space representation above stairs in a room and a porch.

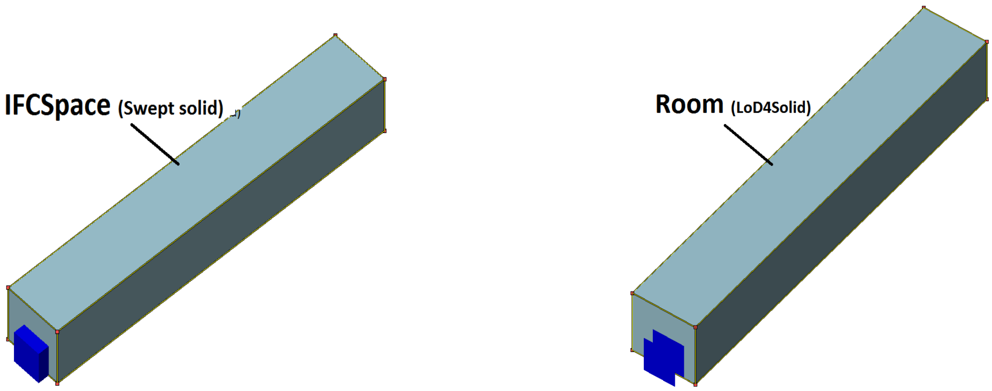
For a successful IFC to CityGML transformation, there is a need for the detailed representation of the abstracted building parts of the building model so that the individual spaces can be identified either as navigable or non-navigable for the specific locomotion type. The detailed representation which may form many elements from the specific element of the IFC building model must be supported by semantic content of the parent element. The detail representation for some of the IFC model elements is explained in the following paragraph. Another important consideration that needs to be considered is the topological relations between building elements so as to generate correct navigation graph structures for different locomotion types.

The *IFCSpace* class defines all volumes and areas that are bounded by different building elements. For example, in figure 5.3, a room contains stairs. The whole space within that room including the stairs is represented as *IFCSpace*. As there is need to compute the subspaces for different locomotion types and since for a specific type of locomotion the stairs are non-navigable (e.g., when using a wheelchair), whereas for another type of locomotion it is navigable (e.g., a walking person). Therefore, there is a need to represent the space above the stairs separately. Furthermore, all steps of the stairs may have different areas and properties. Therefore, each stair step has to be considered individually and, thus, the space above each stair step should have an individual representation (see figure 5.4). If a step is determined as non-navigable for a specific type of locomotion then the space above it, is also non-navigable. The same approach is applied to each building element or area where its navigability is represented (e.g., free space above a ramp, free space within circular stairs, etc.)



(a) *ifcOpeningSpaceElement* (b) *Window* and *Door* MultiSurfaces

Fig. 5.5 Transformation of *ifcOpeningElement* to *Window* or *Door MultiSurfaces*.



(a) *IFCSpace Element* (b) *Room* feature type

Fig. 5.6 Transformation of *IFCSpace* to *Room* feature type.

In the next step, all elements, e.g., *ifcStairs* and *ifcWall* objects, in the building model are checked to determine whether they overlap with the *IFCSpace*. If they *overlap* they are deduced from the *IFCSpace* to ensure that they only have a topological *touch* relationship with the *IFCSpace*. *IFCOpeningElements*, which fill the void spaces in walls, are checked for their topological relationships with the *IFCWallStandardCase*, through the relation *IFCRelVoidsElements*, and *IFCWallStandardCase* relation with the *IFCSpace* is checked through *IFCRelSpaceBoundary*, to be in touch relation and should not have an overlap or gap with the *IFCSpace*. Normally a door or window element fills an *IFCOpeningEle-*

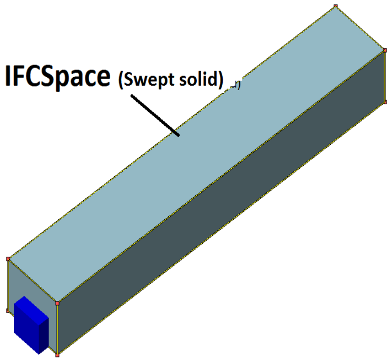
ment. In this case, the author ignores the door or window geometry and considers the geometry of the *IFCOpeningElement* for the transformation because the former overlaps the latter. Moreover, the author has provided simple conversion steps through which the transformation from IFC data into CityGML can be achieved. The conversion from IFC to CityGML is carried out in the following steps given in Table 5.1.

Table 5.1 Semantic mapping and transformation steps from IFC to CityGML dataset.

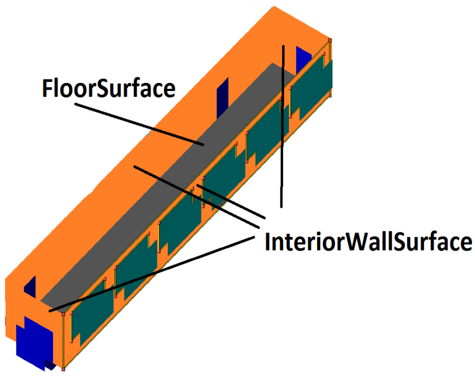
IFC Elements	Transformation details	CityGML Feature Types
IFCOpeningElement	Check the relation *IFCRelFillsElement* of *IFCOpeningElement* with the *IFCDoor* or *IFCWindow* element; then the properties of *IFCDoor* or *IFCWindow* are attached to the respective *IFCOpeningElement*. *IFCOpeningElement* is converted into Door or Window *MultiSurface* geometries in CityGML as shown in figure 5.5.	*Window MultiSurfaces/ Door MultiSurfaces*
IFCSpace	*IFCSpace* geometry, which often is a parametric geometry in IFC is converted into boundary representation geometry and translated into a *Room* feature (LoD4Solid) in CityGML as shown in figure 5.6.	*Room*
IFCSpace	*IFCSpace* is converted into *multiSurfaces*. Based on the height and relative altitude of *IFCSpace* the decision about each surface is taken, whether it is a *CeilingSurface* or a *FloorSurface*. If the height is between specific thresholds then it is tagged as *InteriorWallSurface*. Furthermore, *Window* and *Door* surfaces are deduced from *InteriorWallSurfaces* as shown in figure 5.7.	*FloorSurface, CeilingSurface, InteriorWallSurface*
IFCWall	*IFCWall* is converted into *multisurfaces*. The *multisurfaces* are translated to *WallSurfaces* in CityGML, which represent the exterior shell of the building and have no connection to the *Room* feature type as shown in figure 5.8.	*WallSurfaces*
IFCStairs, IFCBeam, IFCColumn	The *IFCStairs, IFCBeam, and IFCColumn,* are translated into *multisurface* boundary geometries in CityGML. Moreover, IFC elements, which are within a specific room are transformed into *IntBuildingInstallation*. (Currently the transformation process, IFC elements, e.g., *IFCBeam* and *IFCColumn* which extend over more than one room or cross the boundary to the exterior are transformed into *BuildingInstallation* in future this problem will be rectify and will transform into *IntBuildingInstallation*).	*IntBuilding-Installation*

5.2.2 Transformation from CityGML LoD4 to IndoorGML

IndoorGML is defined as an independent data model from the different approaches of building modelling, e.g., CityGML or IFC (Li, 2014). Therefore, the main topographic space

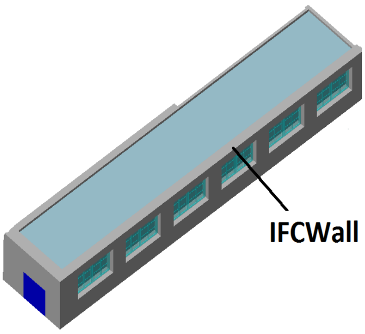


(a) *IFCSpace Element*

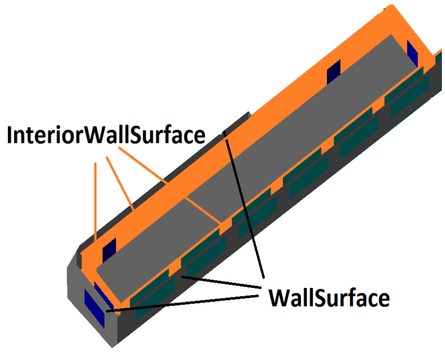


(b) *FloorSurface, InteriorWallSurfaces*

Fig. 5.7 Transformation from *IFCSpace* to *InteriorWallSurfaces, CeilingSurfaces* (not shown here), and *FloorSurfaces*.



(a) *ifcWall*



(b) *WallSurfaces*

Fig. 5.8 Transformation from *ifcWall* to *WallSurface*.

layer in IndoorGML can be represented using the input from a 3-dimensional building model that is represented either in CityGML or IFC or from any other information model describing the interior structure of a building. As discussed in section 5.1.2 there is a need to translate a 3-dimensional building model represented in CityGML into IndoorGML to obtain the main topographic space layer and to be able to compute subspaces according to different locomotion types. The details about *CellSpace, CellBoundary*, the structure model of each space layer, and the integration of multilayers can be found in (Becker et al., 2009a; Li, 2014).The transformation mappings and steps to transform between the elements of CityGML LoD4 and IndoorGML are explicated in Table 5.2.

WallSurface, RoofSurface, and *GroundSurface* objects are treated as outer *CellSpace* objects in IndoorGML and their geometries are not translated. Furthermore, each feature type in the CityGML LoD4 3-dimensional building model is translated into either a *CellSpace* or a *CellBoundary* geometry in IndoorGML with all the related attributes as described in 5.2. Afterwards, the dual space geometries including state geometries (nodes) and transition geometries (edges) representing *CellSpaces* and *CellBoundary* in primal space respectively are computed to generate a space layer based on the MLSEM's method.

Table 5.2 Transformation mappings between conceptual CityGML and IndoorGML classes.

CityGML Feature Types	Transformation details	IndoorGML Elements
Room	*Room* geometry having geometry *CompositeSurface* and geometry *MultiSurface* is enforced to be a closed volume and translated into a *Solid* in IndoorGML	*CellSpace*
Door	*MultiSurfaces* representing a single *Door* are converted into a closed volume *(Solid)* in IndoorGML	*CellSpace*
Window	*MultiSurfaces* representing a single *Window* are converted into a closed volume *(Solids)*	*CellSpace*
Door as a *Surface*	A surface representing a *Door* is translated into a 3-dimensional boundary geometry in IndoorGML.	*CellBoundary*
Window as a *Surface*	A surface representing a *Window* is translated into a 3-dimensional boundary geometry in IndoorGML.	*CellBoundary*
InteriorWallSurface	An *InteriorWallSurface* representing the boundary surface of a *room* in CityGML is translated into a 3-dimensional boundary geometry *(CellBoundary)* of the incident room *CellSpace* in IndoorGML.	*CellBoundary*
FloorSurface	A *FloorSurface* representing the boundary surface of a room is converted into a 3-dimensional boundary geometry *(CellBoundary)* of the incident room *CellSpace*.	*CellBoundary*
CeilingSurface	A *CeilingSurface* representing the boundary surface of a room is converted into a 3-dimensional boundary geometry *(CellBoundary)* of the incident room *CellSpace*.	*CellBoundary*
ClosureSurfaces	Objects sealed using *ClosureSurfaces* are converted into a closed volume *(Solid)* in IndoorGML. Simultaneously, surfaces are converted into 3-dimensional boundary geometries of objects.	*CellSpace* and *CellBoundary*
BuildingFurniture, BuildingInstallation, IntBuildingInstallation	*BuildingFurniture, BuildingInstallation,* and *IntBuildingInstallation* represented by *MultiSurfaces* are converted into closed geometries *(Solid)* in IndoorGML.	*CellSpace*

5.3 Derivation of Subspaces in IndoorGML

After having derived the IndoorGML building model either from IFC or CityGML, in the next step, the navigable subspaces for the different types of locomotion are computed based on their specific navigating physical constraints. For each type of locomotion, i.e., flying, driving, and walking an example is considered based on its common usage in indoor environment. These include Unmanned Aerial Vehicle (UAV), wheelchair, and a walking person respectively. The indoor navigation constraints of each locomotion type are based on the locomotion type's constraints model defined in chapter 3.

In the field of robotics, for the path planning, the mapping from work space to configuration space to determine a safe route for a rigid object resemble to a route for a point through the configuration space map. This approach has withdrawn the requirement for 2-dimensional or 3-dimensional collision detection and simplifies the path planning problem of finding a line that connects the start and target configurations by avoiding the unsafe space. It also distinguishes the work space into three categories based on two solid objects which cannot overlap: obstacle configurations, in which objects overlap; safe or free configurations, in which no overlap occurs and contact surface configurations, in which two or more objects touch each other (Lozano-Perez, 1983; Wise and Bowyer, 2000). This method is not specific to robotics but also has been applied in the areas of construction, auto mechanics, etc. (Wise and Bowyer, 2000). Considering the simplicity, accuracy, and application of this approach in different fields, navigable spaces are intended to be computed for the locomotion types with configuration space mappings. In a 3-dimensional environment, the generalized geometric models of a flying object, a walking person, and a wheelchair as 3-dimensional sphere and cylinders respectively are considered along with their specific navigating physical constraints. The computation of the configuration space mapping was carried out based on the Minkowaski sum method (Bajaj and Kim, 1988; Diktas and Sahiner, 2006).

The decision to determine a specific element of indoor space as navigable or non-navigable for the given locomotion type is taken by considering the physical navigating constraints of the locomotion type and spatial information (semantic, geometric, and topological information) of the element. The indoor space element, which is determined as non-navigable, will determine obstacle space around it to be deduced from the free space.

5.3.1 Example Scenario

Consider a 3-dimensional building model containing a corridor and a room that contains four columns. The representation of building elements in CityGML and corresponding representation in IndoorGML are presented in figures 5.9, 5.10, 5.11, and 5.12 respectively. The extraction of a network model from the building as a main topographic space layer in IndoorGML is shown in figure 5.11. Most of the methods compute the navigable subspace for the locomotion type using constraints of the indoor space at the graph level. For example, the navigable space for the wheelchair (shown in figure 5.12) is computed considering its capabilities and constraints of the indoor space from the network model shown in figure 5.11. The decision of the navigability of each element of a building (e.g., a door) is taken after considering its spatial properties, i.e., length and width. If the length and width of the door is greater than the length and width of the wheelchair, then the door is considered to be navigable.

The network model and the subspace building model representing the navigable space for the wheelchair as shown in figure 5.12 is not precise enough for approximating the reasonable navigable space. This is, because, there are other locomotion types (e.g. flying) which may require precise or the detail geometric indoor navigable space so that they can

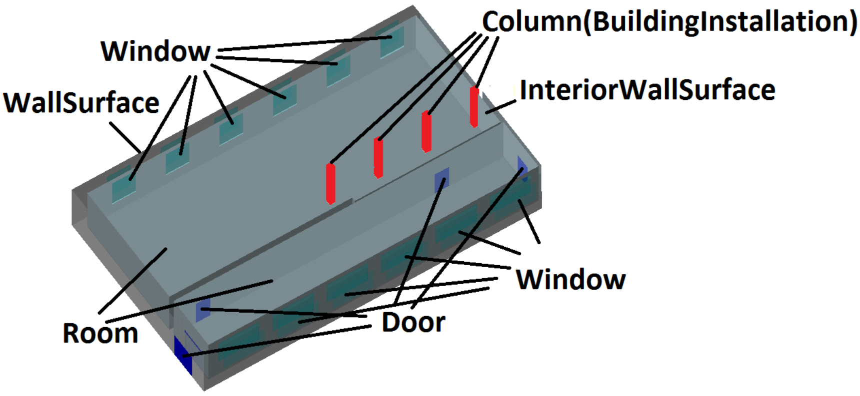


Fig. 5.9 3-dimensional building model in CityGML.

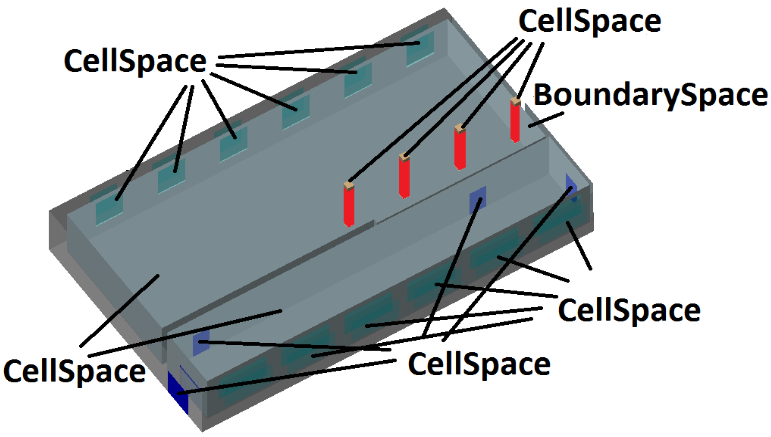


Fig. 5.10 Corresponding 3-dimensional building model in IndoorGML for the building shown in figure 5.9.

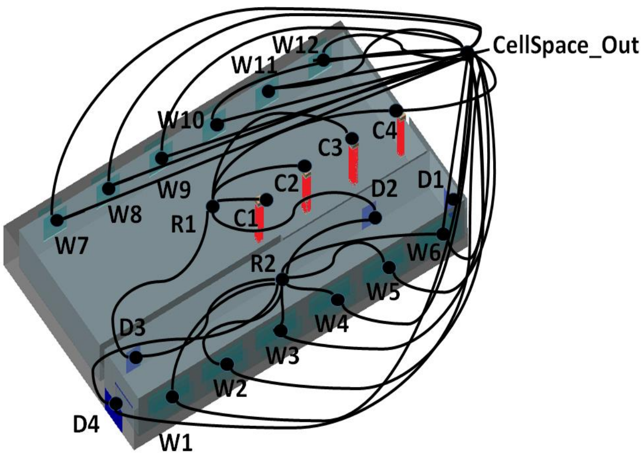


Fig. 5.11 In IndoorGML, the main topographic layer of the 3-dimensional building model.

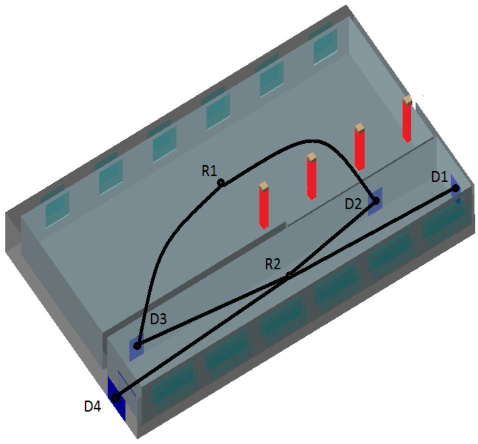


Fig. 5.12 Navigable subspace computed based on a network model according to the wheelchair navigation.

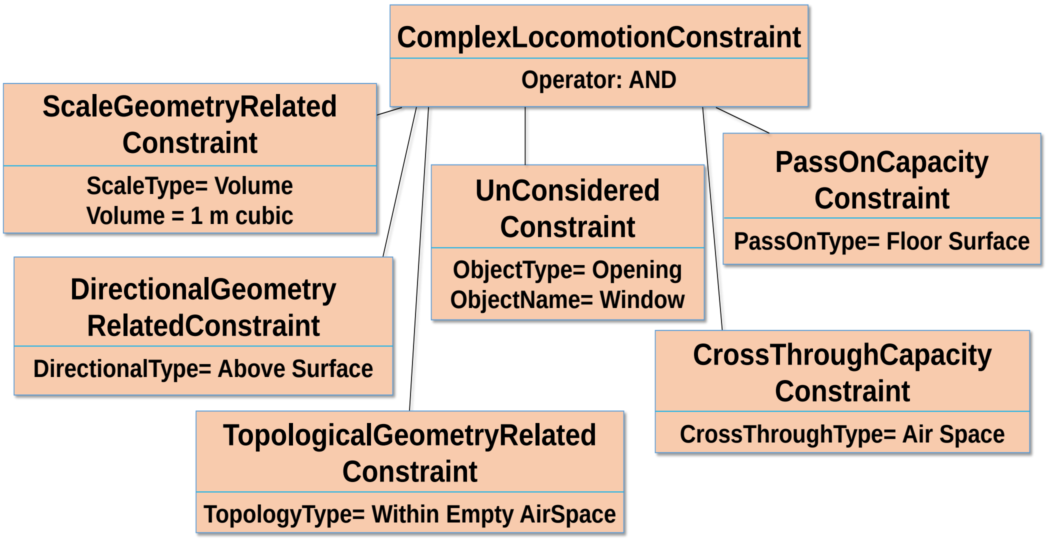


Fig. 5.13 An example of a complex locomotion constraint for computing navigable subspace for a wheelchair formed by aggregating subconstraints.

avoid collision with the obstacles (e.g. a column) located in the room. Therefore, there is a need to compute the actual navigable space after deducing the obstacle space (non-navigable space created by obstacles).

The physical constraints of a wheelchair are considered to determine the obstacles according to the constraints model defined in chapter 3. For example, considering a wheelchair and its navigation constraints, a decision to determine the navigability of a specific indoor element is taken after considering all its properties. If there is a free space element from indoor space then a collection of constraints for a wheelchair are considered which need to be fulfilled to declare the free space. In this example, as a first step, the *ScaleGeometryRelatedConstraint* of the locomotion type is considered. According to this constraint, it needs the volume of 1 cubic meter or more of free space to navigate. Furthermore, more constraints (as given in chapter 3) can be considered, some of them are shown as example in 5.13 and they are combined through the *complexlocomotionconstraint* operator “and”. So, they all need to be fulfilled to determine the free space navigable for the wheelchair. The next constraint is the *DirectionalGeometryRelatedConstraint*, which requires the wheelchair to have a surface to be held on or the free space must have a floor surface. Once that constraint is fulfilled, the free space element is checked for *UnConsiderConstraint*, and whether the indoor element is “Window” (in this case as it is not window so it becomes irrelevant to be fulfilled). Otherwise, if it is window, then it is determined as non-navigable. Then in the next step, the *TopologicalGeometryRelatedConstraint* is considered, which emphasizes that the free space must fulfill the requirement to be navigated “within” the geometry of the locomotion type. If the free space has enough space to contain the locomotion type, then that free space element is navigable. Otherwise, it is determined as non-navigable. In a further realization of the constraints of the wheelchair on free space element of indoor space, *CapacityContraints* are considered that include *CrossThrough* and *PassOn*. In this case, the wheelchair is evaluated to determine if it has the capacity to cross through free space and pass on floor surface of the free space. Thus, the free space is computed as navigable or otherwise as non-navigable.

In this example, after considering constraints from figure 5.13, free space and door spaces are determined as navigable for the wheelchair. Furthermore, considering other constraints from the constraint model of the locomotion type, columns, windows, and walls of the room are considered as non-navigable. The non-navigable spaces (e.g. columns, windows, and walls) determine obstacle spaces (based on Minkowski's sum as shown in figure 5.14 in pink). The actual navigable space is determined after deducing the obstacle space (as shown in figure 5.14 in green). Furthermore, the route graph for the wheelchair is formed using the IndoorGML method (Poincaré duality) from the actual navigable space (as shown in figure 5.15).

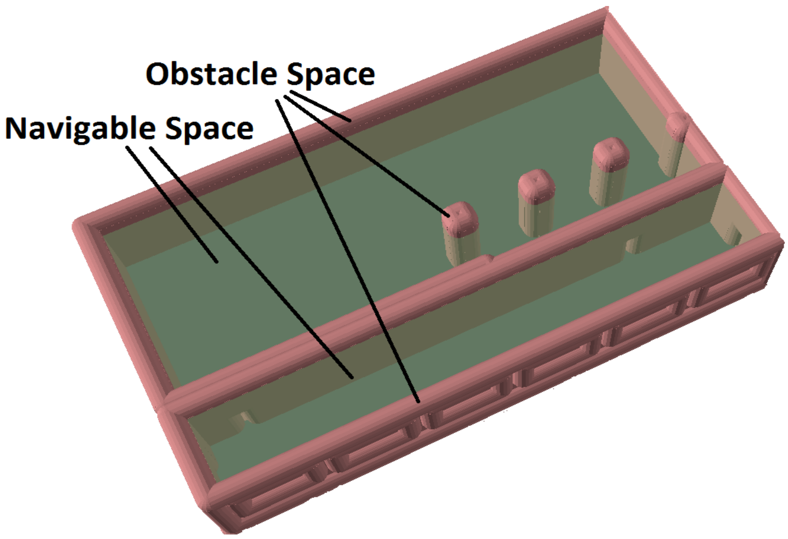


Fig. 5.14 Actual navigable spaces and obstacle spaces according to the wheelchair. Highlighted in green color.

The difference between navigable space that is computed for a wheelchair through graph based approaches and free or safe navigable space which is computed through configuration space approach can be observed in figures 5.12 and 5.13 respectively. The navigable space computed using configuration space is more precise (particularly given geometric details of non-navigable space around the columns). This level of precision is not possible to represent through graph based approaches.

The author has discussed in chapter 3 why it is important to derive geometric subspaces for the different locomotion types in contrast to many other approaches (Dudas et al., 2009; Lertlakkhanakul et al., 2009; Meijers et al., 2005; Petrenko et al., 2014; Stoffel et al., 2007) where subspaces are computed only on a graph model level. The navigable space that is computed through graph based approaches, in essence, uses only some geometric positions

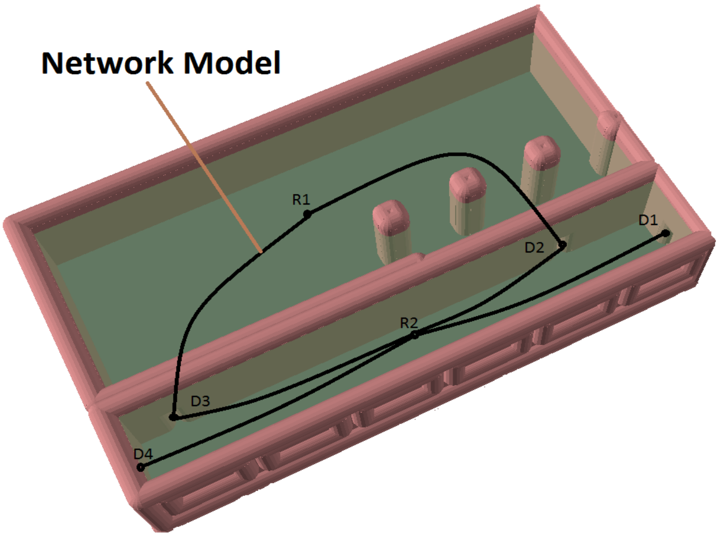


Fig. 5.15 Network model with corresponding actual navigable spaces (shown in green) and obstacle spaces according to the wheelchair.

(centroid of the object) and information about connections between spatial objects (topological graphs). The semantic information (e.g. types of spaces, and properties of building components) and the actual geometry of the object have not been considered yet. In contrast, the subspacing in this thesis carried out through the configuration space approach uses fully geometric and semantic information from a semantic 3-dimensional building model. In addition, if there are obstacles within an indoor space (e.g. column), the methods based on the graphs will fail or be not precise enough for approximating of reasonable navigable space, which may limit the path planning in many route planning applications. From the brief discussion and comparison above, it is apparent that to have accurate subspaces, it is necessary for a given locomotion type to compute and extract the network models from the navigable space at the geometric level.

Chapter 6

Use Case: Generation of Locomotion Types' Subspaces and Route planning using a 3D Building Model of the Technical University of Munich (TUM)

In the context of a Smart Campus project at the Technical University of Munich (TUM), a campus information system is currently being developed. This project is intended to create an integrated platform that provides benefits for managing all kinds of building information and support for various application fields like indoor route planning. As a part of this project, for the purpose of computing safe navigable spaces for different locomotion types within 3-dimensional building model of TUM, a dataset of a part (a part of central city campus) of the building of TUM is considered. More importantly, the model is used to implement concepts discussed in previous chapters. A 3-dimensional model of the building has been provided in Computer Aided Design (CAD) model by the facility management department. This model contains geometric details and semantic information of each object of the building (e.g., room number, condition, etc).

In this chapter[1], the CAD model of the building is transformed into IFC model, and then into CityGML model. Furthermore, the CityGML building model is translated into an IndoorGML model where the subspaces for the different locomotion types are computed. Apart from the transformation process, the issues addressed with the CAD model of the building are highlighted. In addition, the IndoorGML building model is coupled with a cloud-based system to facilitate context aware indoor route planning. At the end of the chapter, the lessons learned and an evaluation of the methods used in this use case are presented.

6.1 3-dimensional Indoor Building Model

6.1.1 Computer Aided Design (CAD) Building Model

Geometric model: The CAD model of (a part of) the main building of the TUM (provided by the facility management department) is shown in figure 6.1. The building model consists of three floors and two under-ground floors. Each floor contains lecture rooms, offices, stores, and corridors. Furthermore, free space within each object of the building is represented with swept solids shown in figure 6.3. An interior view of the small portion of building floor is shown in figure 6.2.

[1]The content of this chapter is partially based on Khan et al. (2014b).

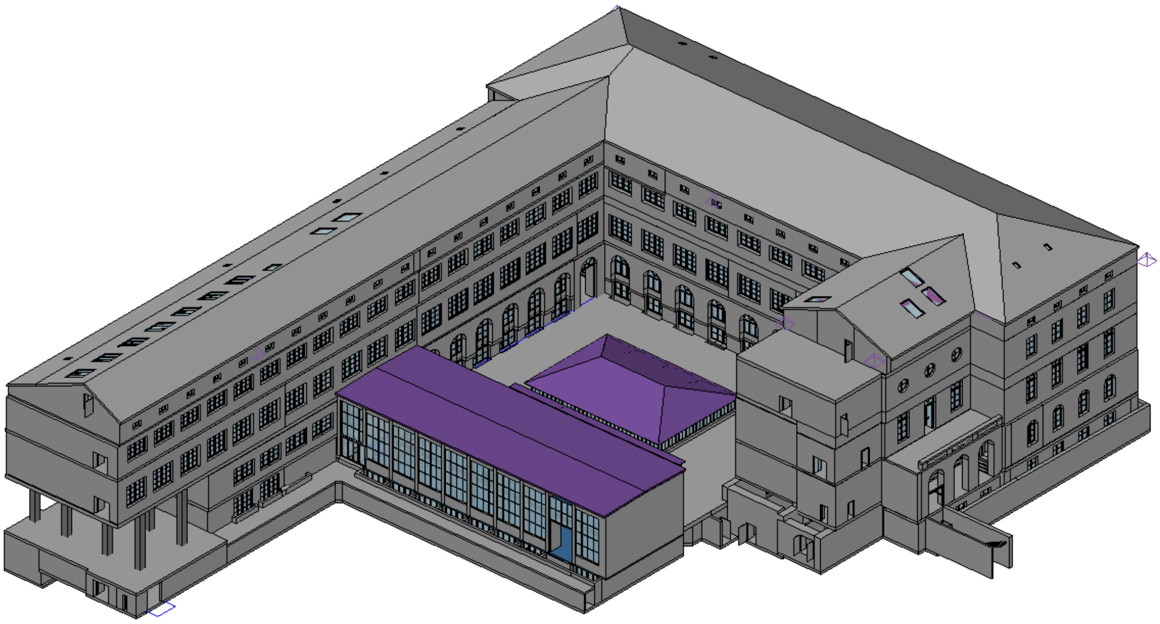


Fig. 6.1 The 3-dimensional CAD model of the main building of TUM.

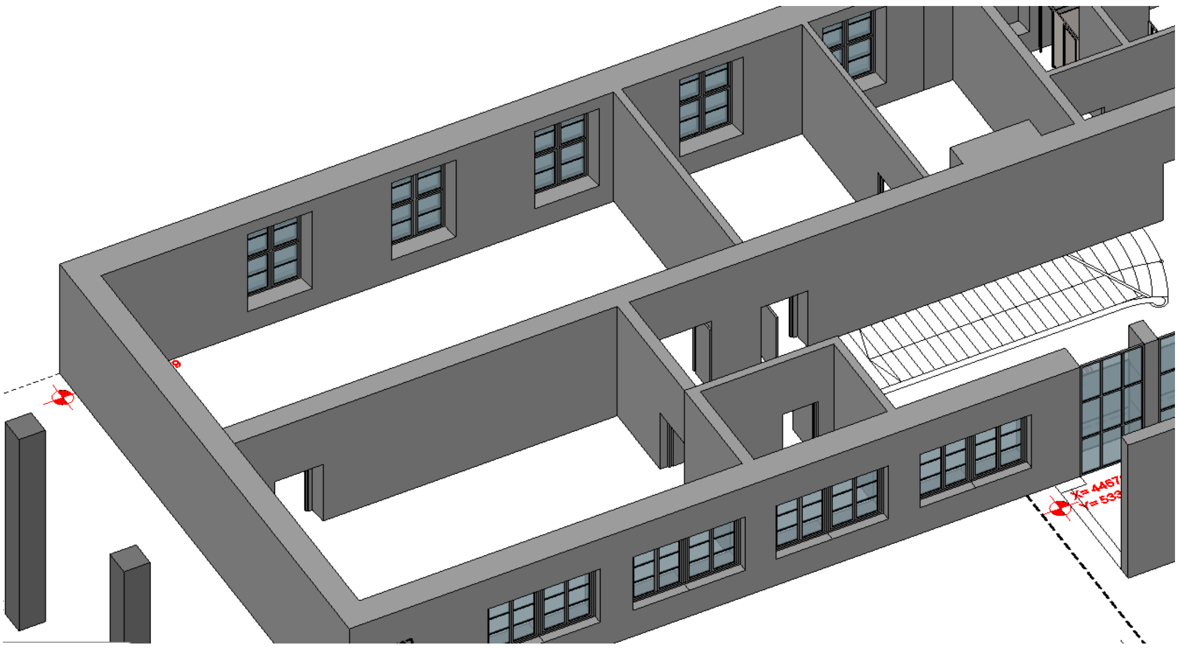


Fig. 6.2 The close interior view of a floor (of the CAD building model).

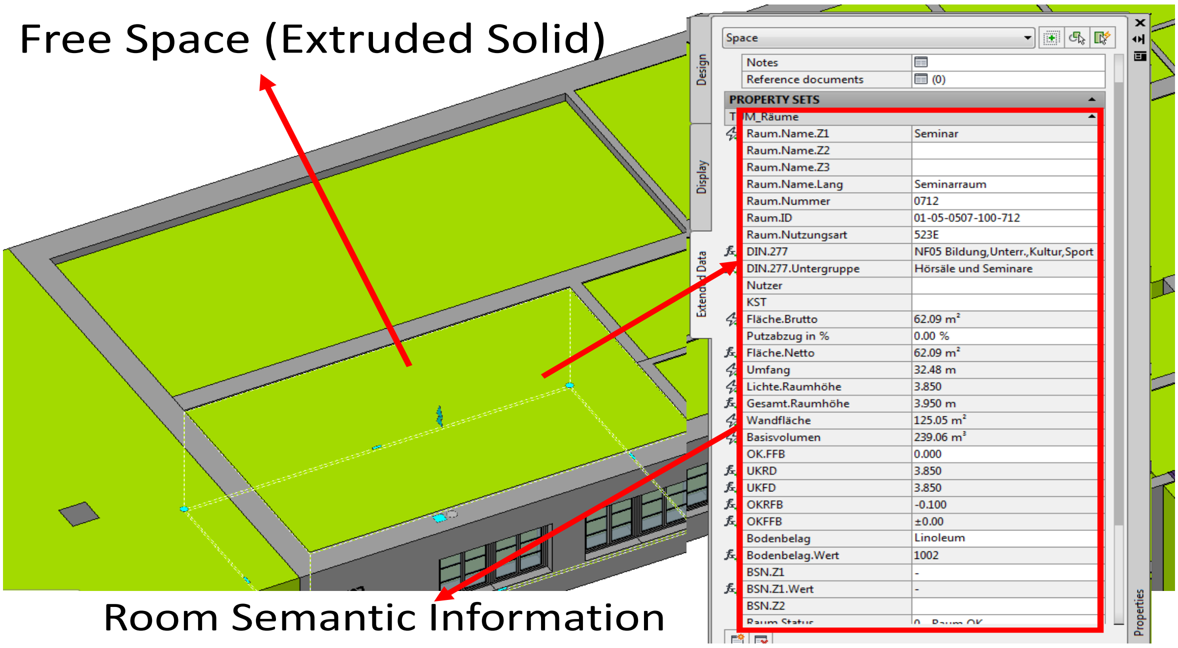


Fig. 6.3 Swept solids representing free spaces of the building and semantic information associated with it.

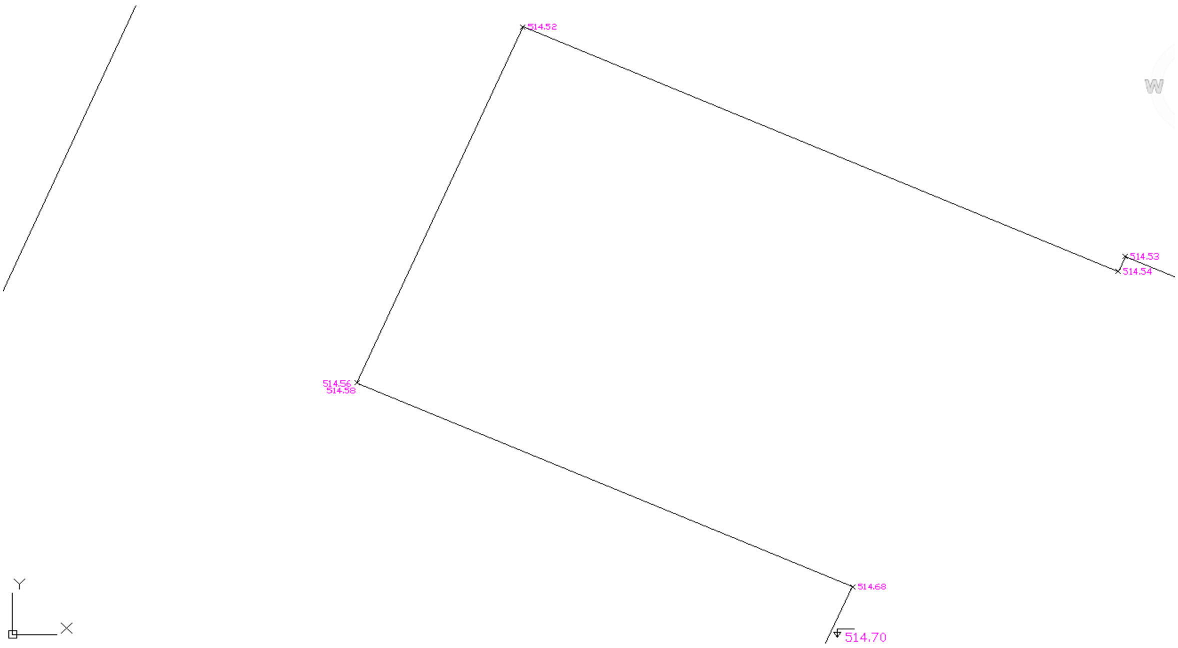


Fig. 6.4 Two-dimensional reference points of building model.

Semantic information: Each swept solid representing free space of the interior space and contains all relevant semantic information. For example, a swept solid representing a free space of a room contains a room number, a floor surface type, the condition (in a situation to use) of a room, etc. as shown in figure 6.3.

Coordinate system information: The model is in local coordinate system and contains 2-dimensional reference points as shown in figure 6.4.

In the first step, the CAD model is exported into an IFC building model by means of the export option of the AutoCAD Architecture[2] 2014. The IFC building model after exporting from the CAD model is shown in figure 6.5.

6.1.2 Automatic Generation of the Topographic Layer in IndoorGML from a CAD Building Model

The transformation process from an IFC model to an IndoorGML model is shown in figure **??** and further details about the transformation processes with their results are given in the following sections.

From Building Information Model (BIM) to a Semantic 3D Building Model (CityGML LoD4)

The concepts discussed in chapter 5 to translate 3-dimensional building models from an IFC to a CityGML model dataset are realized by means of FME werkbench. In the first step, the whole building model is analyzed to determine whether the model has any *IFC-Space* elements which need to be represented as subspaces (e.g., *IFCSpace* element above stairs). After identifying *IFCSpace* elements which need to be subspaced, the elements are subspaced as shown in figures 5.3 and 5.4(the reasons for this subspacing are discussed in section 5.2.1). The whole IFC building model of TUM's main builing with a close view of a room showing IFC elements (e.g., *IFCSpace, IFCColumn, IFCDoor, IFCWall, IFCOpeningElement*) is shown in figure 6.5. In the second step, the building model is transformed from an IFC model to a CityGML LoD4 model using the FME werkbench. The detail FME werkbench is presented in appendix A. After running FME werkbench the result of a 3-dimensional building model in CityGML is shown in figure 6.6 with a detail view of the same room that is shown in IFC building model. The close view of the room shown in figures 6.5 and 6.6 depict the difference of the representation structures in both semantic 3-dimensional building data models, i.e, IFC and CityGML. For example, in IFC model the room has *IFCSpace* and *IFCWall* elements whereas in CityGML they are represented as *InteriorWallSurface*, *Room*, and *WallSurface*.

Issues during Transformation

During the transformation from IFC building model to CityGML building model several issues were addressed. Some of them are presented here as lesson learns.

The IFC building model is translated into CityGML building model by using the FME Werkbech presented in appendix A. The resulted CityGML buildng model is analyzed for the accuracy of feature types. The *doors* and *InteriorWallSurfaces* geometries shown in figure 6.7 are observed, then it came into notice that the CityGML building model is missing the deduction of *door* surface geometries from *InteriorWallSurfaces* shown in figure 6.8. In other words, the *InteriorWallSurface* geometries are inaccurate. To rectify these inaccuracies in *InteriorWallSurface* geometries, the IFC building model is revisited and checked for the

[2]The AutoCAD is a software product of AutoDesk company which is used for designing building models. www.autodesk.com

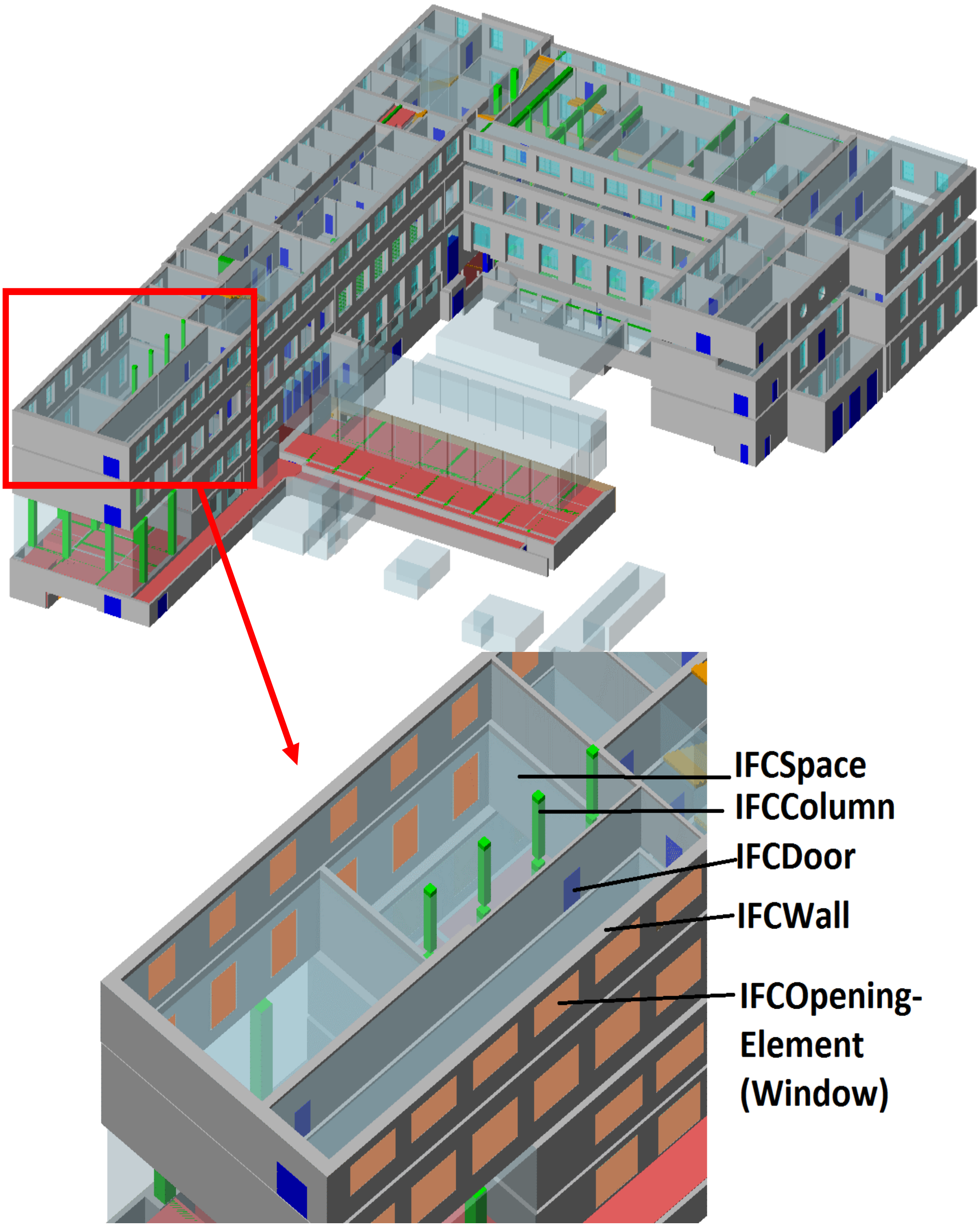


Fig. 6.5 The IFC building model and a close view of a room which shows room's IFC elements.

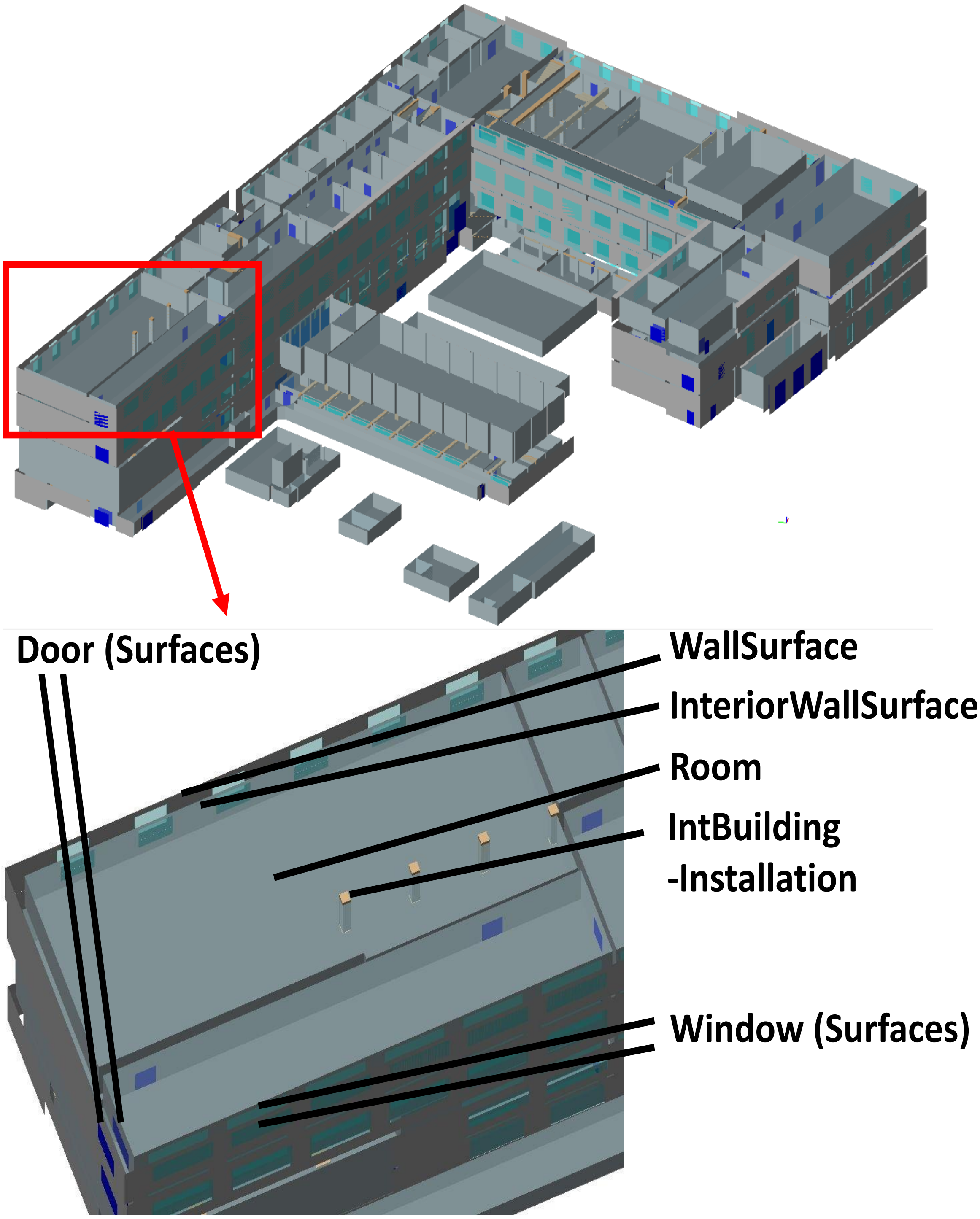


Fig. 6.6 The CityGML building model and a close view of a room which shows room's CityGML feature types.

topology relationship between *IFCDoor* elements and *IFCSpace* elements. Through the manual checking, it is ensured to have *touch* topology relationship between *IFCDoor* or *IFCOpeningElement* and *IFCSpace* elements shown in figure 6.9. After these corrections, the *InteriorWallSurface* geometries are resulted into accurate geometries as shown in figure 6.10.

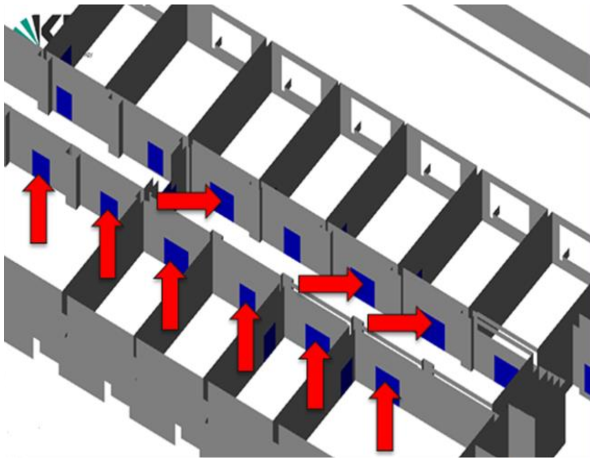


Fig. 6.7 The feature types *Doors* and *InteriorWallSurfaces* of the CityGML building model are observed.

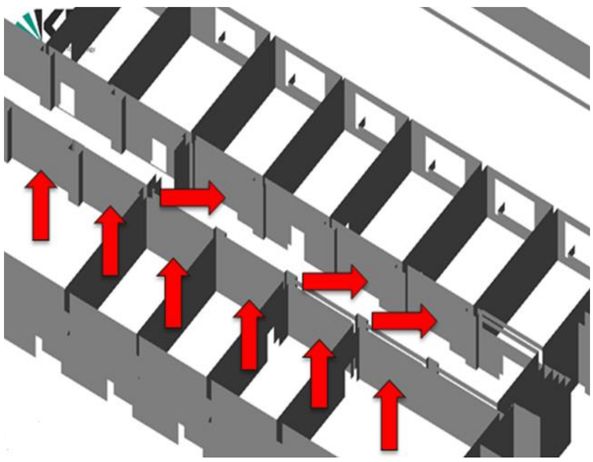


Fig. 6.8 The observed *InteriorWallSurface* geometries are inaccurate.

The second issue addressed during the transformation is inaccurate models of *IFCSpace* geometries. In IFC building model, in many cases, there are gaps between two *IFCSpaces* but in reality they should not be there as shown in figure 6.11. These inaccurate gaps between *IFCSpaces* make the disconnections between rooms and floors of the building. Therefore, they are manually checked and corrected accordingly.

The third issue that is dealt with the existence of inaccurate geometries within IFC building model shown in figure 6.12. These geometries are corrected or removed before transformation.

Another issue that is addressed during this transformation is non-existence of many *IFCSpaces* in the building model. These *IFCSpaces* are created and enriched with basic semantic information. The newly created *IFCSpaces* are shown in figure 6.13.

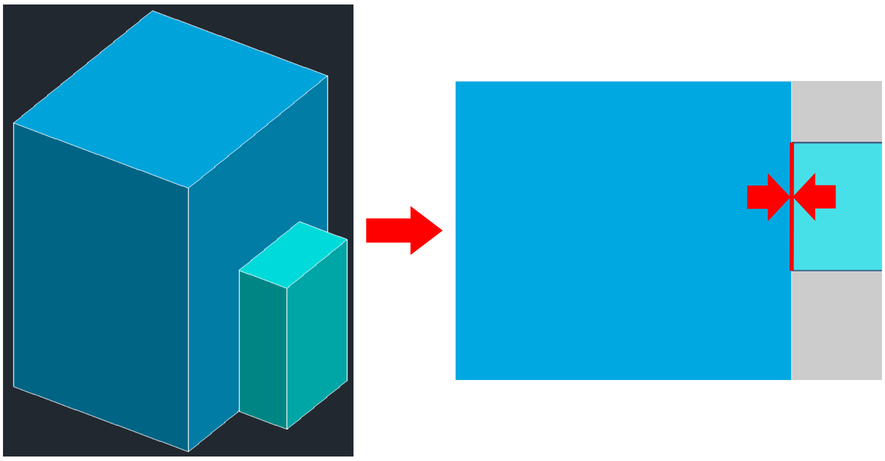


Fig. 6.9 The topology relationship *"touch"* is ensured between the geometries of *IFCOpeningElement (IFCDoor)* and *IFCSpace* element.

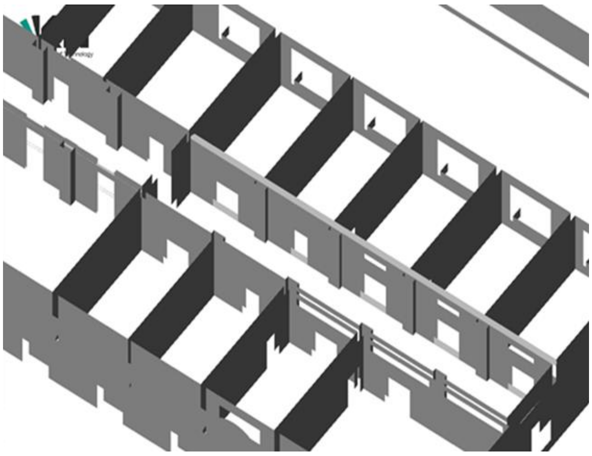


Fig. 6.10 The observed accurate *InteriorWallSurfaces* after corrections.

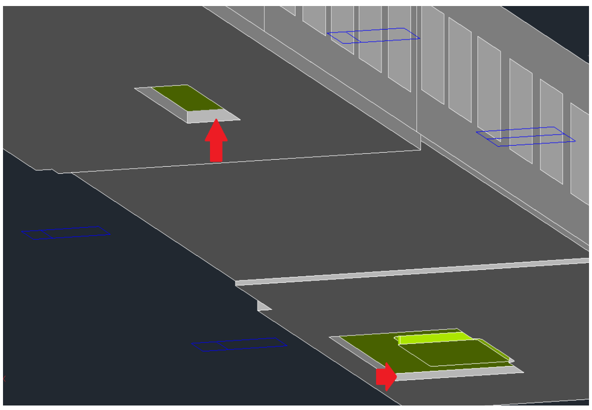


Fig. 6.11 The gaps between two floors of building model.

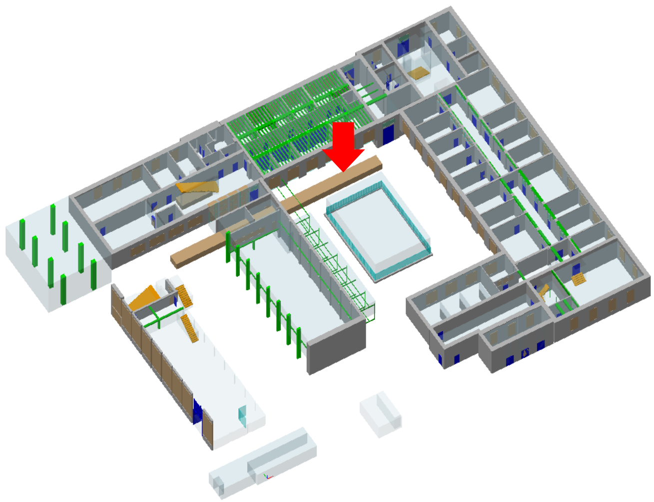


Fig. 6.12 The 3-dimensional building model with inaccurate geometries.

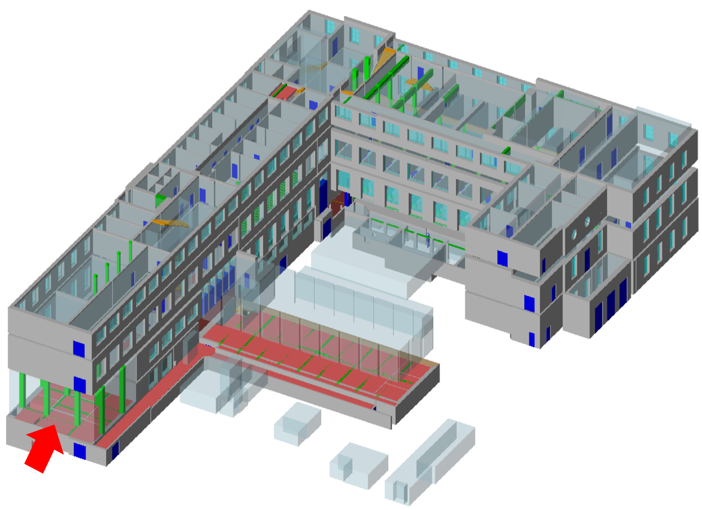


Fig. 6.13 The 3-dimensional building model with the newly created *IFCSpaces* (maroon colored geometries).

Transformation from CityGML LoD4 to the IndoorGML model

The second step of the transformation process is carried out by means of a Java language program from CityGML LoD4 to IndoorGML data building model. The details of conceptual transformation are discussed in chapter 5 and overview of Java program is provided in appendix B. The resulted IndoorGML 3-dimensional building model of this transformation is shown in figure 6.14. The figure 6.14 also shows the close view of a room and a corridor where *state, transition,* and *cellspace* geometries are presented.

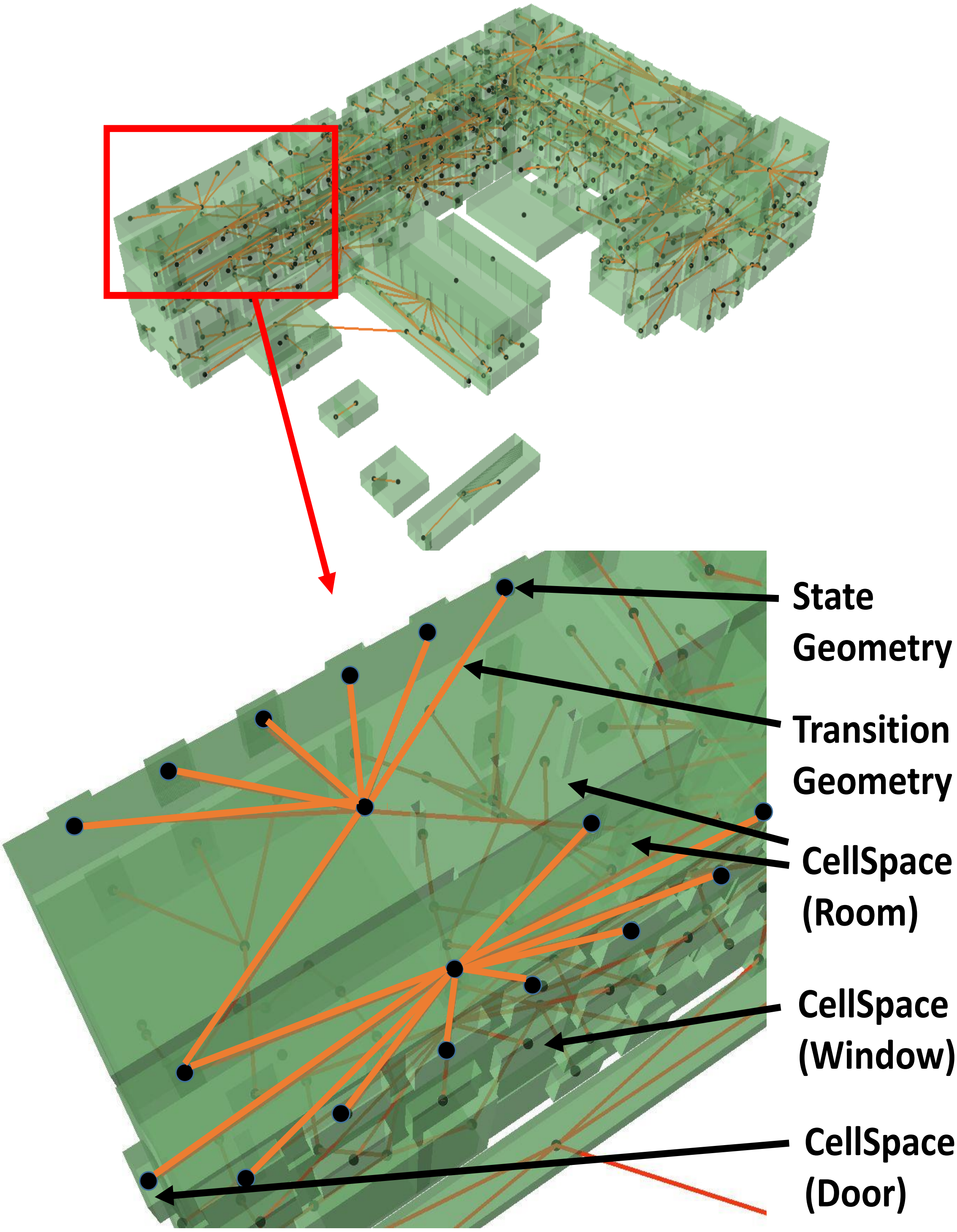


Fig. 6.14 Three-dimensional IndoorGML building model with a close view of a room and a corridor.

6.2 Locomotion Types

The locomotion types considered for this thesis are flying, walking and driving. For each type of locomotion one distinguished example is considered, i.e., UAV, walking person, and wheelchair, respectively. For the realization of concepts discussed in chapters 3 and 4, the locomotion types are represented as generalized geometric objects with their semantic information. The UAV is represented as 3-dimensional sphere shown in figure 6.15, whereas the walking person and wheelchair are represented as cylinders with variation of their height shown in figures 6.16 and 6.17 respectively. Based on these geometric representation of different locomotion types, the subspaces are computed in the next section.

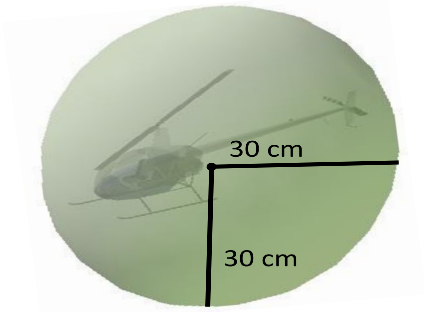


Fig. 6.15 Generalized representation of an Unmanned Aerial Vehicle as 3-dimensional sphere.

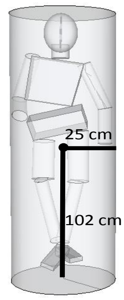


Fig. 6.16 Generalized representation of a walking person as 3-dimensional cylinder.

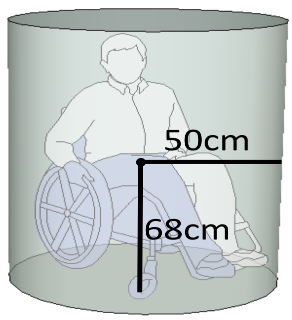


Fig. 6.17 Generalized representation of a wheelchair as 3-dimensional cylinder.

6.3 Subspacing of 3D Indoor Building Model

6.3.1 Subspacing based on the Connected Open Spaces

A small part of the main building of 3-dimensional building model is subspaced based on the connected open spaces with respect to the concept discussed in section 4.6. The building portion before the subspacing is shown in figure 6.18. To have subspacing based on connected open spaces all the connected open spaces in the building are considered (e.g., all the doors or windows adjacent to the room or corridor) and each door or window making 3-dimensional boundary surface with the room or corridor is extruded towards the room or corridor that need to be subspaced. The extrusion distance is taken as equivalent to the unsafe length of the locomotion type from its reference point (e.g., in this case the author considered 30 cm as radius of sphere representing UAV shown in figure 6.15). After determining extrusion geometries from boundary surfaces the room or corridor geometries are deduced. Thus, achieving subspace geometries for each room and corridor. The subspace and main geometries after the subspacing are shown in figure 6.19. Once these geometries are extracted into a network graph model, then the more number of geometries representing single room gives more realistic representation.

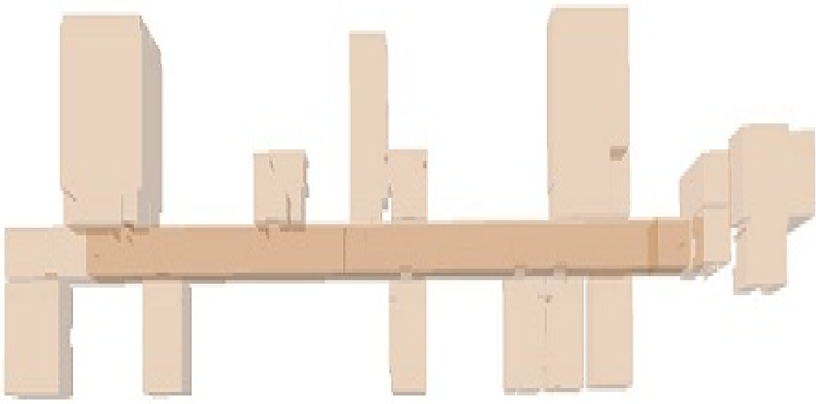


Fig. 6.18 A portion of the first floor of the 3-dimensional main building model before subspacing based on connected open spaces.

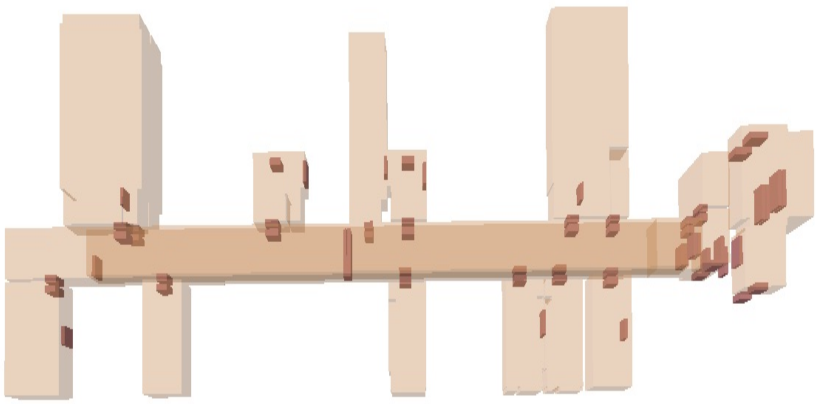


Fig. 6.19 A portion of the first floor of the 3-dimensional main building model after subspacing based on connected open spaces. The maroon color geometries are sub-geometries.

6.3.2 Subspacing according to the different Locomotion Types

The subspaces computed according to different locomotion types in a semantically enriched 3-dimensional building model within the IndoorGML database (see figure 6.20) are presented in the following sections. Some of the constraints considered for each type of locomotion are given in appendix D.

Subspaces for:

1. Driving: The subspacing for the wheelchair which represents the driving locomotion is computed by geometrically represented as 3-dimensional cylinder and with the support of semantic information. To compute the navigable subspace for the wheelchair, a small portion of the building model is considered illustrated in figure 6.21. The considered building model contains six stairs at the different places of building shown in figure 6.22. The network model for the main topographic model represents all the indoor spaces including (rooms, corridors, doors, windows, and stairs spaces) as shown in figure 6.23. In the first step, to compute navigable subspace for the wheelchair based on its constraints information, it cannot drive on stairs, therefore, all the stairs spaces are determined as non-navigable and dropped from its navigable subspace. Similarly, windows are also declared as non-navigable, so, after considering these spaces as non-navigable the main topographic network model is different which is illustrated in figure 6.24.

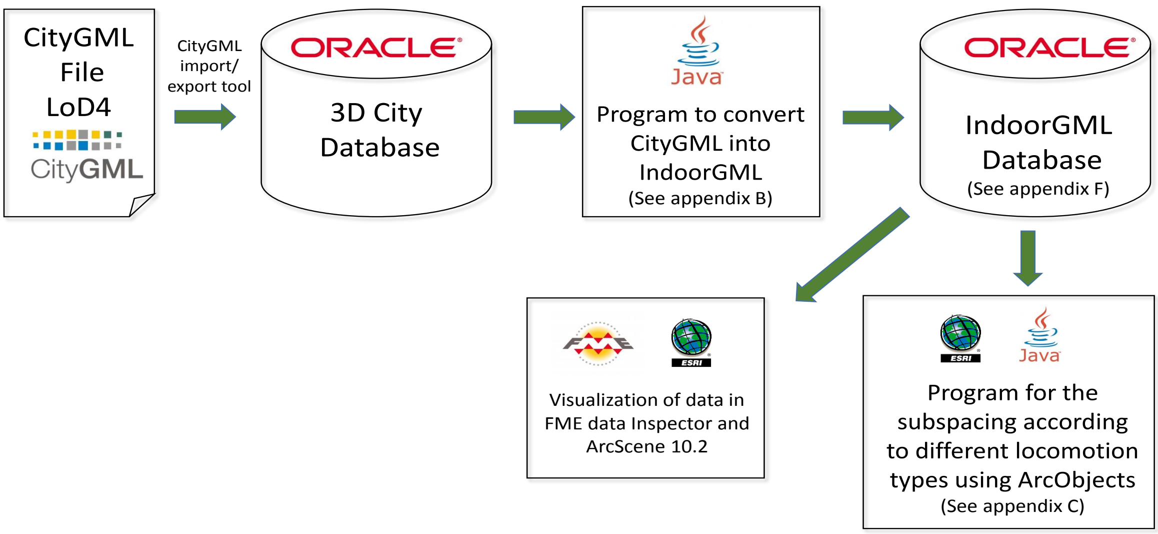


Fig. 6.20 Procedure to import building dataset into IndoorGML database and creating subspaces.

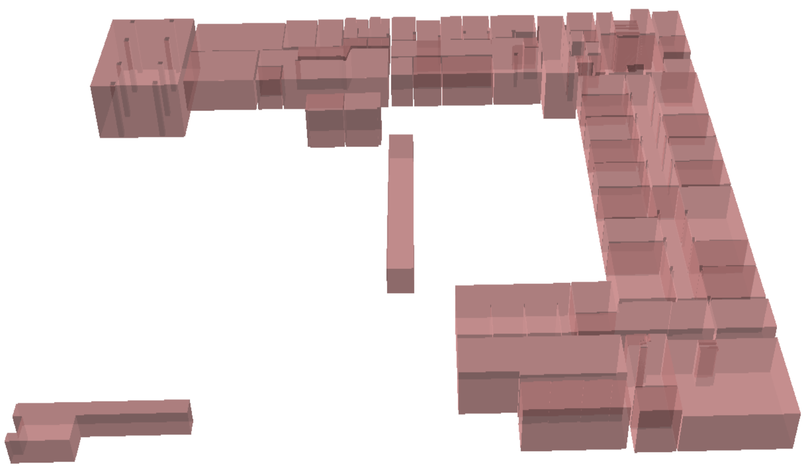


Fig. 6.21 A portion of the first floor of the 3-dimensional main building model of TUM.

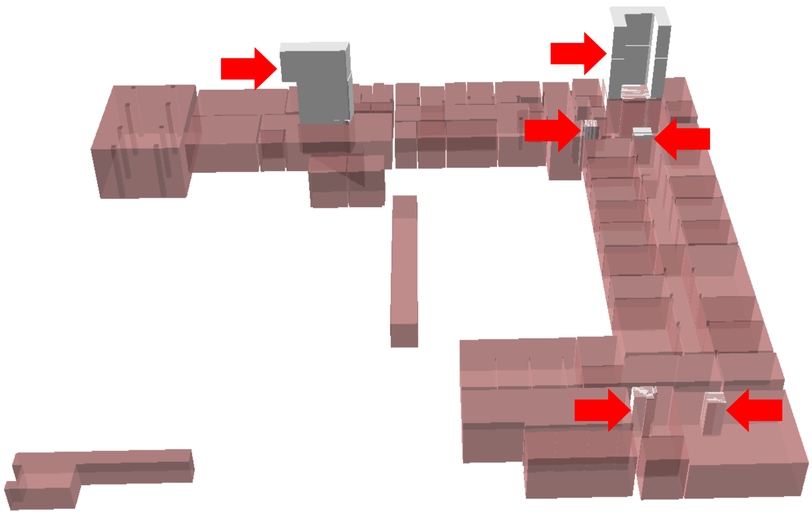


Fig. 6.22 Stairs are highlighted in a portion of the first floor of the 3-dimensional building model.

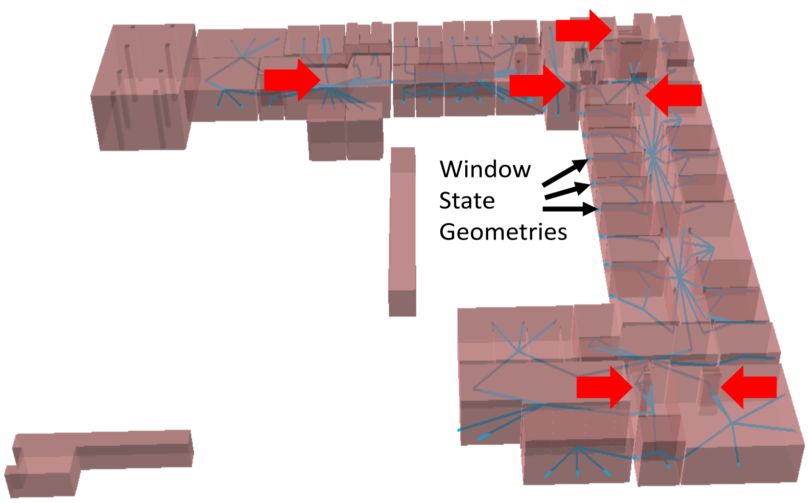


Fig. 6.23 A portion of the first floor of the 3-dimensional main building model of TUM with the network model.

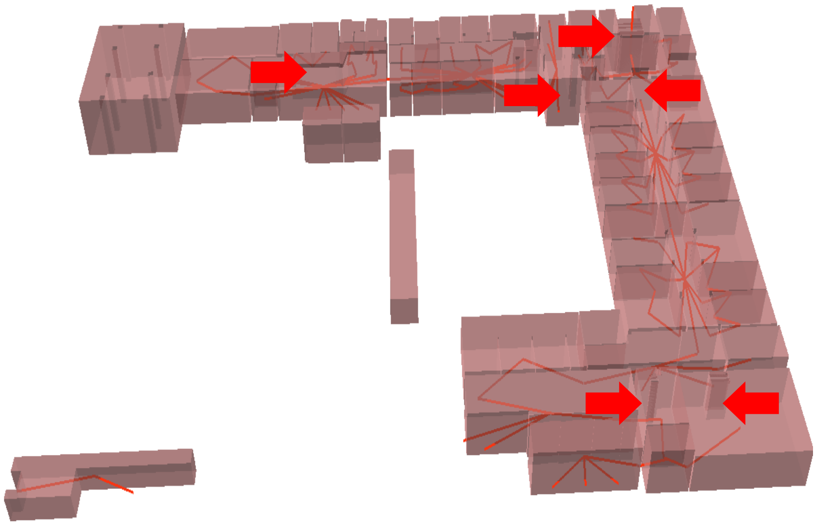


Fig. 6.24 The building model, after stairs, windows spaces, and state geometries are excluded for the wheelchair.

Moreover, based on the wheelchair's constraints the *wallSurfaces* of the building model are determined as non-navigable.

In the next step, the non-navigable spaces (e.g, wallsurface, window surface, etc.) adjacent to the navigable spaces (e.g., room free space) determine obstacle spaces around them. They (obstacle spaces or unsafe regions) must be deduced from the navigable spaces. Therefore, to compute the unsafe regions around obstacle spaces the configuration space method is used. In this method, by means of Minkowaski's sum the unsafe regions are computed. For that, in the first step, the 3-dimensional boundary surfaces between obstacle spaces and navigable spaces are computed. Then, the edges, vertices, and surfaces of the boundary surfaces are extruded to determine the Minkowaski's sum of boundary surface and locomotion type's geometry representation (in this thesis case wheelchair is represented as 3-dimensional cylinder and based on assumptions given in chapter 4). The edges, vertices of the boundary surfaces adjacent to free space geometry are shown in figure 6.25. Figure 6.26 shows only the boundary surfaces containing vertices and edges. These vertices are extruded shown in figure 6.27 by means of 3DBuffer (which is a 3-dimensional feature of ArcGIS), the extrusion distance is equal to the radii of the 3-dimensional cylinder representing wheelchair. Similarly, the edges and surfaces of boundary surfaces are extruded shown in figures 6.28 and 6.29 respectively. The figures show each vertex is converted into a sphere and edge into a cylinder. The sphere and cylinder is built with small Triangular Irregular Network (TIN). The 3DBuffer feature gives facility to control the density of the network to represent cylinder and sphere as per requirement of the user. Once the unsafe regions around the obstacle spaces are computed, then they need to be deduced from the navigable spaces as shown in figure 6.30. When the obstacle spaces are deduced then the navigable spaces are shrinked from the boundary surfaces as shown in figure 6.31. Finally, the actual navigable space for the wheelchair is computed and network graph is extracted from the real navigable space according to the wheelchair shown in figure 6.32. The figure 6.33 shows a network model for the real navigable space for the wheelchair and a close view of a room, where the windows' state geometries are not connected with the navigable network model because windows are determined as non-navigable spaces.

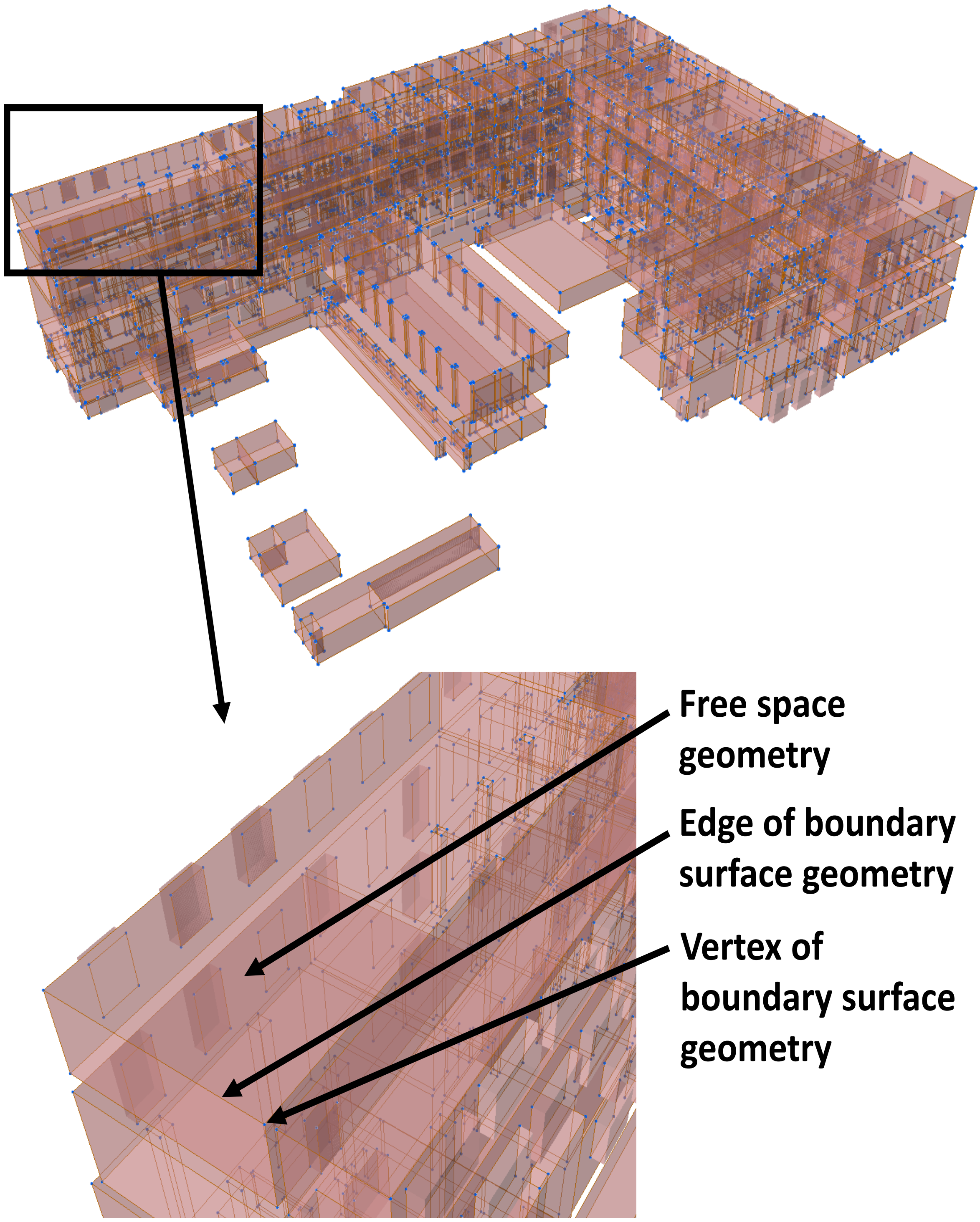


Fig. 6.25 The free space geometries and boundary surface geometries.

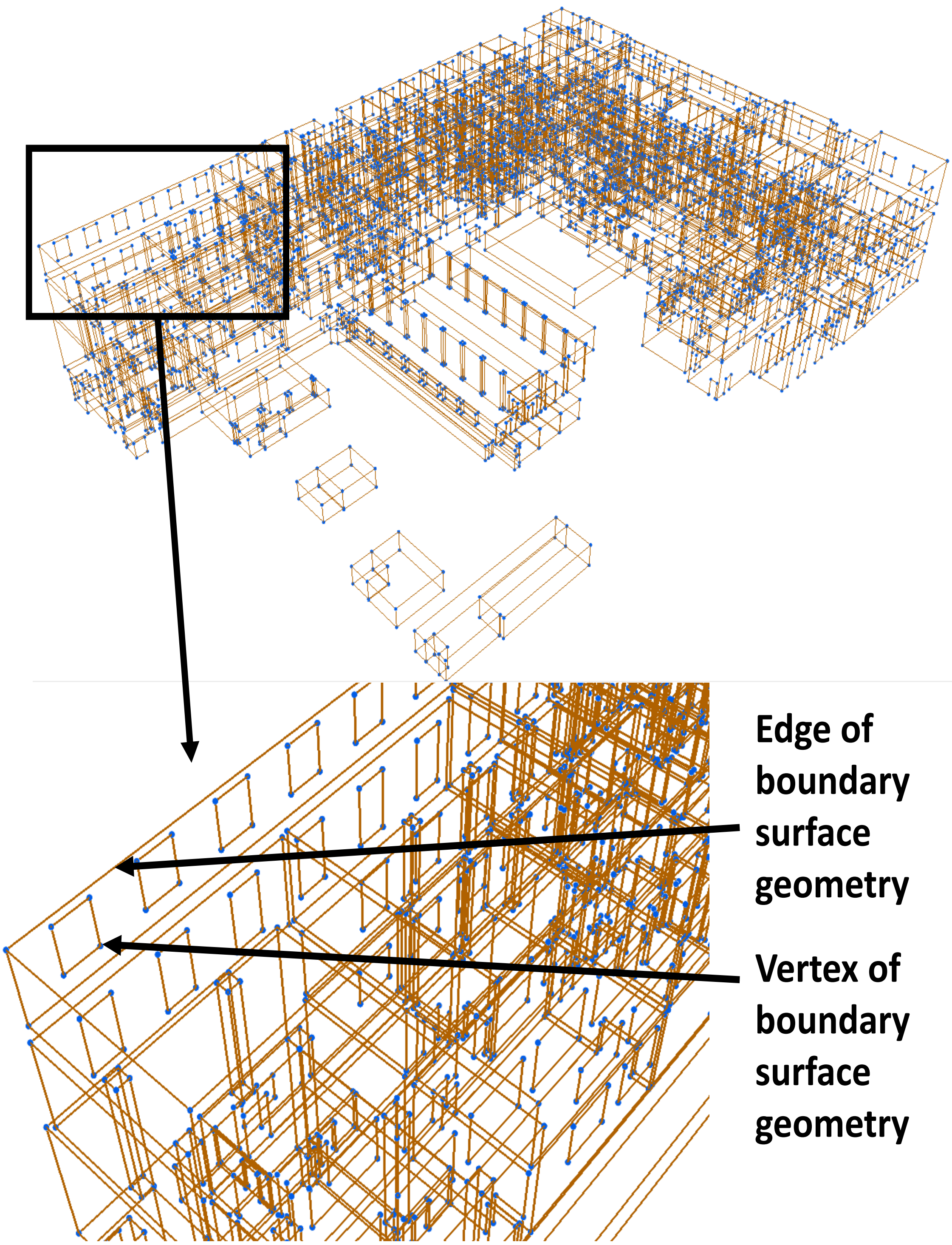


Fig. 6.26 The boundary surface geometries containing edges and vertices.

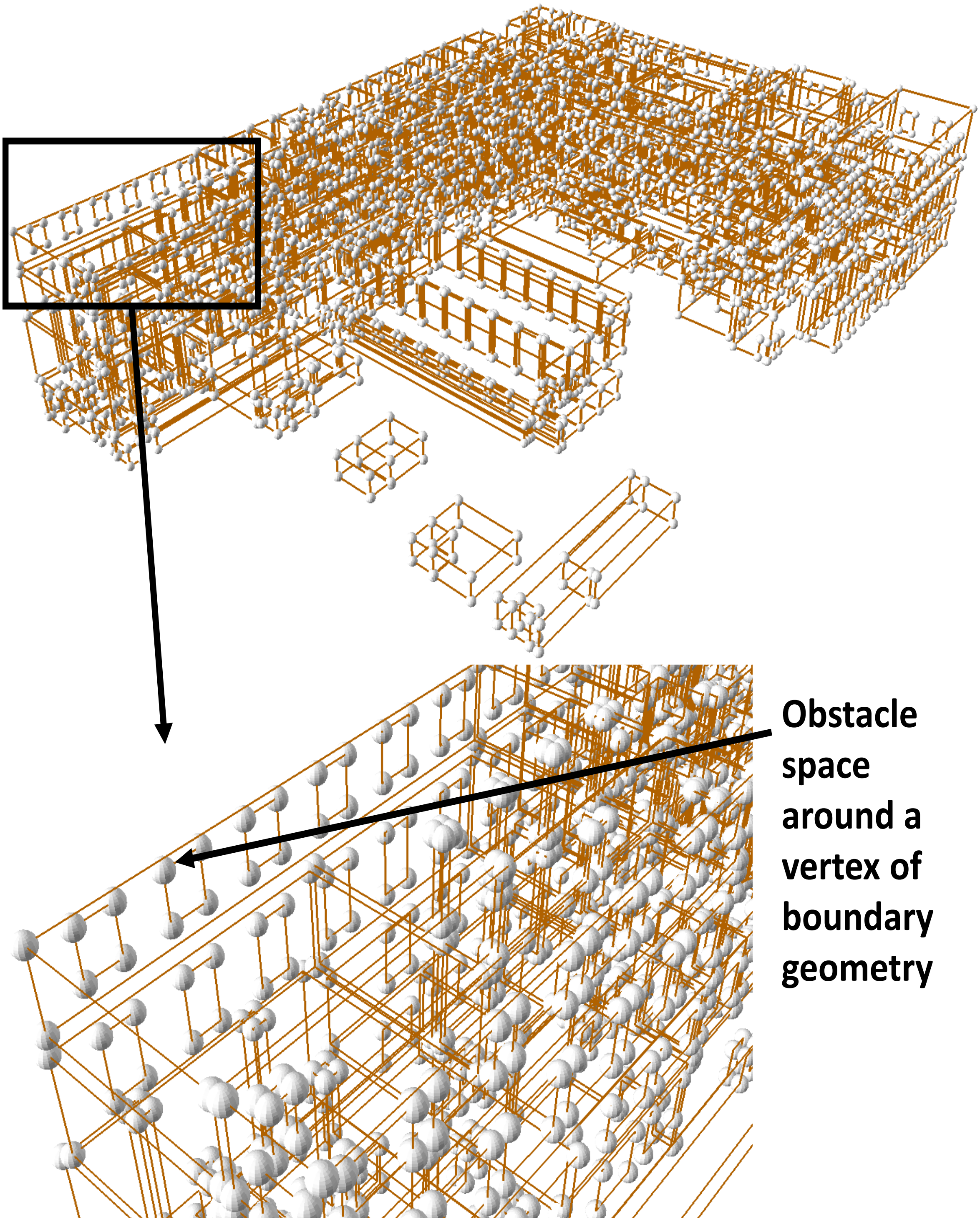


Fig. 6.27 The vertices geometries of boundary surfaces are extruded.

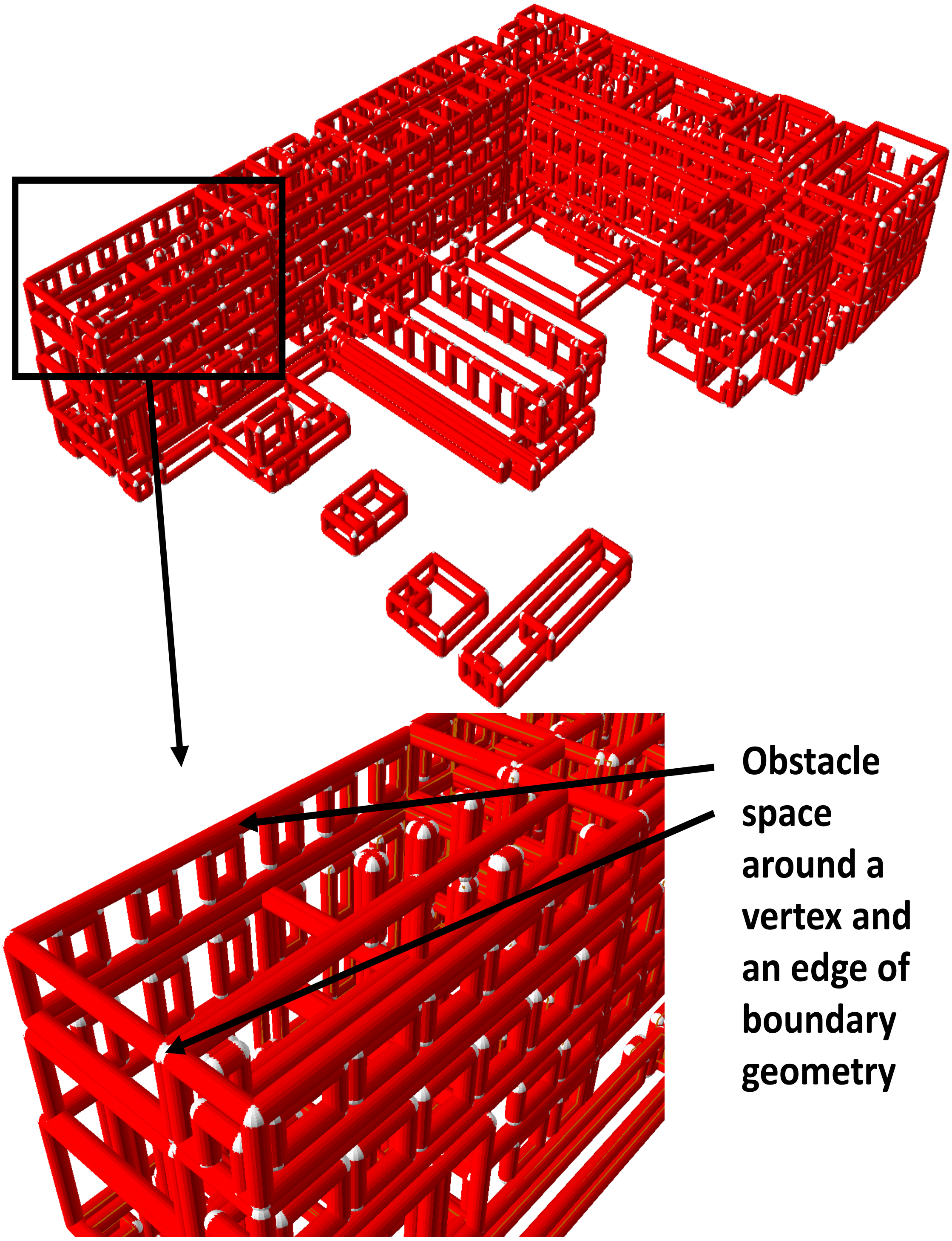


Fig. 6.28 The edges geometries of boundary surfaces are extruded.

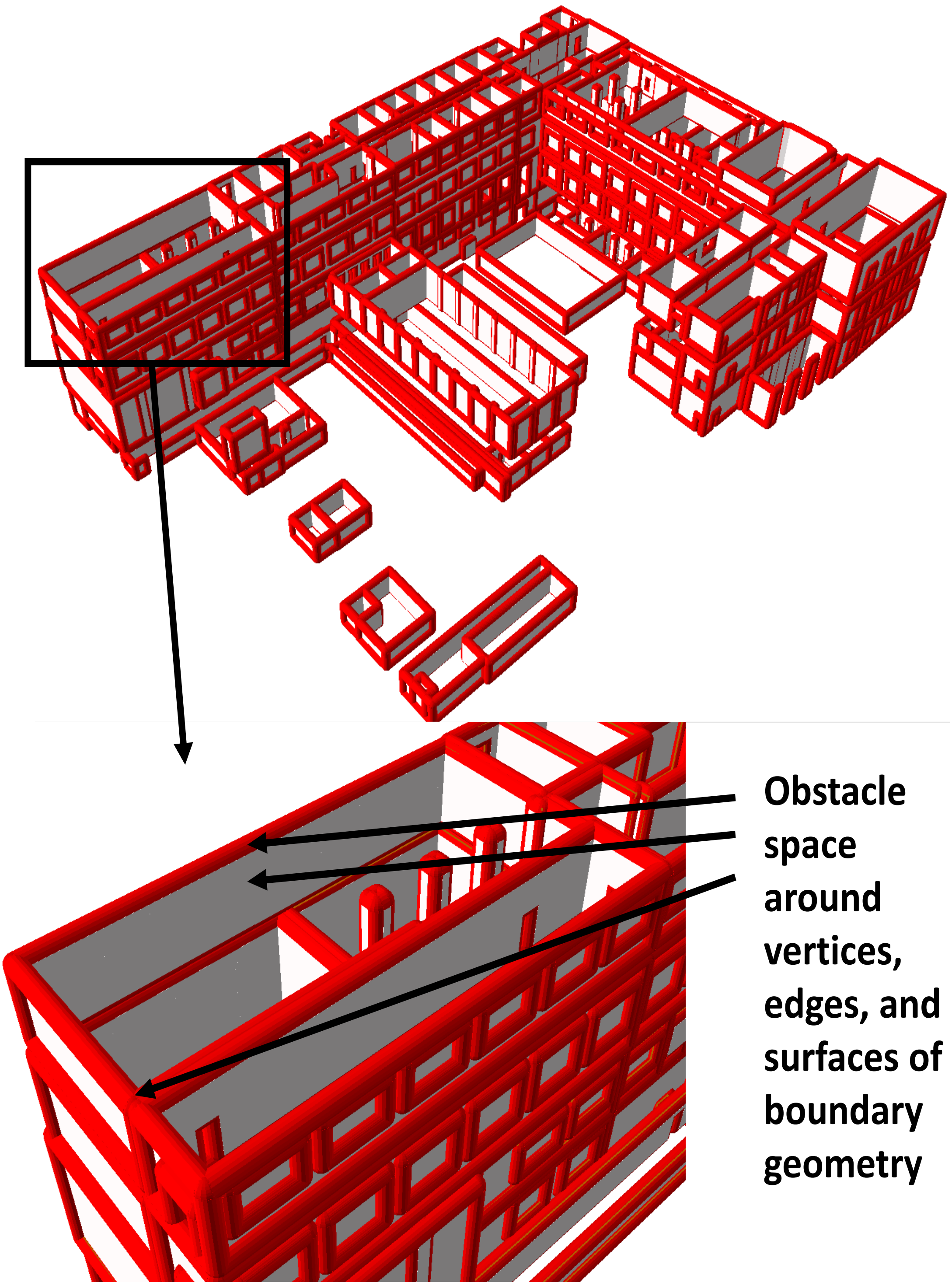


Fig. 6.29 The vertices, edges, and surface geometries of boundary surfaces are extruded resulting Minkowski sum of obstacle space and wheelchair geometry(cylinder).

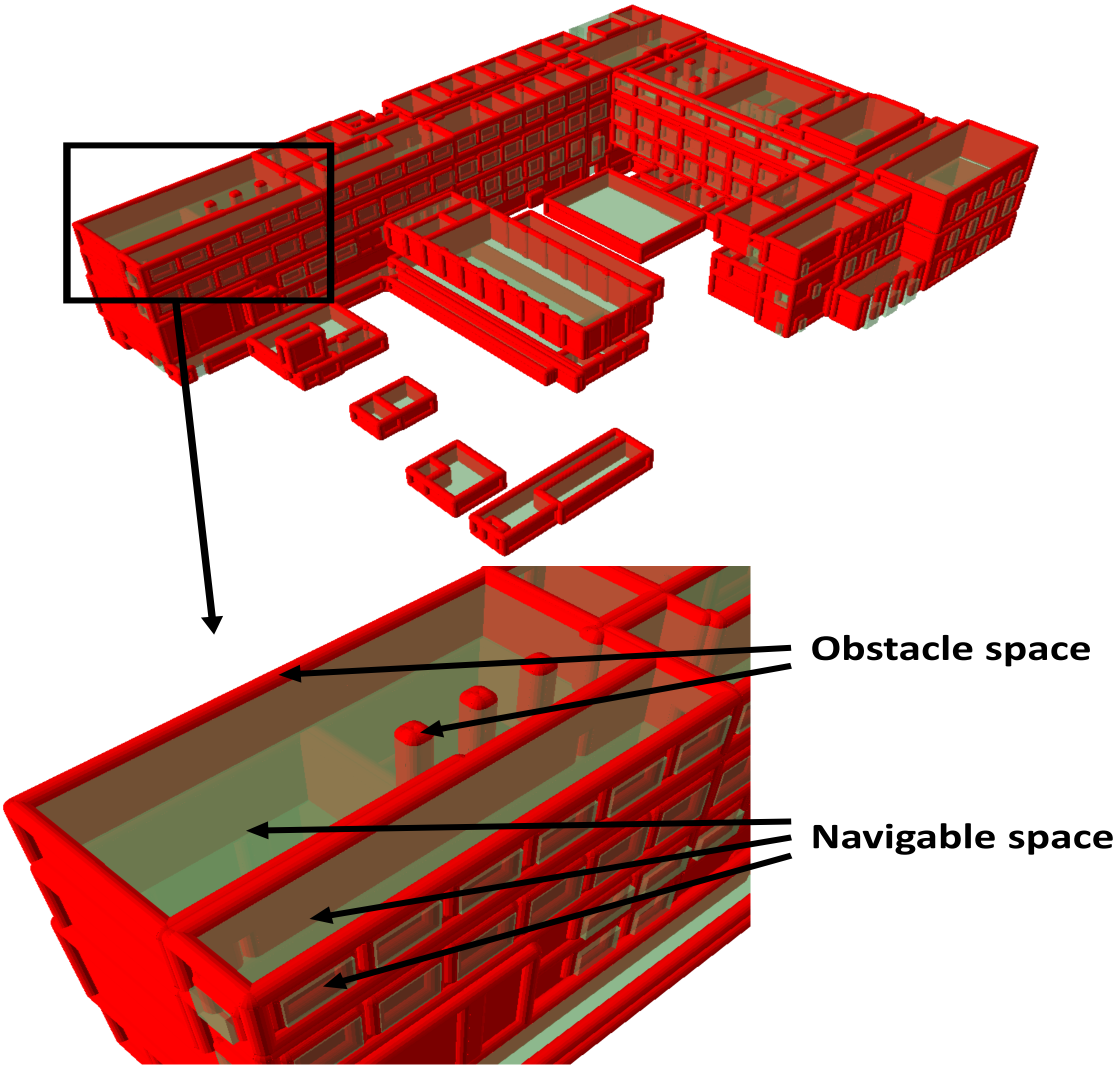


Fig. 6.30 The obstacle space and navigable space for the wheelchair and a close view of a room and a corridor.

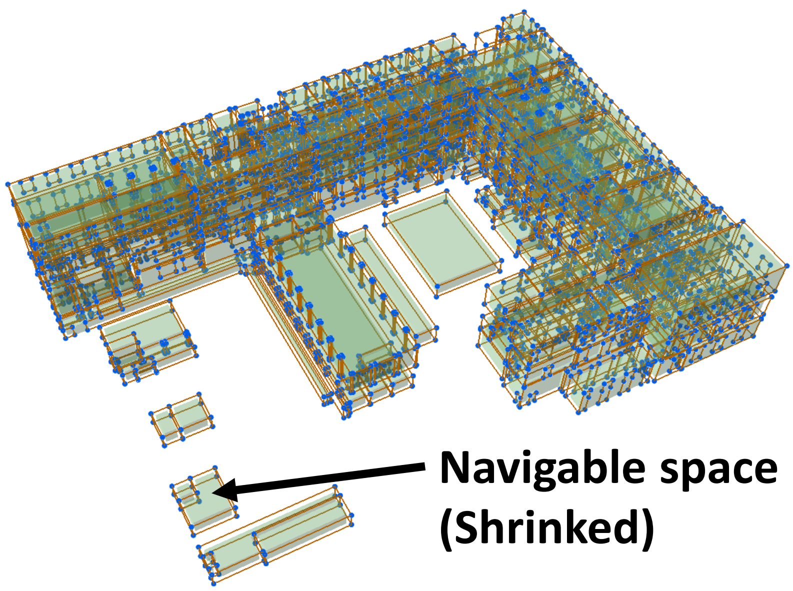


Fig. 6.31 The navigable subspace (shrinked) for the wheelchair with the boundary surfaces.

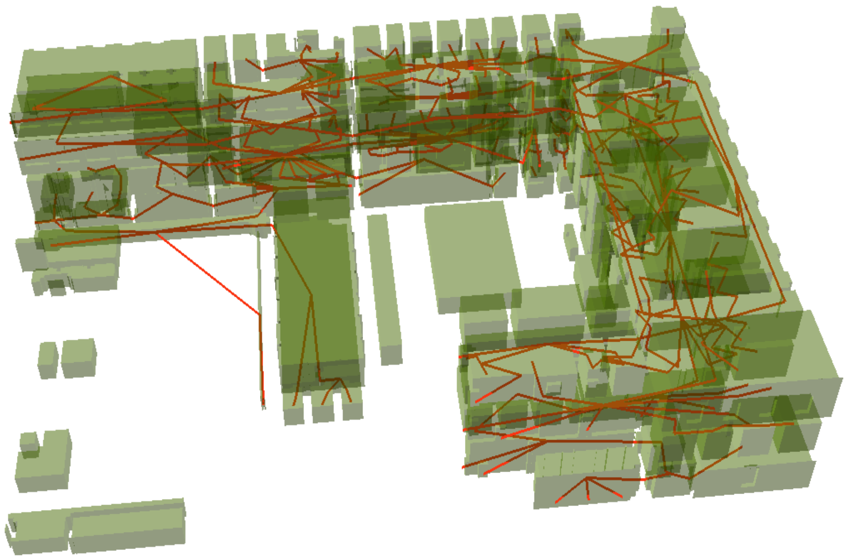


Fig. 6.32 The navigable subspace for the wheelchair.

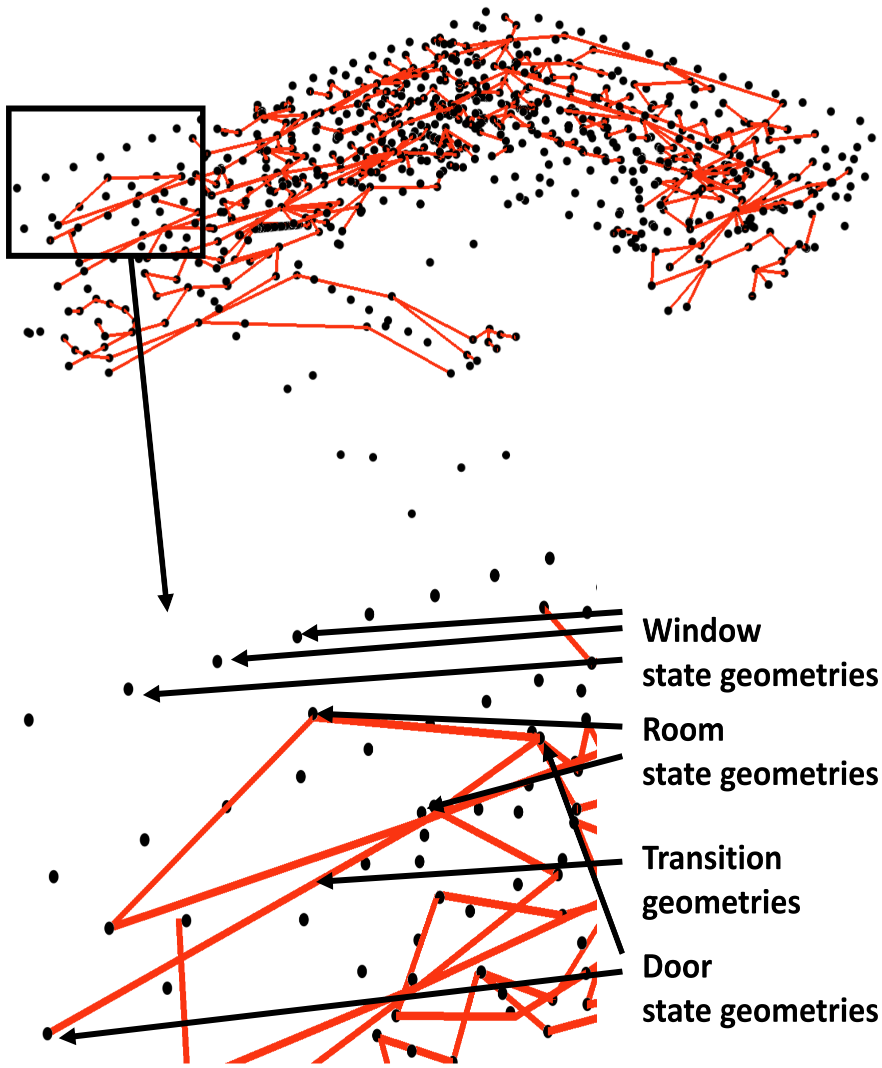


Fig. 6.33 The network model representing navigable subspace for the wheelchair and a close view of a room and a corridor.

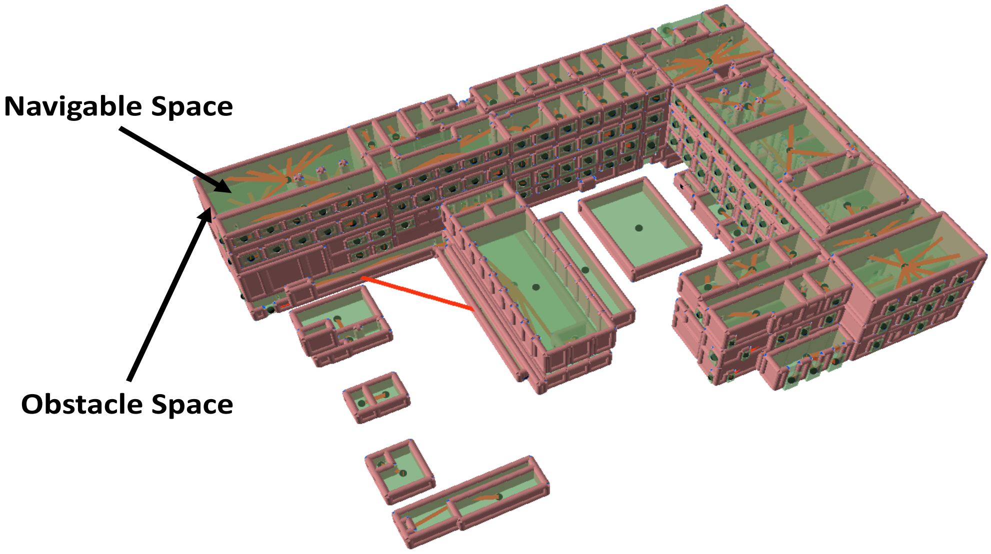


Fig. 6.34 The obstacle space and navigable space for the UAV.

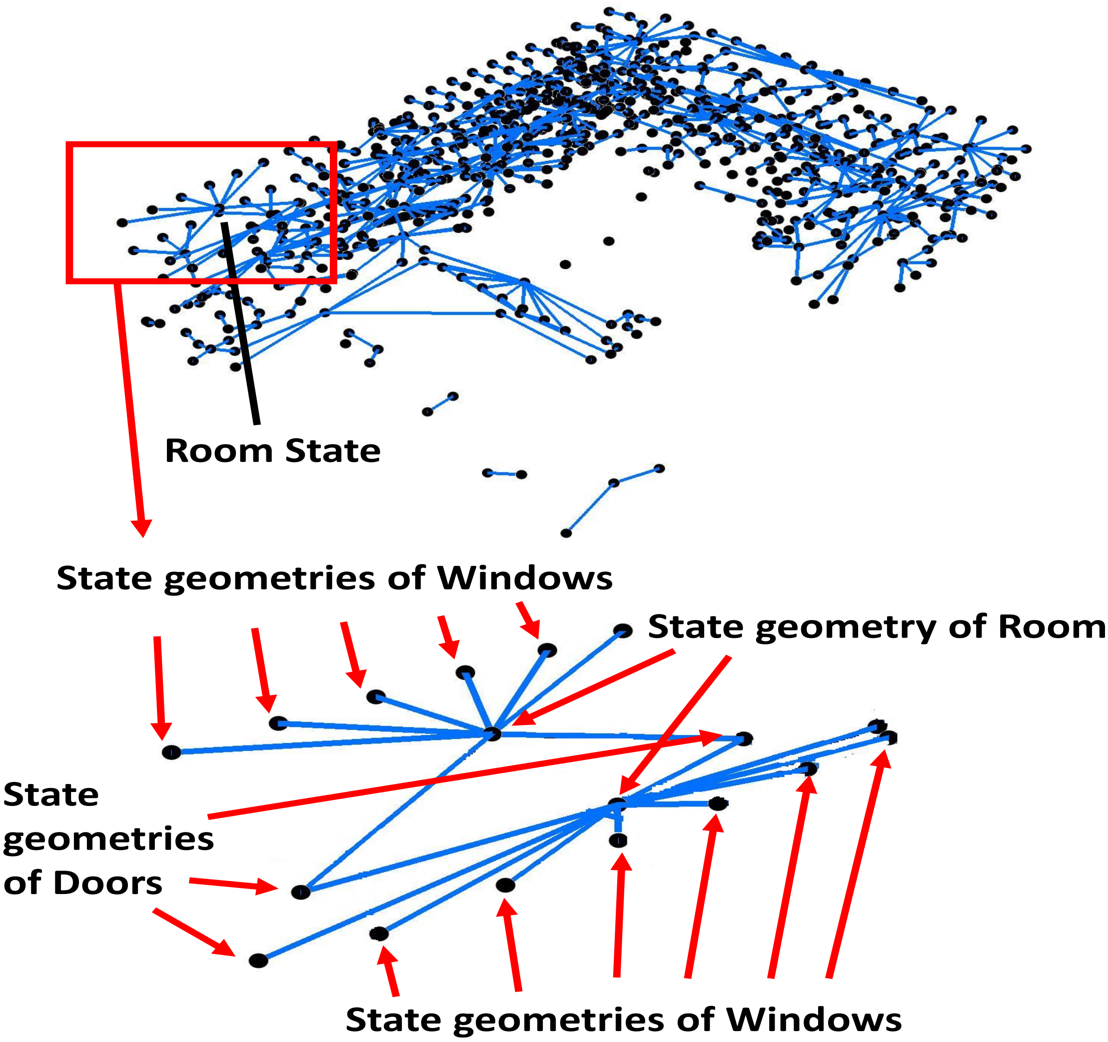


Fig. 6.35 The network model extracted from the navigable subspace of the UAV and a close view of a room and a corridor.

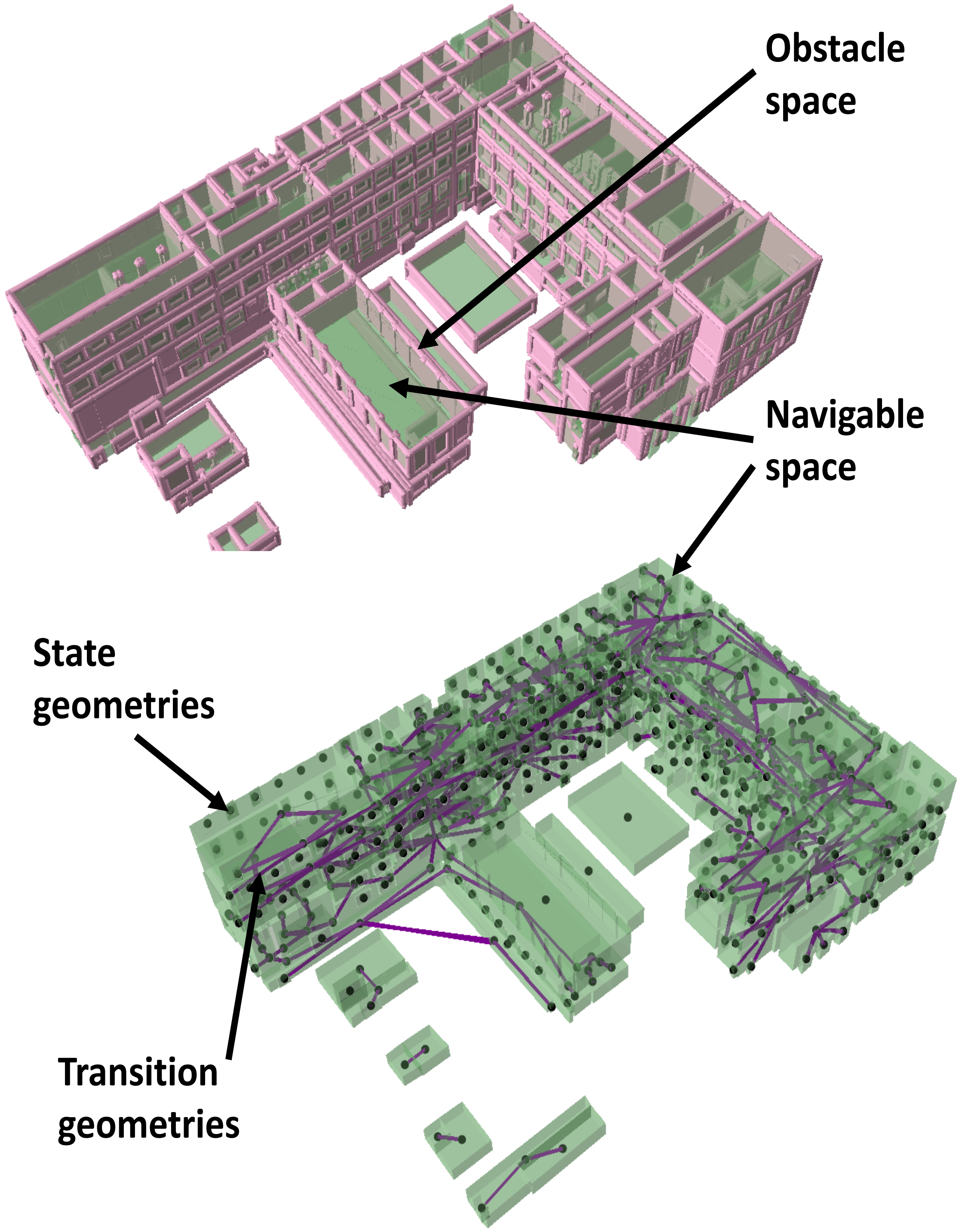


Fig. 6.36 The navigable space (green) and obstacle space for the walking person (Top). The network model is extracted from the navigable subspace of the walking person.

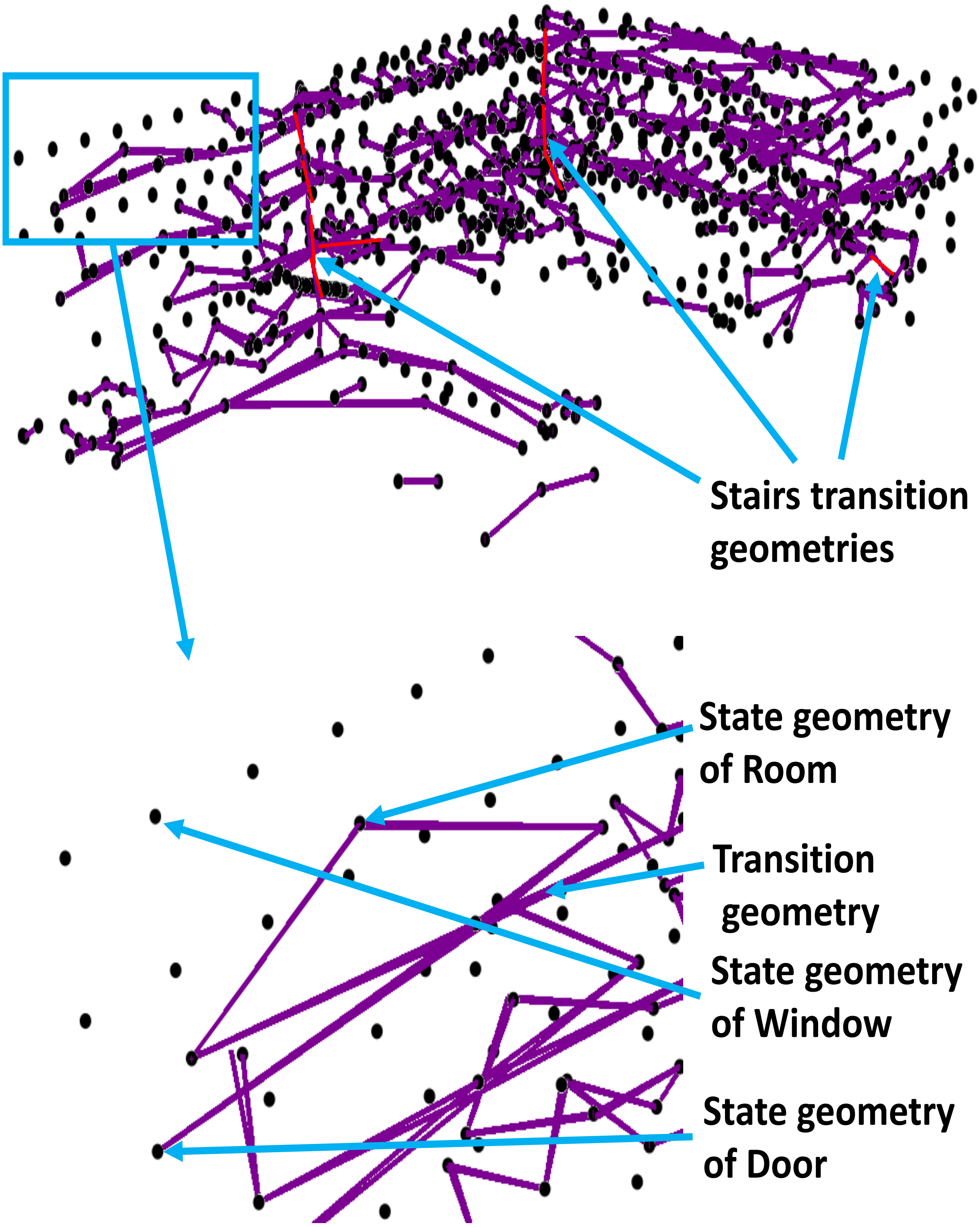


Fig. 6.37 The network model extracted from the navigable subspace for the walking person and a close view of a room and a corridor.

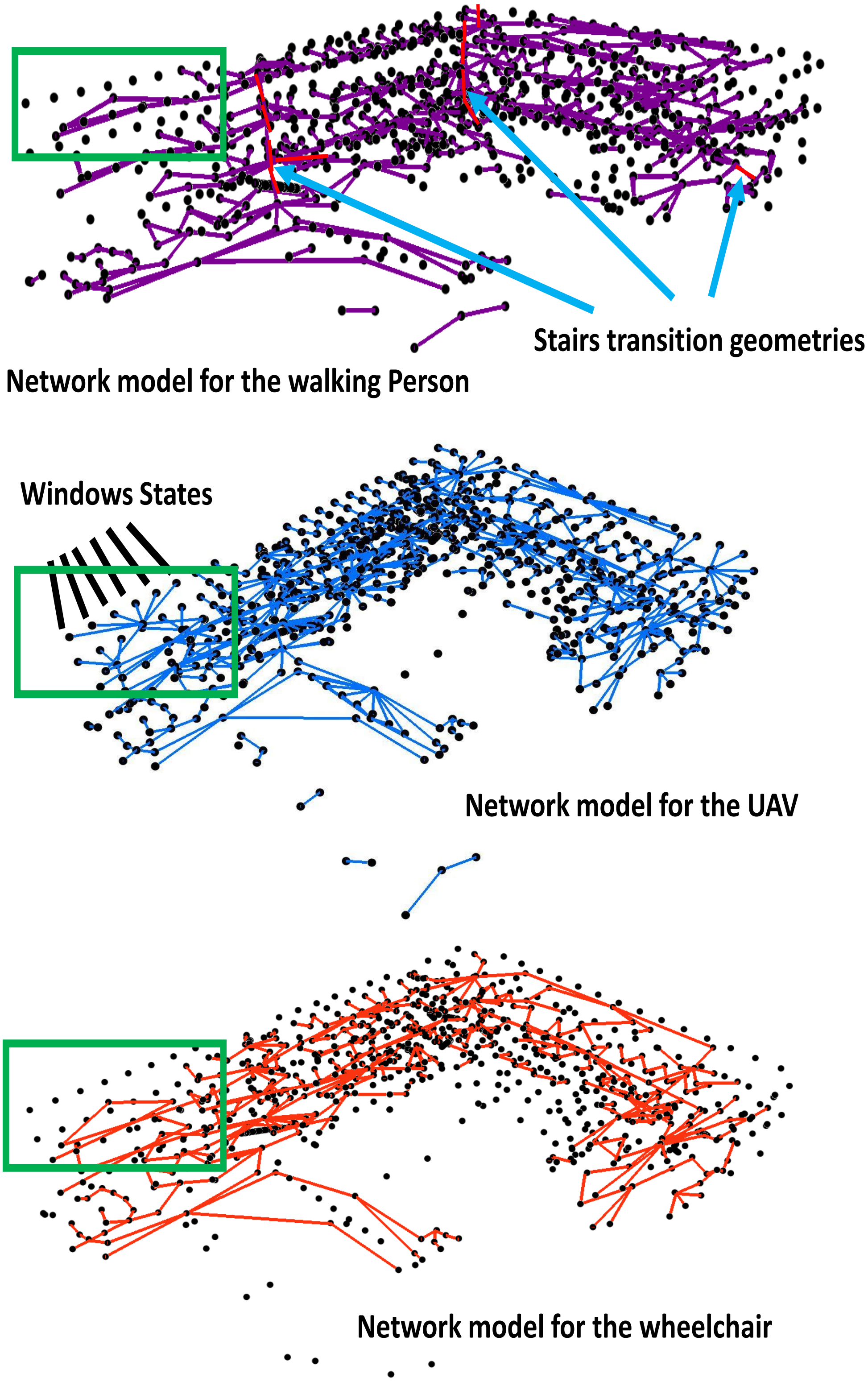


Fig. 6.38 The network models extracted from the navigable subspaces for the walking person, UAV, and wheelchair. It can be noticed that they are different from each other.

2. Flying: A UAV is considered as an example for the flying locomotion type. The geometric representation of a UAV is generalized as a 3-dimensional sphere for the computation of navigable space. As the author discussed the approach, to compute navigable space for the wheelchair in detail in the previous section, is also adopted for the UAV in the same way. In the first step, the obstacle spaces are determined, then unsafe regions are computed as shown in figure 6.34. In the second step, unsafe regions are deduced from navigable spaces and network model is extracted from the navigable subspace within the IndoorGML. The network model representing the real navigable subspace according to the UAV is shown in figure 6.35. In the figure 6.35, close view of the network model for a room and a corridor shows that the windows' state geometries are connected with navigable network model of the building because a UAV can fly through the windows in contract to the network model for the wheelchair shown in figure 6.33.

3. Walking: A walking person is considered as an example for the walking type of locomotion. The geometric representation of walking person is generalized as 3-dimensional cylinder. Based on the constraints model and the subspacing method presented in chapters 3 and 4, the navigable subspaces are generated using the approach discussed in the previous section (for the wheelchair) for 3-dimensional building model. In the first step, obstacles are determined based on the constraints of the locomotion type. Then, unsafe regions around the obstacles are computed using the method of Minkowski sum as shown in figure 6.36. In the second step, the unsafe regions are deduced from the navigable spaces. Finally, the real navigable subspaces and their corresponding network models for the walking person are computed as shown in figure 6.36. The figure 6.37 showing the network model, representing the navigable space for the walking person, illustrates the stairs transitions which are missing in the network model for the wheelchair shown in figure 6.33. Because, for the walking person the stair spaces are navigable. Similarly, figure 6.37 also shows a close view of a room and a corridor, where windows' state geometries are not connected with the network model for the walking person as they are non-navigable in the normal situation.

6.4 Coupling IndoorGML with a Cloud-based System

6.4.1 Introduction

Indoor route planning has been widely investigated in Robotics, Computer Graphics, and Geographical Information Science for emergency evacuation, automation, and in-door navigation. Traditionally, most applications or services supplied for route planning are constructed by means of the client-server model that typically combines the database server with the application server for storing the relevant network model, per-forming the routing calculation, and sending the result back to the client. However, this client-server based approach mostly restricts users from changing, modifying, or augmenting the network model with respect to their specific contextual routing requirements. However, there is a strong demand of developing a systematic approach that allows users to customize the network model according to their particular context in order to obtain the desired route planning result without needing to alter the original data stored in the central database.

In the context of a Smart Campus project at the Technical University of Munich (TUM) a campus information system is currently being developed. This project is intended to create an integrated platform that provides benefits for managing all kinds of building information and supports for various application fields like indoor route planning. The IndoorGML data model, which allows to model and describe the geometric, topological and semantic information of the complex indoor environment, can be utilized as the information backbone stored in a central database for all indoor navigation aspects of the Smart Campus platform. Normally, the datasets stored in the database should remain unchanged to ensure stable database maintenance. However, for the individual route planning use cases the users always demand to customize the dataset to perform the routing calculations accordingly. For instance, in case of a conference on the campus, the local organizing committee may want to exclude some areas and hallways from route planning by modifying the original datasets through adding some obstacles into the network model. However, this is neither supported nor permitted by the facility management department, who maintains the central database. Furthermore, IndoorGML has a complex data structure, and it is therefore very difficult for the normal users to use and customize this data model.

In this work, the author proposes a specific three-tier cloud-based system architecture. Which on the one side facilitates the IndoorGML data model managed within a 3-dimensional geodatabase to represent the complex interior environment and supports to carry out complex reasoning tasks like the determination of routing plans according to different contextual requirements of different users. On the other side it provides an intuitive and simple user interface realized by a 3-dimensional webclient. Both levels are linked by a dedicated information and application layer which employs cloud computing to provide the possibility for the normal user to customize the network model of the building according to their specific needs without altering the original data. The proposed approach allows exporting and uploading simplified subset of the complex IndoorGML data model to the cloud services serving as an intermediate system-level to make the exported network model easily accessible and modifiable over the Internet and for performing context-dependent route planning. The results of the route planning calculations are visualized and can be explored in the 3-dimensional webclient in a highly intuitive and user-friendly way.

6.4.2 Related Work

The notion of context plays a key role in the development of indoor navigation systems (Becker et al., 2009b). Contextual information defines as any information that relates and uses to enrich the knowledge about the user's state, his or her environment, and capabilities (Afyouni et al., 2012). Context changes with respect to the requirements of the specific application and the user's activities in the given environment. Context aware indoor routing which is comparatively a new area of research (for the last two decades) many projects and research works are carried out to facilitate the user for indoor route planning in various indoor applications, e.g., facility management, disaster management, etc. Some of the related work is discussed in the following.

The Cyberguide system is one of the first indoor guiding system to guide tourists through both indoor and outdoor environments (Abowd et al., 1997). The system is based on 2-dimensional map and gives location information to user through displaying an arrow on a room map according to the user's location. Furthermore, the system is equipped with the information of interesting sights within the building, or pathways that the user can access and visit. The authors' main wish list to improve their system at that time was modifiable information base so the real contextual information can be collected from the user and give him response from the system in real time.

One of the early 3-dimensional indoor routing application is presented by Meijers et al.

(2005). For the purpose of routing for evacuation the authors extracted the graph model of 3-dimensional building model and used Oracle Spatial 10 g to store and manage geodata in the application. The application has limitations to consider real contextual situations, for example, cannot put a walking restriction on a specific room considering a specific situation. It only computes the shortest path from one place to the other or the exit areas. The application's limitation to modify graph model according to users' requirements make its usage limited to a few scenarios.

iNav an indoor navigation system is presented by Kargl et al. (2007) for the real time routing and navigation, which is based on client-server architecture. The navigation system can be used on different PDA devices and consists of many distributed web services. The system provides user with his location information and details of events occurring around him. The events are regularly updated by service providers. So, it makes the system more contextually aware. iNav has major performance issues and its restriction on the user to modify the base information according to his needs makes the system dependent on service providers, and flow of the contextual information (from service provider to user) become one sided in indoor space.

Using the similar approach of client-server architecture Inoue et al. (2008) have provided indoor mobile navigation system which has some main features those include providing the current position of the user on a 2-dimensional floor map, changing the floor map according to the user's position, and showing the routes from current location to destination. The system lacks flexibility in terms of dealing with contextual requirements of users (e.g. user cannot modify in floor map if he require to change).

Karimi and Ghafourian (2010) introduced an indoor application to consider different requirements of the users to facilitate indoor navigation. The application considers user's capabilities (checking mobility impaired or visually impaired) and provides graph of the building accordingly for the routing purpose. The application lacks flexibility, the graph model of the building which is the base information for all users cannot be modified by user according to his contextual needs.

Another 3-dimensional indoor routing application for the decision support in the emergency situations is presented by Schilling and Goetz (2010). The application utilizes a 3-dimensional building model in CityGML and uses client-server architecture. The application is implemented through three system domains; federal, regional, and local to help the clients or users in rescue operations. In case of fire eruption, it provides a local spatial map of danger zone on request of the client from the event location. The application has a major drawback that is users (rescue staff at the event location) cannot modify or create constraints on the building routes (graph models) which are affected by fire to restrict other users to navigate. A similar 3-dimensional indoor routing web application is developed by Goetz (2012) using crowdsourced (OpenStreetMap) indoor geodata. The system provides routing services for the static situations based on the precomputed routes making system's application limited to some predefined scenarios. It also restrict users to make on-demand route or modify route considering user's contextual requirements.

Apart from above discussed research motivated indoor routing systems there are 2-dimensional visualization web-based indoor routing maps developed by commercial companies like Google Indoor Maps (GoogleIndoorMaps, 2014) and Microsoft indoor navigation maps (Microsoft, 2014).

From the above brief overview, it is apparent that there are several research motivated and commercial indoor navigation systems to facilitate user considering its con-textual requirements. However, most of the above discussed indoor applications or navigation systems are based on 2-dimensional maps, although some of the systems are implemented on 3-dimensional building models. They operate on traditional client-server architecture which restrict end users to modify or change in 3-dimensional or 2-dimensional maps at their source according to his or her contextual requirements. Because the system always intends to ensure consistency in source geodata. Furthermore, most of the systems use only 2-dimensional visualization for the end user in contrast to the fact that 3-dimensional visualization is advantageous.

On the other hand, there is a new indoor representation model, i.e., IndoorGML which is based on Multi Layered Space-Event Model (MLSEM) Becker et al. (2009b); Li (2014). The MLSEM allows to represent different thematic decompositions of indoor space through multi space layers, e.g., sensor space, topographic space, etc. Further it provides technique to integrate different layers to utilize for indoor navigation or localization of the subject or object. As the multilayer represent different themes of indoor space they collectively make a complex representation of a 3-dimensional building model represented in IndoorGML to understand and use for the normal user. Therefore, there is a need of an approach that should simplify, extract, and utilize the complex representation of 3-dimensional building model represented in IndoorGML for the normal user to use in different applications, e.g., context aware routing. In addition, it should enable users to modify or change the topographic space layer according to his contextual requirements without modifying the main sourced geodata, and visualize results in a 3-dimensional visualization tool.

6.4.3 Coupling IndoorGML with Multilevel Cloud-based System

Most of the indoor navigation systems or applications discussed are constructed by the client-server architecture. The client-server based approach mostly restricts clients from modifying the base information on servers according to their specific contextual routing requirements. However, there is need of developing an approach that enable users to create subsets (e.g. routing network models) of the base information (e.g. main topographic network model) and modify in those subsets ac-cording to their specific contextual needs without changing in the original base information. Furthermore, the intended approach should use of new technologies based on the Internet that should enable users or clients to have a quick access to the stored data to address their real time contextual routing requirements. In addition, the normal user or the client should be able to access his relevant subset (network model) and give him a simple view from the complex base information (main routing network model) to deal with his contextual routing requirements. Considering these requirements, a new approach is developed through which a user will be able to create subgraphs of the main topographic network graph according to his contextual needs using a 3-dimensional user interactive and user friendly webclient. The subgraphs of the main network model can be modified, updated, and uploaded with the corresponding 3D building model to the cloud service to store in a Google Spreadsheet in real time. The uploaded subgraph and the corresponding 3-dimensional building model will be accessible to other users over the Internet instantly.

In recent years, the advent of cloud computing has enable to address the problems of resource scarceness, finite energy, and low connectivity (Satyanarayanan et al., 2009) on client devices to execute many useful programs that could aid the user and response to his queries in real time. Cloud computing is a combination of applications delivered as services and the hardware and systems software in the datacenters that provide those services over the Internet (Armbrust et al., 2010). Once these datacenters provides services to the general public in a pay-as-you-go manner, it becomes a public cloud. The main advantages of cloud

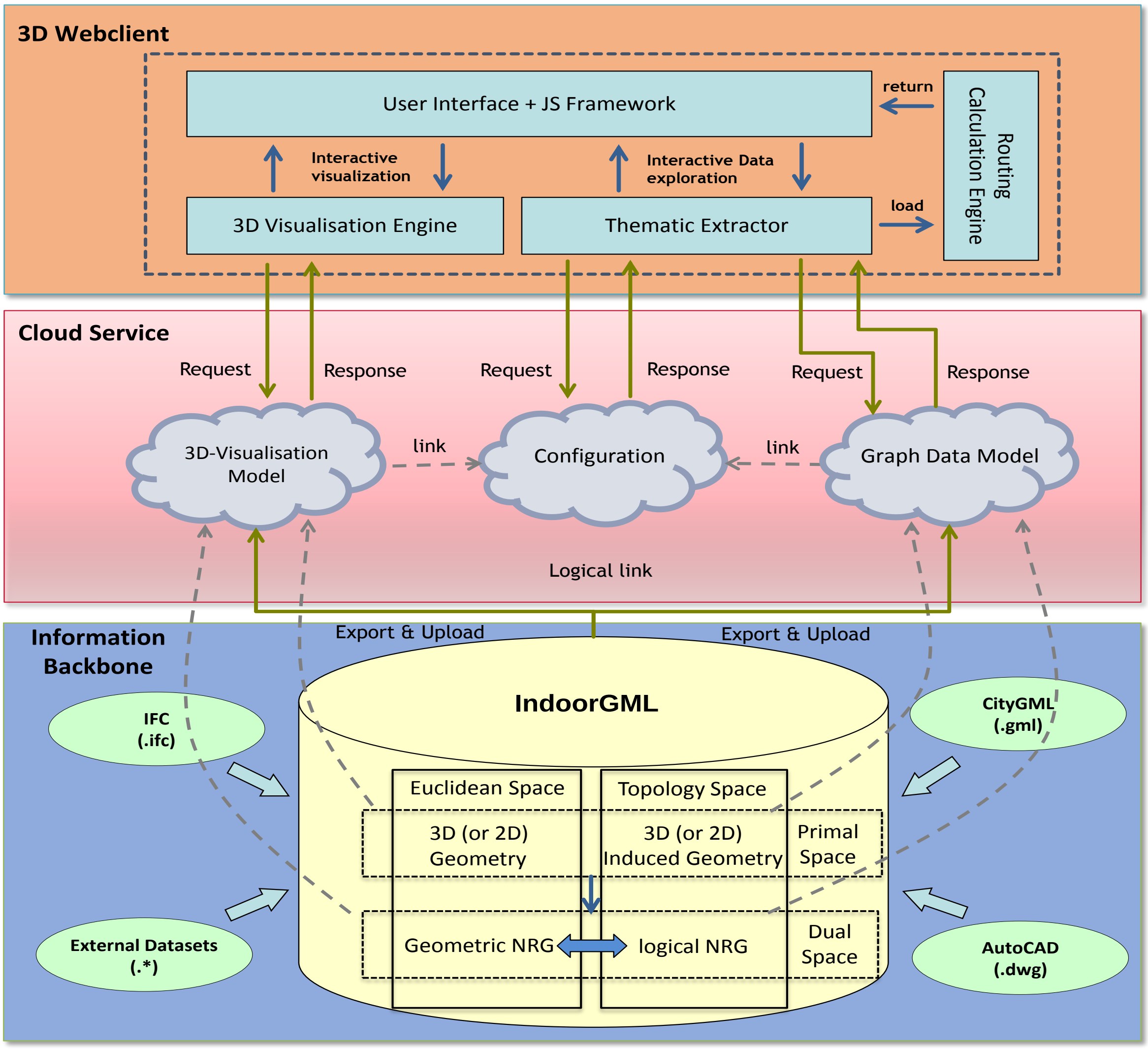


Fig. 6.39 Three-tier system architecture for user-modifiable indoor route planning application (Khan et al., 2014b).

computing are the availability of infinite computing resources on demand, enable cloud user to start at small scale, and increase resources only when there is an increase in their demand. In our proposed system we used a cloud service to facilitate the context aware indoor routing for the users.

The generic idea of coupling the IndoorGML data model with a multilevel cloud-based system to perform context aware indoor route planning is illustrated in figure 6.39. The whole system architecture consists of three tiers; information backbone, cloud service, and 3D webclient. In the information backbone tier, the semantic and geometric model of building are stored in an IndoorGML database, which allows to store and manage different contexts of indoor environment, as well as the mutual relationships of building parts. Other 3D data model standards like IFC, DWG, and CityGML, which are well-known in GIS, Architecture Engineering, and Construction (AEC) community, can be imported into the IndoorGML database. The network model can be extracted from the topographic space in IndoorGML using Multilayered Space-Event Model (MLSEM) method, which paves the way for the integration of multiple space layers such as topographic space, sensor spaces, and logical spaces to support navigation services (Becker et al., 2009b).

Details about translation process and FME werkbench for the coupling of IndoorGML

with a cloud-based system are presented in appendix E.
A specific 3-dimensional webclient acts as user interface to the end-user. It is developed to perform the functions such as route planning computation, interactive 3-dimensional visualization, and exploration. The main features and working architecture of the 3-dimensional webclient related to the context aware routing are explained in the following.

Web-based and friendly user interface:

The client application is web-based and therefore available from any location with Internet access. Users can view the 3-dimensional webclient over the Internet using a web browser to use directly without having to install any other software locally. It is a JavaScript-based static application and can operate with any web-server like Apache without the need of an application server which reduces the administrative effort. The basic structure of the user interface is created using the *ExtJS JavaScript*-based web framework. The 3-dimensional webclient enables to visualize graphical representation of the 3-dimensional building models and perform spatial operations such as geocoding. Furthermore, user can control the dynamic elements of 3-dimensional building models using JavaScript commands embedded with the Google Earth Plugin and the Google Maps *API*. Through an inter-active 3-dimensional visualization a variety of features are available to display information of the target area. For example, panning, zoom, rotation with 3D view are provided by the Google Earth Plugin with its tools that provide the basic functions for navigation in the 3-dimensional map. In addition, the 3D webclient allows to select one or more objects and display their attribute values in a table. The selected objects can be both highlighted in the 3-dimensional view, as also be hidden from the current view.

Interactive modification of thematic properties of the building model:

The editing feature of the webclient allows authorized users to change the thematic properties of the building model interactively for individual objects or entire groups of the selected objects (e.g. corrections, updating or adding more information). The edited property data is automatically stored in Google Spreadsheets.

Context aware routing:

By means of this cloud-based system architecture it is possible to export arbitrary subgraphs of the main routing graph of the building model which are generated based on the different contextual requirements of the user and upload these to the cloud services to make them accessible over the Internet. Besides, a 3-dimensional visualization building model linked with the exported subgraph can also be generated and exported in a similar way.

Furthermore, more than one pair of the exported datasets (graph data model and 3-dimensional visualization model) can be grouped and referenced using one configuration document that allows users to control the distribution of different datasets and facilitates web applications to fetch sets of distributed datasets at once for speeding up loading time. The criteria to create subgraphs from the super graph of the building depends on the specific user and his authority to modify the main graph as well as his contextual requirements. The 3-dimensional webclient provides opportunity to each user to directly create constraints or edit attributes of building elements in an interactive way to create sub-graphs which can be further uploaded to the cloud service to serve other users.

Integration:

By using the Google Spreadsheet web application users can add more columns or other properties to the indoor objects. In addition, arbitrary KML files published through web or cloud services can be loaded into the webclient as a separate layer. This can either be a simple raster data such as OGC Web Map Services or 2-dimensional and 3-dimensional vector data.

Queries:

Thematic inquiries are frequently used by analytical methods in GIS applications. In the webclient tool the building objects can be filtered by simple conditions on one or more attributes. In the described application context aware routing, for example, search for a specific type of rooms (e.g. lecture halls) or office of a specific person. Selected objects can be highlighted graphically and their relevant thematic properties can be displayed.

Visualization of the topographic layer and the network model:

The main topographic space layer from IndoorGML building model is selected and uploaded as a layer into the cloud service to make it accessible over Internet. Furthermore, the corresponding network model from IndoorGML is uploaded as another layer to the cloud service. Both the 3-dimensional building model and the corresponding network model of the building with their semantic information are accessible from the webclient to visualize and analyze.

Path computation and visualization:

The computation of the route plan from one room to the other amounts to the calculation of the shortest route between the two locations is performed directly in the webclient. In the application of the context aware routing, by simply selecting an initial room and target room the route for the user can be calculated. The result of the computed route will contain the list of rooms or corridors through which the person has to walk can be highlighted. As shown in Fig. 1, a 3-dimensional visualization engine is embedded in the 3-dimensional webclient. It is responsible for the rendering of the visualization model. Another client component named "thematic extractor" is involved to fetch and interpret the network model of the 3-dimensional building model stored in the cloud services. The users can utilize the "routing calculation engine" that performs the route calculation at the client-side with high performance due to the local caching of the network model. The results of route planning calculations can be directly visualized in the 3-dimensional webclient in an intuitive way.

6.4.4 Application Scenarios

The work flow supported by the mentioned system architecture in section 4 is illustrated in figure 6.40. Users can be typically categorized into three groups: building administrator, scenario manager, and navigating user.

The building administrator can export the configuration file associated with 3-dimensional visualization models and network models, and upload to the cloud services to make them accessible from the 3-dimensional-webclient. These outsourced network models can be added, deleted, or modified by the authorized users (e.g. scenario manager) at any time without altering the original datasets stored in the central database (Herreruel et al., 2012). This strategy allows the scenario manager to modify and customize the network model in order to adapt it for the specific use cases. The modified network model can be fetched immediately from the cloud services by the 3-dimensional webclient for the route planning calculation. The desired route planning result will be intuitively presented to the navigating users via the 3-dimensional webclient. Since the cloud services provide support for access control, privileged navigating users or user groups can also be authorized by the scenario manager or the building manager, so that they are able to modify the network model by means of the functionalities shipped with 3D webclient such as exploration, query, and aggregation. On the other hand, since more than one outsourced dataset can be grouped and referenced in a separate configuration document, it is therefore possible to handle several application scenarios within one web application session, and one web application instance can also be used by more than one user or user group in turn. Example scenarios and screen shots of the results are given in the following paragraphs.

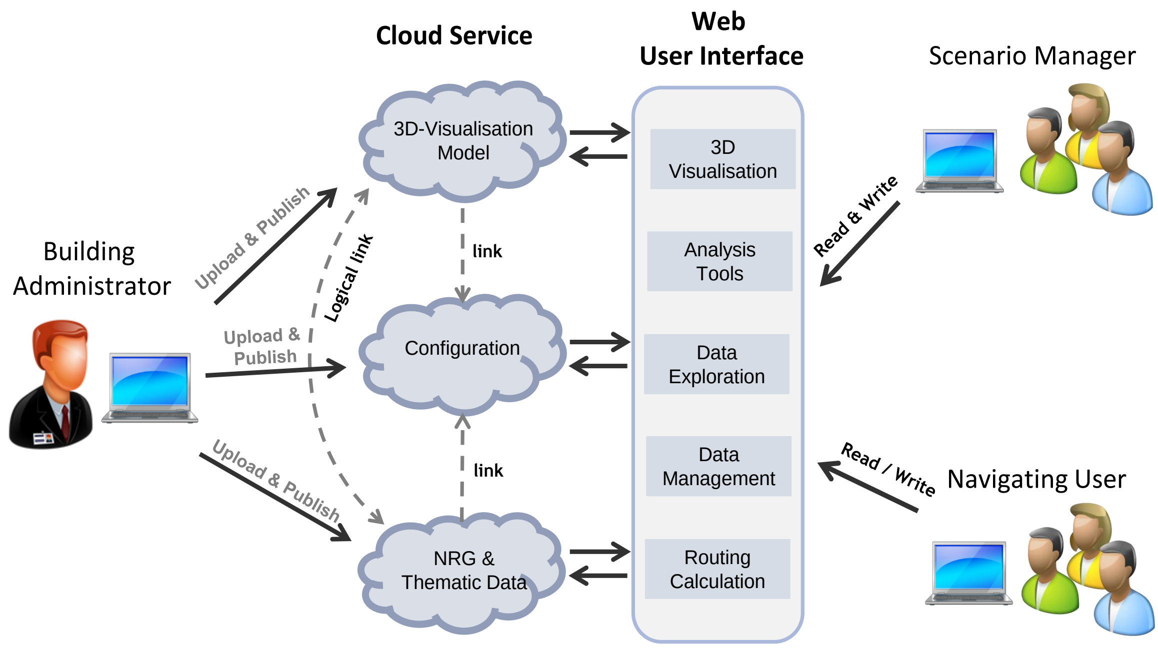


Fig. 6.40 Application scenarios with different user groups with different access rights to perform functions on the information backbone (Khan et al., 2014b).

Example Scenario 1:

Consider a scenario in the main building of Technical University of Munich, where a GIS conference is going to be organized between dates 10-12 July, 2015. To facilitate conference participants with accurate indoor routing according to their specific requirements the building administrator assigns the task to the scenario manager and provides him the main topographic model of the building as shown in figure 6.41. He further provides him with the network model representing the navigable space for the walking persons shown in figure 6.42 (2-dimensional view of a building). The scenario manager studies the conference plan and sessions' schedule and came to the decision that for two days room R3 and R4 must be closed to walk through by all participants because those are booked for private discussions. Therefore, he makes those rooms inaccessible (blocked) for all participants by editing the graph directly using the 3-dimensional webclient and upload the new network model as shown in figure 6.43 to the cloud service to access for participants so whenever they compute the route plan, then those two rooms should be inaccessible and not appear in their route computation by the system. Now the participants are able to compute routes with 3-dimensional visualization of the building model considering the specific context (in this case without disturbing the private discussions in room R3 and R4) during the conference.

Example Scenario 2:

In continuation of scenario 1, the conference has many sessions and each session is chaired by a session chairperson. Scenario manager provides the network model shown

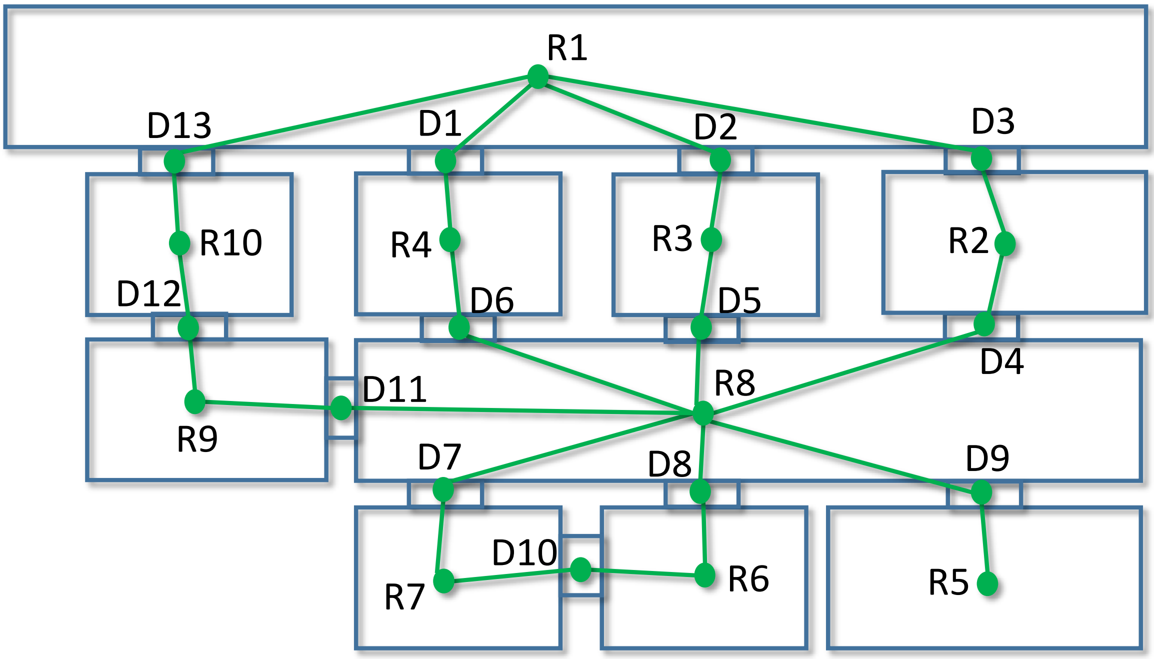


Fig. 6.41 The main topographic model and the network model of the building (2-dimensional view).

in figure 6.43 to the each session chairperson with permission to modify it according to specific requirements for the session participants. The conference has a visualization theme and its session is chaired by Mr. Yao in room *R7* which has two entry doors *D7* and *D10*. After having details of the conference sessions, and considering the requirements of the session participants he came with idea to close or block the door *D10* for participants because it would be disturbing for the other session in room *R6* that will be in progress during the closing and starting of his session. So participants should not walk through *R6* to reach *R7*. Considering this visualization session's contextual requirement Mr. Yao modifies the network model of building and he blocks *D10* for the participants of his session. He uploads the modified network model and the 3-dimensional visualization model of the building as shown in figure 6.44 to the cloud service so that the participants will get adapted routes without disturbing the session in R6.

The system architecture and example scenarios discussed in sections 6.4.3 and 6.4.4 are realized in the context of a Smart Campus project at Technical University of Munich (TUM) where a campus information system is currently being developed. It will facilitate personnel of different departments and will support for various application fields like indoor route planning. The visualization of the 3-dimensional model of the main building of TUM and its network model in the webclient are shown in figure 6.45 and figure 6.46 respectively. From figure 6.45 it can be observed that apart from the 3-dimensional visualization of the building model the webclient provides a user friendly user interface to visualize all the attributes of each element of building which can be also edited by user. In figure 6.46 the network model or dual space of building is given where each node and edge represent room space cell and boundary cell of the building model respectively from primal space. Figure 6.46 further shows, webclient gives direct access to the user to interact and modify network model based on attributes of building model. In figure 6.47 the route plan (list of room numbers to go through and rooms are highlighted in yellow color) for the user is computed through Dijkstra's algorithm by selecting two rooms (start and target room) of the building based on the main topographic layer (network model provided by the building administrator explained

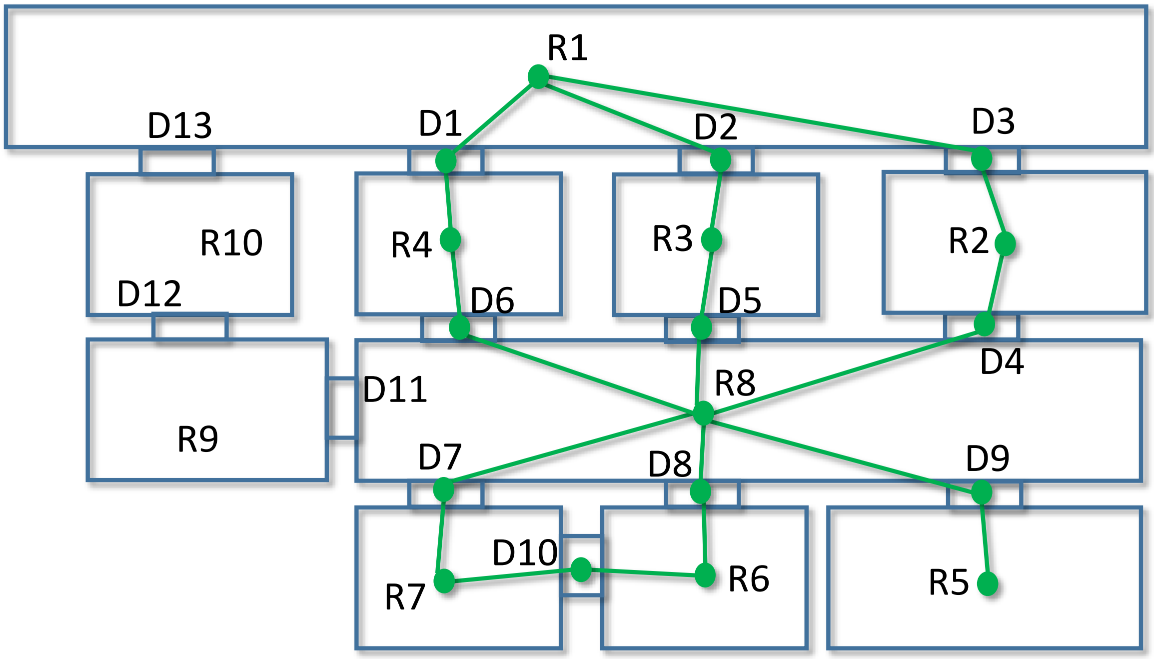


Fig. 6.42 The topographic model and the network model of the building provided by the building administrator (2-dimensional view).

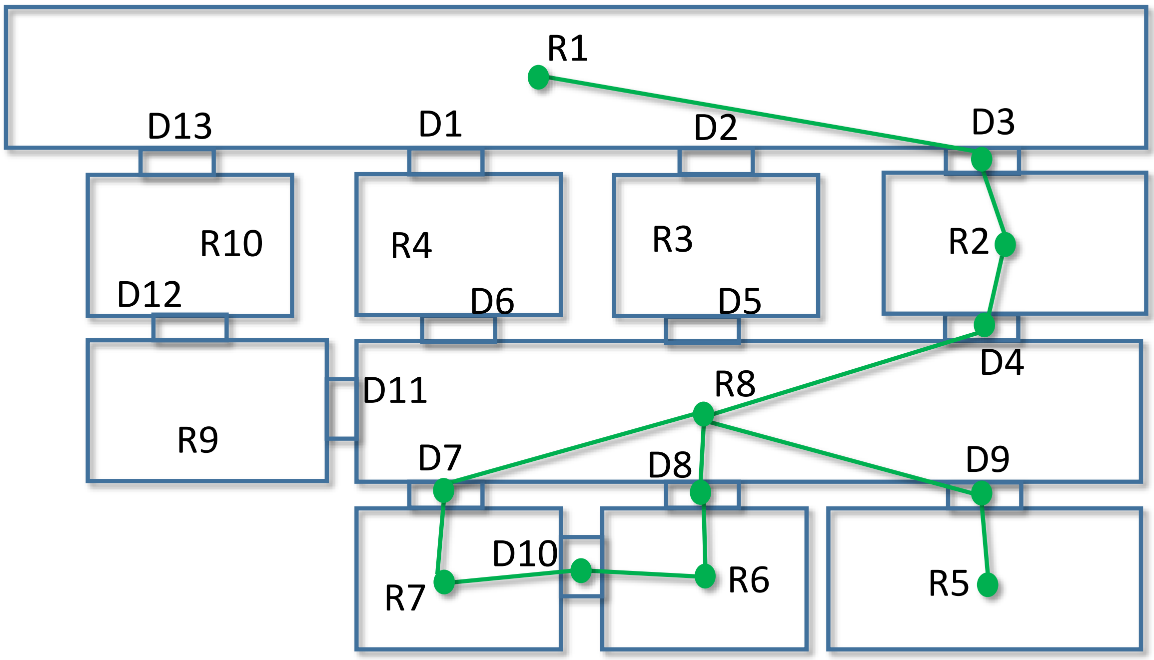


Fig. 6.43 The topographic model and the network model of the building after making rooms R3 and R4 inaccessible by the scenario manager (2-dimensional view).

in example scenario 1 shown in 6.46). Figure 6.48 shows the computed route plan (rooms are highlighted in yellow color) for the user by selecting the same two rooms (start and target selected earlier in figure 6.47) after putting restriction on room no *RMB7411* to pass through for users by the scenario manager due to some construction work. It can be observed that the rout plan in figure 6.47 differs from the route plan shown in figure 6.48 due to the fact that the users were provided two different network models by building administrator and scenario manager.

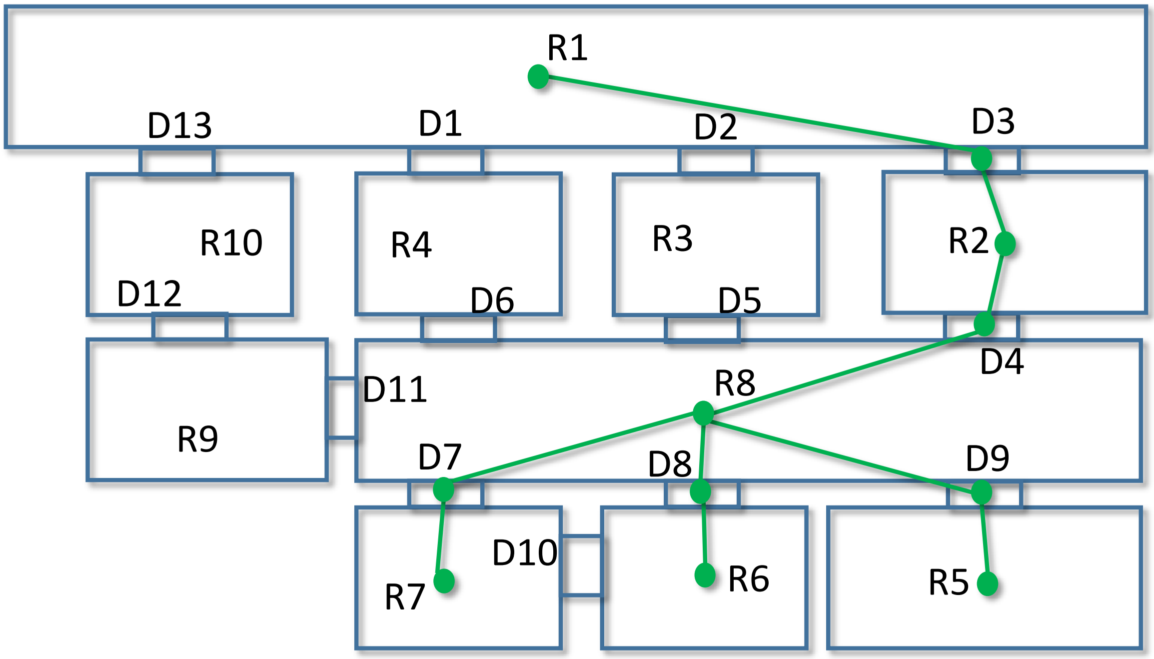


Fig. 6.44 The topographic model and the network model of the building after making door D10 inaccessible by the session chair (2-dimensional view).

Furthermore, the webclient gives opportunity to users (building administrator, scenario manager, session chairperson, or normal user) according to their accessibility and modification rights to put constraints on the building elements through different attributes, for example, based on flooring type, usage, area, etc. and generate corresponding network model to upload into cloud service to use for the user or user group.

6.5 Lessons Learned and Evaluation of the Method

6.5.1 Observations

The author investigated a multi-step transformation process and demonstrated that IndoorGML datasets can be automatically derived from existing semantic 3-dimensional building models. In addition, navigable subspaces according to the different locomotion types can be computed to provide support for their indoor navigation. Some of the observations, noticed during the transformation process and the computation of subspaces, are in the following.

1. In IFC building models, the *IFCSpace* class represents an area or volume within a building bounded by different building elements. A space can consists of several connected spaces or can also be divided in parts. Therefore, IFC is quite flexible and provides the user opportunity to represent space as per his requirements. In many cases, *IFCSpace* is shared by different stairs, rooms or corridors or even represented for the whole floor of the building. However, in CityGML, the free space or area is associated to a specific room or corridor. Therefore, there is always a requirement in an IFC model to ensure that the space represented is associated with a specific room or corridor to which it belongs, thus, that can be converted into a CityGML room feature type. Furthermore, to generate detailed representations of navigable spaces and graph models of the indoor space, there is a need to divide the space into its parts based on particular elements. For example, space above the stairs is divided into spaces for each stair.

Fig. 6.45 The 3-dimensional main building model of TUM in the 3-dimensional webclient (only interior rooms are shown).

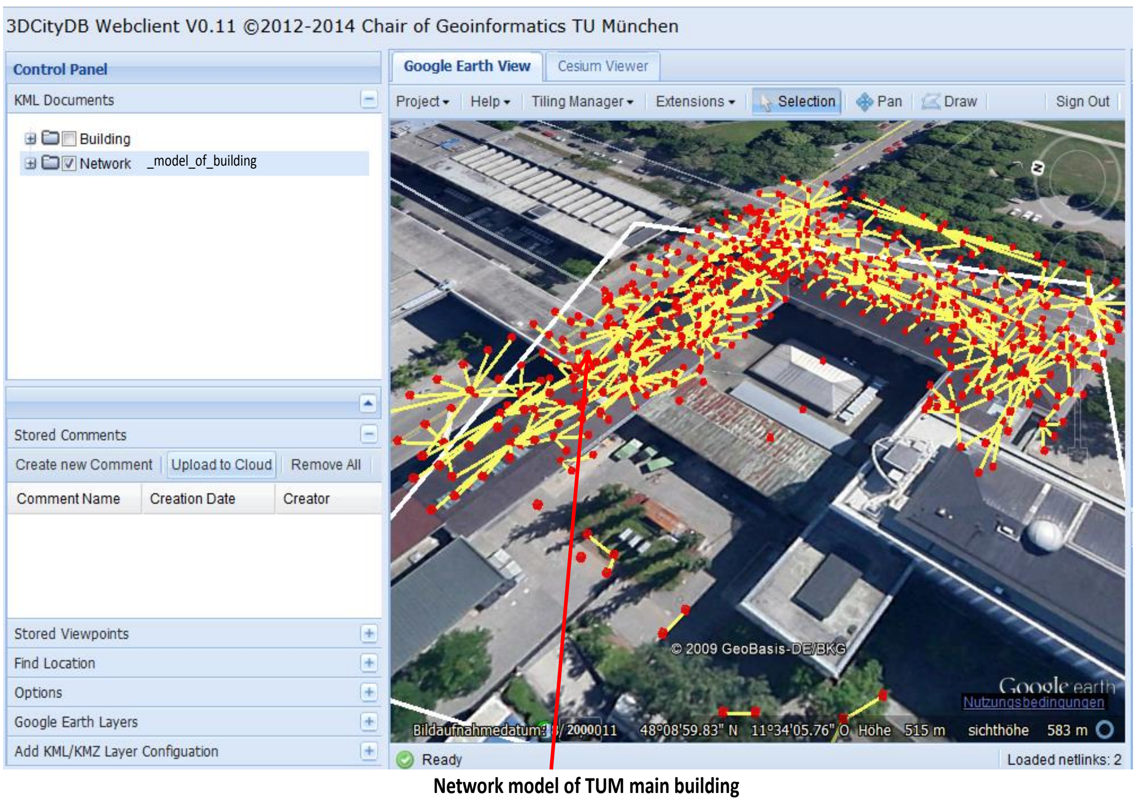


Fig. 6.46 Network model layer of TUM's main building model in the 3-dimensional web-client.

Fig. 6.47 Route plan (with all the semantic and geometric information of the route) from the start room to the target room based on the main network model provided by the building administrator.

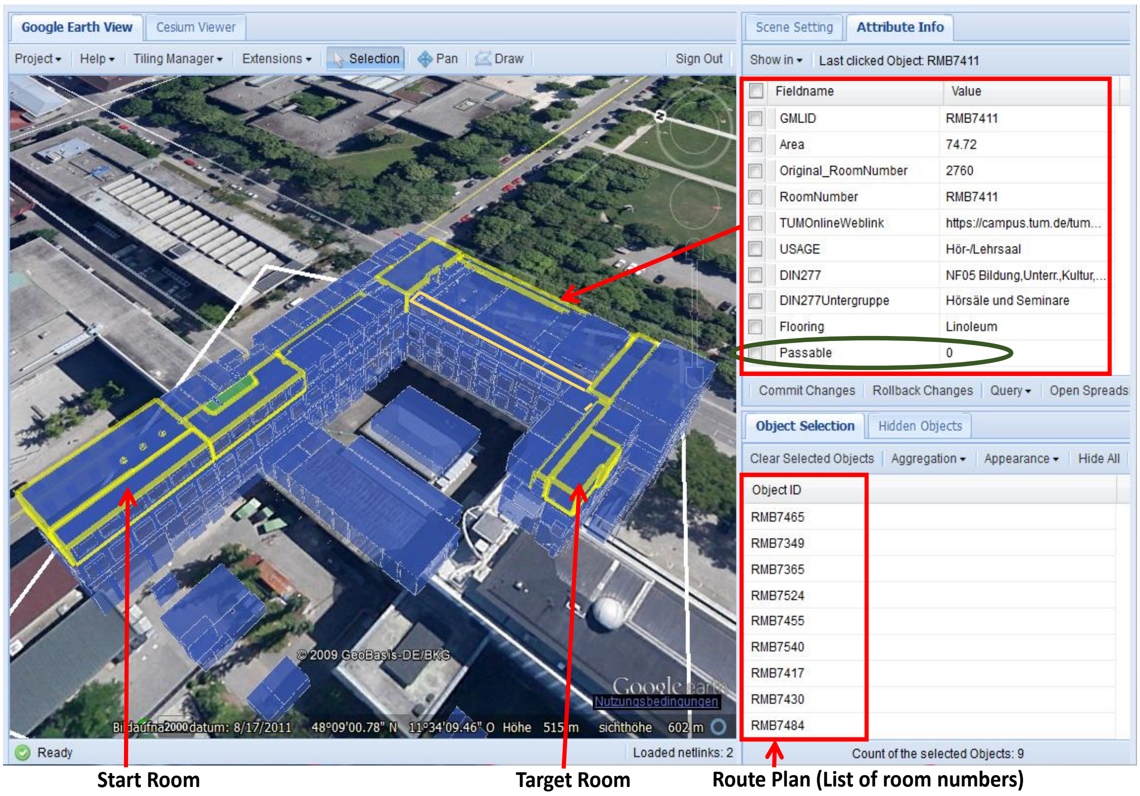


Fig. 6.48 Route plan for the user from start to target room using the network model provided by the scenario manager (after restricting room no RMB7411 to pass through).

2. Once the spaces are individually represented for each functional space (e.g., the space above a ramp or stair), they need to be ensured that their mutual topological connections are correct, thus, generating accurate network models for indoor navigation according to different locomotion types. For example, a room space and a door space which are connected, must be in *touch* in a topological relationship to extract a network model from the two spaces.

3. There is the requirement of representing the indoor environment in boundary representation to determine navigable and non-navigable spaces according to the different types of locomotion because locomotion types interact with boundary representations of an indoor environment and they compute their unsafe regions around boundaries of obstacle spaces. Therefore, to compute navigable subspaces for the different locomotion types, there is always a need to translate volumetric representations of indoor environments into boundary representations.

4. The semantic 3-dimensional models of indoor environments play a main role in determining navigable and non-navigable spaces for the specific locomotion type due to the availability of semantic information of the indoor environment. Therefore, there is always a need to have correct and structured semantic information of an indoor environment to support subspacing for each type of locomotion. Thus, to have an indoor environment in an international semantic 3-dimensional standard, contributes towards simplifying and supporting the subspacing process for the different locomotion types.

5. There is always a need to use geometric methods (e.g., computation of unsafe regions through configuration space method) to compute accurate and detailed navigable subspace for each type of locomotion as it can be observed from the implementation of subspacing approach that each subspace for the specific locomotion type is unique from the other. Thus, network models can be extracted from navigable subspaces to manage and store, as well as to address indoor space queries for the different locomotion types.

6. At the implementation level, the author uses an Oracle[3] database to store indoor building models (CityGML building model and IndoorGML building models) and *ArcObject's* 3-dimensional features tools of ESRI [4]are used for the computation of 3-dimensional subspaces for the different locomotion types. The Oracle Spatial database contains 3-dimensional functions to handle spatial relationships and filtering, for example, *SDO_ Relate* operator and *SDO_Filter* operator. However, Oracle Spatial still does not have 3-dimensional functions to compute the subspaces (e.g., 3-dimensional computation functions which include *union*, *intersect*, and *difference*) of this thesis implementation work, whereas ESRI provides tools for 3-dimensional computations. For example, *Difference3D* tool, *Intersect3D* tool, *Union3D* tool, etc. Therefore, during implementation of subspacing, the building model is transformed from the Oracle database to the ESRI *geodatabase* to use 3-dimensional feature tools for the computation of subspaces. This transformation process increases the usage of processing resources.

[3]Oracle is an IT company, provides solutions to address complex business processes. Internet: www.oracle.com

[4]ESRI is a commercial company, works in software development of Geographical Information Systems established in 1969. Internet: www.esri.com

6.5.2 Possibility of transfer of this Use Case to other Building Models, Locations, and Sources

Overall, the automation of the transformation process and subspacing process to support different types of locomotion for the indoor navigation for a public building shows that our methods simplify the process and help to avoid manual errors and demonstrate the feasibility of applying the approach on other building models. The approach is applied and presented while keeping in view the requirements for the CityGML LoD4 model, but in the case of different levels of detail, the transformation processes may be changed, which the author does not discuss in detail. Furthermore, the computation of subspaces may also vary depending on the level of detail of an indoor environment. If the same indoor environment is represented in different levels of detail, then it will also generate different navigable subspaces for the locomotion types. In this thesis, the author considered a consistent level of detail, LoD4.

This approach has some limitations, which include the manual checking and ensuring of topology relations among the building objects. Nevertheless, it can be used on different data building models (e.g., CityGML and IFC formatted building models) to generate routing graphs and for context-aware indoor route planning using a cloud-based system. To use the same approach on other data models located in a different place it needs to be georeferenced accordingly.

6.5.3 Evaluations and Recommendations

The method of using a constraint model of different locomotion types and computing subspaces using existing semantic 3-dimensional building models has major advantages. Some are listed in the following:

1. The use of a conceptual constraint model for the different locomotion types provides the opportunity to support indoor navigation of different locomotion types using 3-dimensional semantic building models.

2. The transformation of work flow from IFC to CityGML LoD4 and further to IndoorGML allows the source data to be structured either according to IFC or CityGML, which are well-known international standards.

3. The transformation procedure from IFC to CityGML can be kept quite flexible using Safe's[5] Feature Manipulation Engine (FME)[6] workbenches while accounting for the high degree of flexibility offered by IFC for structuring building models, whereas the CityGML to IndoorGML transformation has fixed and simpler transformation rules.

4. The author presented the subspacing approach and demonstrated it for a public building using IndoorGML while taking into account different locomotion types. The subspaces are computed using the real 3-dimensional geometry based on the configuration space method and subsequently network models are extracted. The subspaces created at the geometric level are more precise and, consider semantic and geometric information of the 3-dimensional building model, making this approach different and more realistic from other approaches.

[5]Safe Software Inc. is a private company and the maker of FME and works in spatial data transformation technology that assists GIS professionals and organizations to overcome their data interoperability challenges. Internet:www.safe.com

[6]FME helps in conversion and includes a library of 400+ data transformers so that data structure and content can be manipulated. Internet:www.safe.com/fme/

5. The detailed representation of the 3-dimensional building model's elements (e.g. detailed representation of stairs free space) and their topology checking supports extracting correct and detailed graphs for indoor navigation.

6. The author also presented a structured approach to combine two frameworks (multilevel cloud-based system and IndoorGML) to facilitate users for context aware indoor route planning. Based on IndoorGML, the network model, along with the semantic and geometric information of the building, can be completely stored in an IndoorGML database. This allows users to carry out complex analyses on the one side, and to generate and export arbitrary subsets of the original network model on the other side. The proposed system architecture utilizes cloud services to store the exported network model that can be dynamically customized and applied in different scenarios and disciplines for the route planning, whose outcomes can be visualized and interactively explored via a specific 3-dimensional webclient.

7. The proposed system architecture (multilevel cloud-based system and IndoorGML) can also be used to model navigation constraints generating from indoor space according to different contextual requirements, which can be directly stored in IndoorGML database by taking the input from user through 3-dimensional webclient interface. The constraints stored in IndoorGML database can be used for the different types of locomotion in their indoor navigation.

There are some recommendations based on the implementation of this work, which are as follows:

1. There is a need to take into account the correct topology connection (e.g., touch relationship) between indoor objects of a building model during its creation. Thus, it will create accurate navigable network models for indoor navigation.

2. Apart from geometric information, the semantic information of the building model plays a pivotal role in determining subspaces for a specific locomotion type. Therefore, there is a need to take special care to transform all the semantic information during the transformation steps from one schema to another (e.g., IFC to CityGML model).

3. The computation of subspaces using geometric methods (e.g., the configuration space approach) are very accurate as compared to the subspaces computed based on network models. Therefore, it is always better to use geometric methods with the support of semantics information to compute navigable subspaces for different locomotion types.

4. The subspacing approach used in this chapter provides support for the indoor navigation of different locomotion types. Thus, it is recommended to use a conceptual constraint model for subspacing to support for indoor navigation for different types of locomotion (e.g., flying and driving).

5. The two step transformation process that uses existing semantic building models for the navigation of different types of locomotion can also be used to convert building models from other sources (e.g., pure geometric models) into one of the structured semantic models and then compute the subspaces.

6. There is a need to introduce 3-dimensional computation tools in Oracle spatial. For example, 3-dimensional intersect and 3-dimensional difference tools for computing

Intersect and *Difference* between two 3-dimensional objects. So, the subspace computations of building models for different locomotion types could be carried out within Oracle Spatial database.

7. The 3-dimensional feature tools from ESRI fully support 3-dimensional computations of 3-dimensional objects. For example, 3-dimensional *Buffer*, *Intersect*, etc. However, the processing time of these tools on a personal computer is slow and it takes weeks to compute subspaces for the whole building model. There is a need to improve in computation processes of those tools to improve overall performance.

8. The author has used building model CityGML LoD4 for the implementation part of this thesis, but the building models can be in other levels of detail (e.g., LoD3 or LoD2 building model). Once there is a change in the LoD in the source building model, the IndoorGML model and subspaces generated from that source data model can also vary. There are automatic generalization methods to convert CityGML building models from low level of detail to higher (Baig and Rahman, 2013; Fan and Meng, 2012; Meng and Forberg, 2007). There is a need to explore the automatic methods to generate IndoorGML building models and navigable subspaces as per variation in levels of detail in CityGML building model.

9. The author has considered some constraints of each locomotion type and realized their outcome by means of determining navigable subspaces. The author did not take into account of the obstruction created by obstacle geometries and their non-navigable spaces (e.g., a gap between two floor surfaces can create obstruction obstacle above the gap for a locomotion type to navigate). There is a need to explore methods to determine the obstruction obstacles and their areas of influence in indoor space for the different locomotion types.

10. Last but not least, the use of IndoorGML to compute subspaces will support an increase of the horizon of applications of a specific semantic building model. For example, the conversion of a CityGML building model into an IndoorGML model, will not only enable it to be used for indoor navigation but will also support its usage with different indoor thematic contexts (e.g., sensor model or specific contextual subspace). Therefore, it is recommended to transform the semantic building model into IndoorGML for the computation of subspaces.

Chapter 7

Conclusions and Outlook

This chapter summarizes the main results of the thesis and recapitulates methods as well as approaches applied during this research work. In addition, the chapter discusses contributions to the field of indoor navigation and outlines future research.

7.1 Summary and Review

At the start of this thesis, one of the main challenges of indoor navigation has been highlighted: the lack of support for different types of locomotion in indoor navigation. Considering this as main motivation, the objectives for this thesis have been identified as the development of a conceptual constraints model, a subspacing method for the computation of navigable subspaces, and integration of different semantic 3-dimensional building models to use for the computation of unconstrained subspaces for the different types of locomotion. The summary and review are determined along these objectives.

A detailed study of the related work in the fields of indoor space modelling and abstraction methods to use these indoor space models for indoor navigation has shown the concepts of semantics 3-dimensional building modeling and their usage for indoor navigation for different types of locomotion. The related works were analyzed for their weaknesses and strengths with regard to the highlighted challenges to indoor navigation. From the argumentations and analysis, the requirements were extracted which play as a foundation for the design of a conceptual constraint model for the different types of locomotion.

One of the objectives of this thesis was to determine the navigation requirements and to define a formal model of these requirements for the different types of locomotion based on their specific properties. This is realized through the definition of locomotion types, and exemplified by presentation of use cases showing locomotion types role for constraining indoor movement. Moreover, requirements for the locomotion types to navigate in indoor space are determined and categorized based on their types. Based on these requirements, the constraints for the specific locomotion types are formed which define the conditions or requirements to be fulfilled for the navigation (question 1 in section 1.5.1). The constraints are categorized into specific types based on their requirements type, and this categorization of constraints plays a pivotal role in defining the conceptual constraint model for the locomotion type (question 2 and 4 in section 1.5.1). Furthermore, the conceptual constraint model for the locomotion type is defined that supports the determination of navigable and non-navigable space. On the one hand, the constraint model allows for the modelling of physical requirements of each type of locomotion to navigate in a semantically enriched indoor environment, on the other hand, it provides opportunity to navigate different types of locomotion in indoor space (question 3 in section 1.5.1).

Following the conceptual constraint model, another main objective of this thesis was to define a subspacing method to support for the indoor navigation of the different types of locomotion (question 1 in section 1.5.2). To present this method arguments were discussed to have a framework for indoor subspacing according to the locomotion type (question 2 in section 1.5.2). Moreover, based on these arguments the locomotion type's navigating constraints were categorized into distinguished types and indoor space was partitioned on the base of constraints of the locomotion type (question 3 in section 1.5.2). For the implementation of the navigating constraints of the locomotion type for indoor semantic environments the idea of navigational cells was used where each part of the 3-dimensional environment was considered as a cell space. In addition, to operate the subspacing method in a well-established framework, the MLSEM was used in which parallel and hierarchical layers of subspaces can be created and integrated based on different contextual needs (question 1 and 2 of section 1.5.3). Finally, the procedure and method for subspacing in a 3-dimensional semantic building model based on the constraints of the locomotion type was presented to determine navigable and non-navigable space using a geometric based method (question 4 and 5 of section 1.5.2).

The subspacing method for the different locomotion types was intended to use semantic 3-dimensional building models but it was realized that there are different international standards for semantic building models which are representing distinguished domains (e.g., Topography Information Modeling and Building Information Modeling) and have unique representation data models. To integrate these different types of semantic building modeling standards (CityGML and IFC) into IndoorGML (IndoorGML is a new complementary indoor building modeling standard, store and manage essential data for indoor navigation systems), a two-step transformation process was presented and realized this process on a real dataset of TUM main building model (questions 2, 3, and 4 in section 1.5.4). Furthermore, the semantic building model represented in IndoorGML would be very complex for a common user to interact and use. In addition, traditionally, most of the indoor routing applications are developed by means of client-server model that typically restrict users from changing, or augmenting the network model according to their specific contextual routing requirements (questions 5 and 6 in section 1.5.4). Therefore, IndoorGML building model is coupled with a cloud-based system to facilitate context aware indoor route planning (questions 8 and 7 in section 1.5.4).

Finally, the proposed conceptual constraint model, the integration of existing semantic building models, and the subspacing method for the different locomotion types namely flying, walking, and driving, each with a specific example, i.e., unmanned aerial vehicle, walking person, and wheelchair respectively, are demonstrated on a real data set of 3-dimensional building model of the TUM. The semantic building model of the TUM main building formatted in CityGML and IndoorGML were stored in an Oracle spatial database and subspaces for each type of locomotion (for computation of subspaces ESRI's 3-dimensional feature tools were used) were computed. Based on this practical implementation some observations, recommendations, and evaluations were made about computation of subspaces using currently available spatial databases management systems (questions 1, 2, and 3 in section 1.5.5).

7.2 Conclusions

Based on findings and results of this research work the following conclusions regarding the research hypotheses described in chapter 1.5 can be drawn.

Hypothesis 1 claims that the semantic, geometry, and topology constraints derived from the locomotion type and its environment are sufficient for determining navigable and non-navigable space for the locomotion types in indoor space. The results show that this is true. The proposed conceptual constraints model in this thesis models the navigating requirements which derive from the properties of the specific locomotion type and its environment. Based on these requirements the navigable and non-navigable subspaces are computed in a semantically enriched indoor environment.

In this thesis, the 3-dimensional subspacing approach considers the navigating requirements of different locomotion types and computes the navigable and non-navigable subspace for the specific locomotion type at the geometric level and then extracts the graph models from navigable or non-navigable subspace. The competing approaches, which extract the graph models from the main topographic space and compute subspaces from the main graph model cannot support for the different locomotion types. In this thesis, the approach to compute subspaces at the geometric level was adapted which supports the determination of navigable and non-navigable space for different types of locomotion. Therefore, the results in this thesis shows an affirmative answer to the Hypothesis 2.

The subspacing for the different types of locomotion was carried out within the framework of MLSEM. MLSEM provides an application schema, i.e., IndoorGML, in which the sub-layers representing subspaces for the different locomotion types from the main topographic layer were created. The subspacing idea within MLSEM presented in (Becker et al. 2009) was conformed through the realization of the computation of subspaces in IndoorGML in this thesis. The answer to the Hypothesis 3 is true.

The Oracle Spatial Database Management System (SDBMS) was used for the realization of subspacing for the different types of locomotion using semantic 3-dimensional building models. But there was limitation in Oracle SDBMS to compute subspaces (e.g., 3-dimensional difference, intersection, etc.). Therefore, ESRI's 3-dimensional feature tools (some of which include *Buffer3D*, *Intersect3D*, and *Difference3D*) were used to overcome this limitation. Hypothesis 5 which states limitations of today's 3-dimensional GIS and SDMS can be overcome to compute indoor subspacing is true because the integration of tools from different 3-dimensional GIS solutions is feasible and overcomes the limitations of today's specific product.

It can be concluded that the conceptual constraint model presented in chapter 3, the subspacing method described in chapter 4, and the integration of existing semantic building model standards in chapter 5 in this thesis fulfill the requirements for computation of accurate navigable subspaces for indoor navigation supporting different types of locomotion using semantic 3-dimensional building models. The main goal of this thesis addressing some of the challenges mentioned in chapter 1 has been achieved. Thus, this conceptual constraint model, the subspacing method, and the method to integrate the semantic building model standards can play as benchmark for the implementation of different indoor navigation systems.

7.3 Scientific Contributions

This research work in principle contributes to the field of indoor navigation. The application of the developed concepts and methods can also be viewed from the prospective of robotics and building information modelling fields.

Indoor Navigation: The main contribution of this thesis is a conceptual constraint model and a subspacing method to support the different types of locomotion types in indoor navigation. The constraint model models the requirements from properties and behaviors of the specific type of locomotion which needs to be fulfilled to navigate in an (semantically enriched) indoor environment. The model also categorizes constraints based on the requirement types of the locomotion type so it simplifies the process to capture knowledge about the locomotion type which later needs to be utilized for deciding navigability of the indoor space. Another main contribution is the subspacing method which determines the navigability of the indoor space for the considered locomotion type. This subspacing method utilizes the information from constraints of the locomotion type and navigational cells of 3-dimensional building model to compute navigable subspace.

Furthermore, different semantic 3-dimensional building model standards (CityGML and IFC) were transformed into IndoorGML to use for the computation of subspaces for the different types of locomotion. This transformation process not only considered the schema transformation but also analyzed the topological considerations of the building model to extract detail navigable spaces according to the different locomotion types. In addition, the extracted IndoorGML model of building was coupled with a cloud-based system to make easily understandable for the common user where he/she can change, modify, and update the model as per his/her contextual requirements as in contrast to the traditional client-server systems where users are restricted from changing or modifying the original dataset.

The concepts were realized on a real 3-dimensional semantic building model of the TUM main building model and lesson learned and recommendations were shared.

Building Information Modelling: This research work contributes to building information modelling by providing a method to generate accurate and detailed navigable subspaces for the different navigating objects or subjects. Particularly, for the analyses and simulations in different scenarios. For example, the constraint model and the subspacing method can help to determine the feasibility of navigability in parts of a building for a specific type of construction assisting vehicle (e.g., crane truck). Similarly, in emergency scenarios, the methods presented in this thesis can contribute to find the nearest navigable exits for different types of locomotion.

This research work can also be used to generate network graphs from building models which represent the building situation in the easiest possible way to understand for the common user. Furthermore, these network models of buildings can not only be used for routing purposes but can also be integrated with the other network models representing other thematic contexts of indoor space, for example, within IndoorGML different layers representing different thematic spaces can be integrated systematically and can be used for different analysis purposes (e.g., which rooms of the building have strong wifi signal?).

The work in this thesis can also be applied to facility management by integrating the navigable subspaces of different locomotion types with the utility networks of Building Information Models (BIMs). For example, if there is a need to repair a “bulb extension” in a huge hall, a supervisor of the building wants to determine which locomotion type (a robot or a person) is the most feasible to repair that bulb extension with minimum resources in that particular huge hall, in this case, the work in this thesis can contribute to help the supervisor by computing the navigable subspaces for the different locomotion types in combination with the knowledge of the utility network of the building.

Robotics: Route planning is an old problem in the field of robotics and there are well established specialized route computation methods for the specialized navigating objects. The methods of route planning and navigating objects considered (e.g., humanoids) in robotics field are very specialized in contrast to the filed of GIS where the methods still needs to be explored and navigating objects considered for indoor navigation are still very abstract (e.g., human being is represented as cylinder). This research work can contribute to lessen the gap between these two different domains. In robotics this work can contribute to use the 3-dimensional semantics building models for indoor navigation whereas in GIS it can contribute to use the methods of robotics to compute navigable spaces for different types of locomotion.

7.4 Outlook and Future Research

In the following, open issues and future research directions are outlined.

Extension of the conceptual constraint model: The conceptual constraint model presented in chapter 2 provides a rich description of semantic and geometric information of locomotion types to determine its navigability in indoor spaces. In addition, it provides opportunity to support for indoor navigation of different types of locomotion by defining common and differing constraints of various locomotion types. Based on these common and differing constraints, the navigable subspaces are determined. Currently, the constraints model only support for requirements and constraints at the whole body level of different locomotion types, whereas in the field of robotics the constraints for locomotion types are considered at the micro or body parts level. Therefore, there is need to model body part level constraints and requirements (e.g., in a human being case, the body parts' joints are considered for the motion constraints in robotics which are completely ignored in this research work). The detailed models of these constraints (they are already designed and used in robotics field but there is a need to use those models for indoor navigation with semantic models) will support specialized robots (e.g., household robot cleaner) to navigate in semantically enriched 3-dimensional environments. The constraints and navigating requirements of these robots can be modeled by means of extending the currently available conceptual constraint model. Moreover, with the enrichment of new constraints there would be a need to extend the method of subspacing discussed in chapter 3 to handle the newly introduced constraints. Once these specialized constraints are modeled and the subspacing method is described, then this work can initiate other tasks which may include the development of a specialized robotics navigation module in IndoorGML and an Application Domain Extension (ADE) model in CityGML for moving objects.

In this thesis work, the conceptual constraint model only considers the dynamic aspects of a specific constraint (e.g., start and end time of a specific constraint) but there is a need to take into account the dynamic aspects of environment too. Example are a fire break or disaster in a part of a building. Thus, there is still need to explore methods to compute navigable space for different locomotion types during or after extra-ordinary situations and also considering the other moving objects in indoor environment.

Connection with outdoor environment: The application of the constraint model and the computation of navigable subspaces using semantic 3-dimensional building model are illustrated in chapter 6. Most of the common users need indoor navigation as well as outdoor navigation so they are able to navigate into a building from the outside environment or vice versa. Therefore, there is a need to integrate IndoorGML models with outdoor routing models, and use multi-modal routing to facilitate user for the computation of indoor and outdoor navigable spaces. An integrated model would be beneficial to owners of buildings who have building information models and want to have indoor and outdoor routing using open source routing models (e.g., open street maps). The author has initiated work on this research as co-supervisor for a master's thesis which is in progress now.

Facility management: Different locomotion types have great inter-dependency with the utilities of a building. In many cases, there is a requirement to determine which utilities are reachable for the specific locomotion type in an indoor space. Similarly, in many situations there is a need to know which locomotion type is most resourceful to reach or in access of the specific interested utility point. To address these requirements and to have a better management of resources, there is a need to explore a method for the integration of this thesis work with utility networks of buildings.

Coupling with cloud-based 3-dimensional webclient: In chapter 6 of this thesis , the IndoorGML is coupled with a cloud-based 3-dimensional webclient, where users can compute route plans according to their contextual requirements. This work can be extended to serve real navigable subspaces for different locomotion types on the cloud-based 3-dimensional webclient. Moreover, specific contextual requirements of the different locomotion types can be considered on these navigable subspaces to compute route plans and sub-networks to share with other users on the cloud.

Subspacing with only geometric models: In this thesis, the author used a semantically enriched 3-dimensional building model, with implicit knowledge of indoor environments for subspacing. However, in case of only geometric building models, there is a need to determine how subspacing can be carried out using the knowledge of the locomotion type based on its conceptual constraint model. The author carried out some initial work but still there is a need to explore how the building models can be enriched with semantics information based on conceptual constraint model of the locomotion type and compute navigable subspaces. This future work may contribute to the photogrammetry field, where in many cases, at the initial stage, the indoor 3-dimensional environments are developed only geometrically (e.g., through laser scanning) and later they need to be enriched with semantics for location based services.

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Appendix A

Transformation from IFC to CityGML: FME Workbench

The transformation from IFC to CityGML data models is carried out using FME transformers[1]. The whole overview of transformation werkbench is shown in figure A.1. The werckbench is divided into four portions, i.e., A, B, C, and D. and each portion's transformers are shown in detail in the following pages.

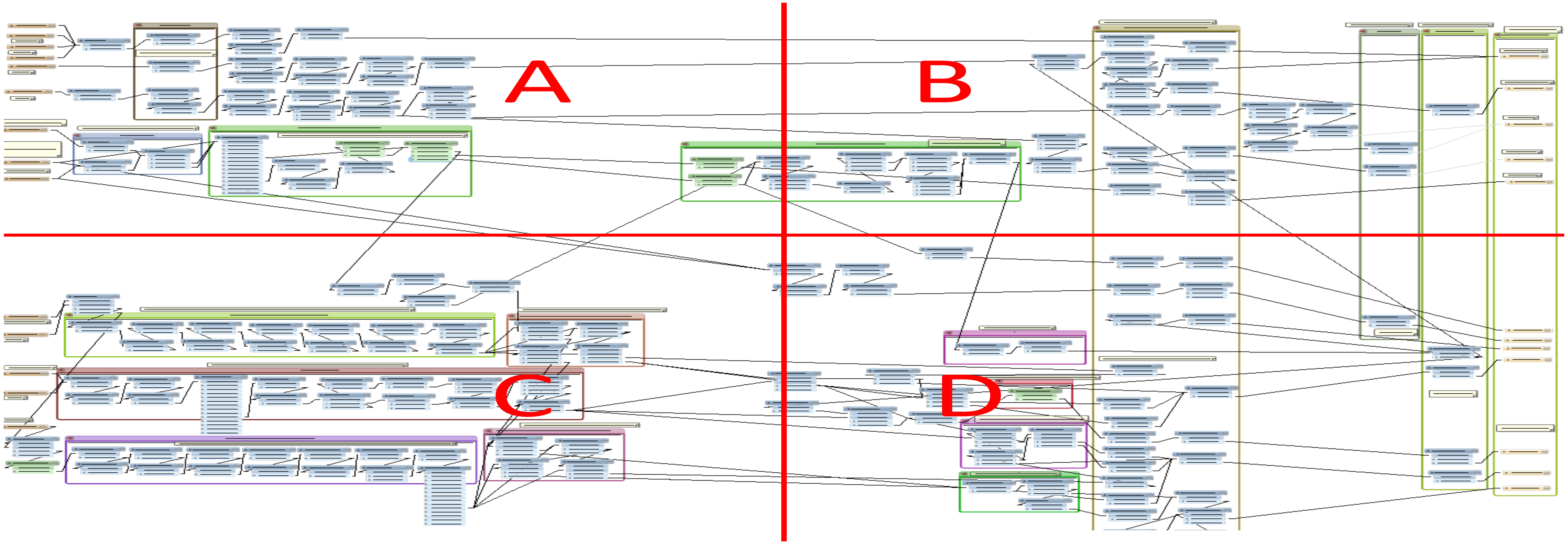

Fig. A.1 The whole overview of FME Workbench transformation from IFC to CityGML.

[1]The detail documentation about each FME transformer can be assessed on internet from Safe software's website: www.http://www.safe.com/fme/key-capabilities/data-transformation/all-transformers/.

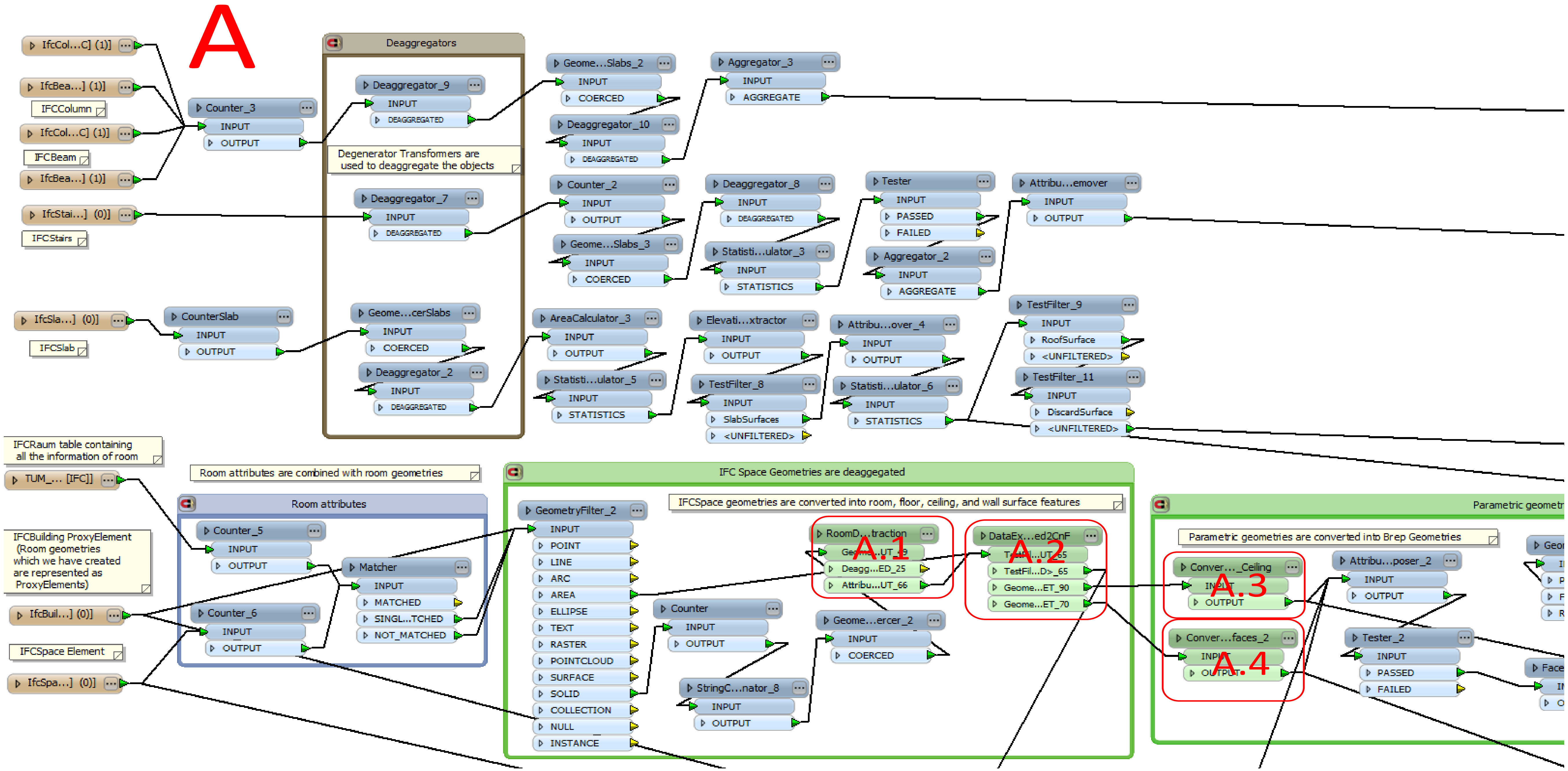

Fig. A.2 The FME Workbench transformation from IFC to CityGML, detail view of portion A from figure A.1.

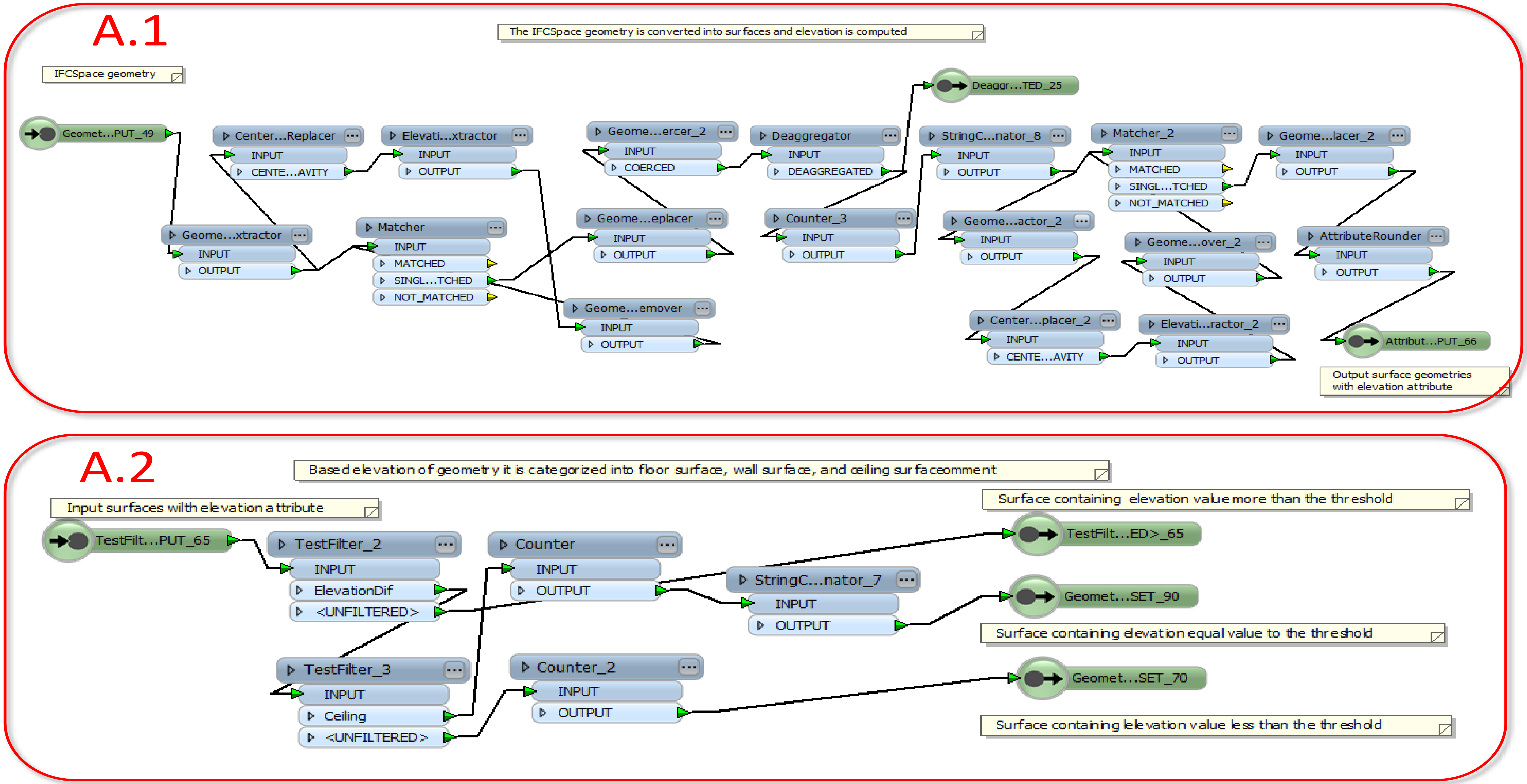

Fig. A.3 The FME Workbench transformation from IFC to CityGML, detail view of transformers A.1 and A.2 shown in figure A.2.

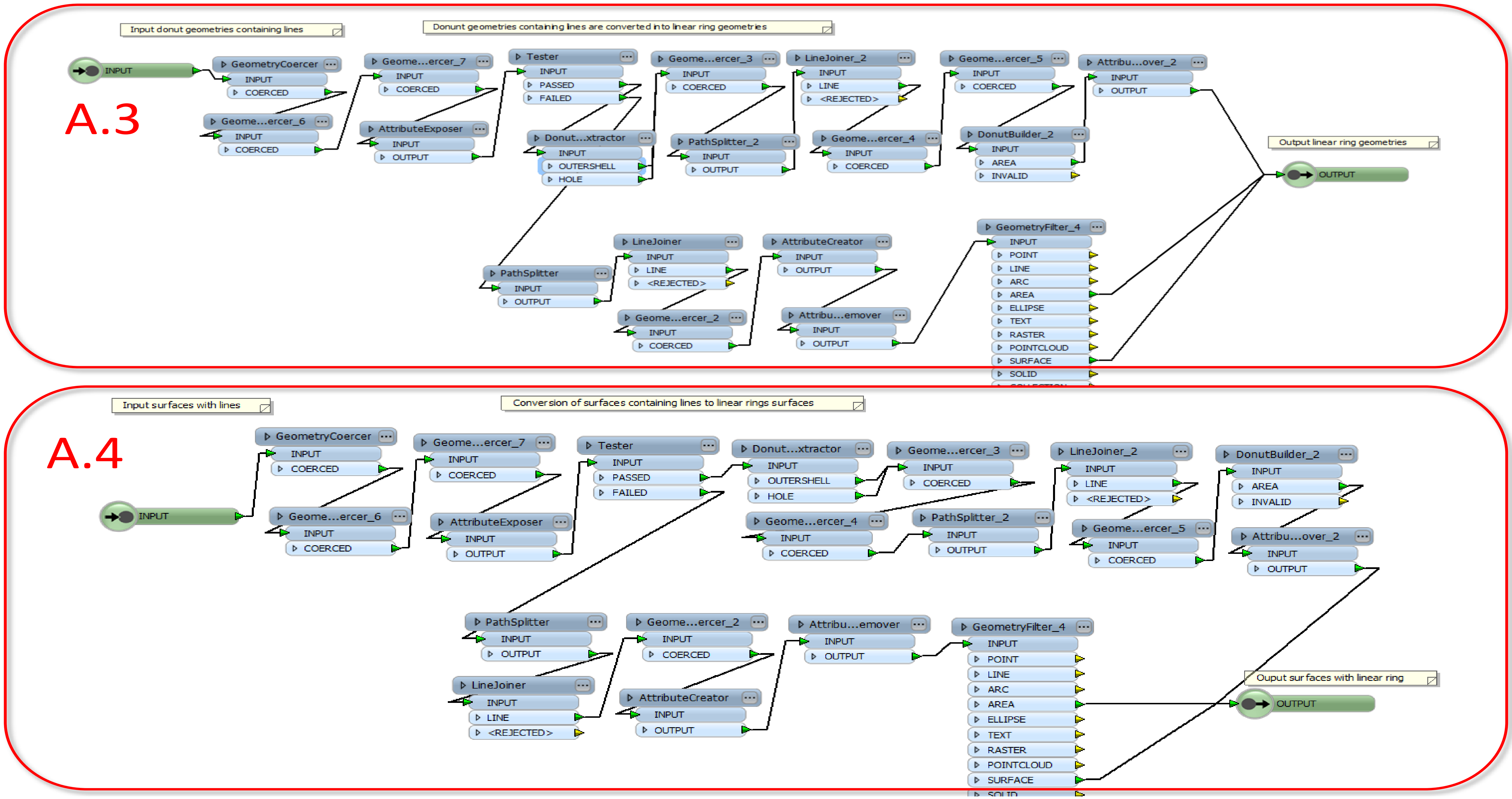

Fig. A.4 The FME Workbench transformation from IFC to CityGML, detail view of transformers A.3 and A.4 shown in figure A.2.

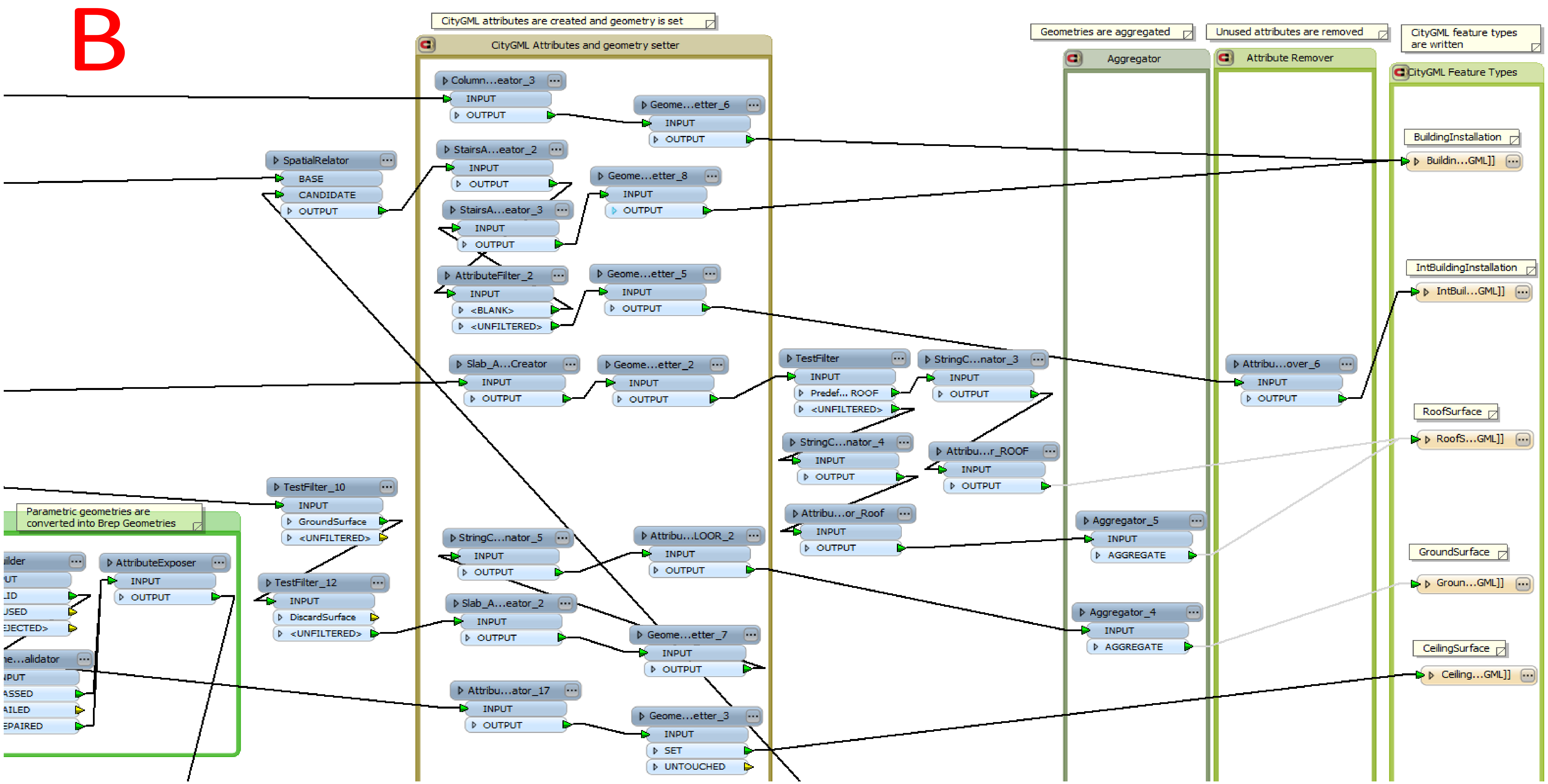

Fig. A.5 The FME Workbench transformation from IFC to CityGML, detail view of portion B from figure A.1.

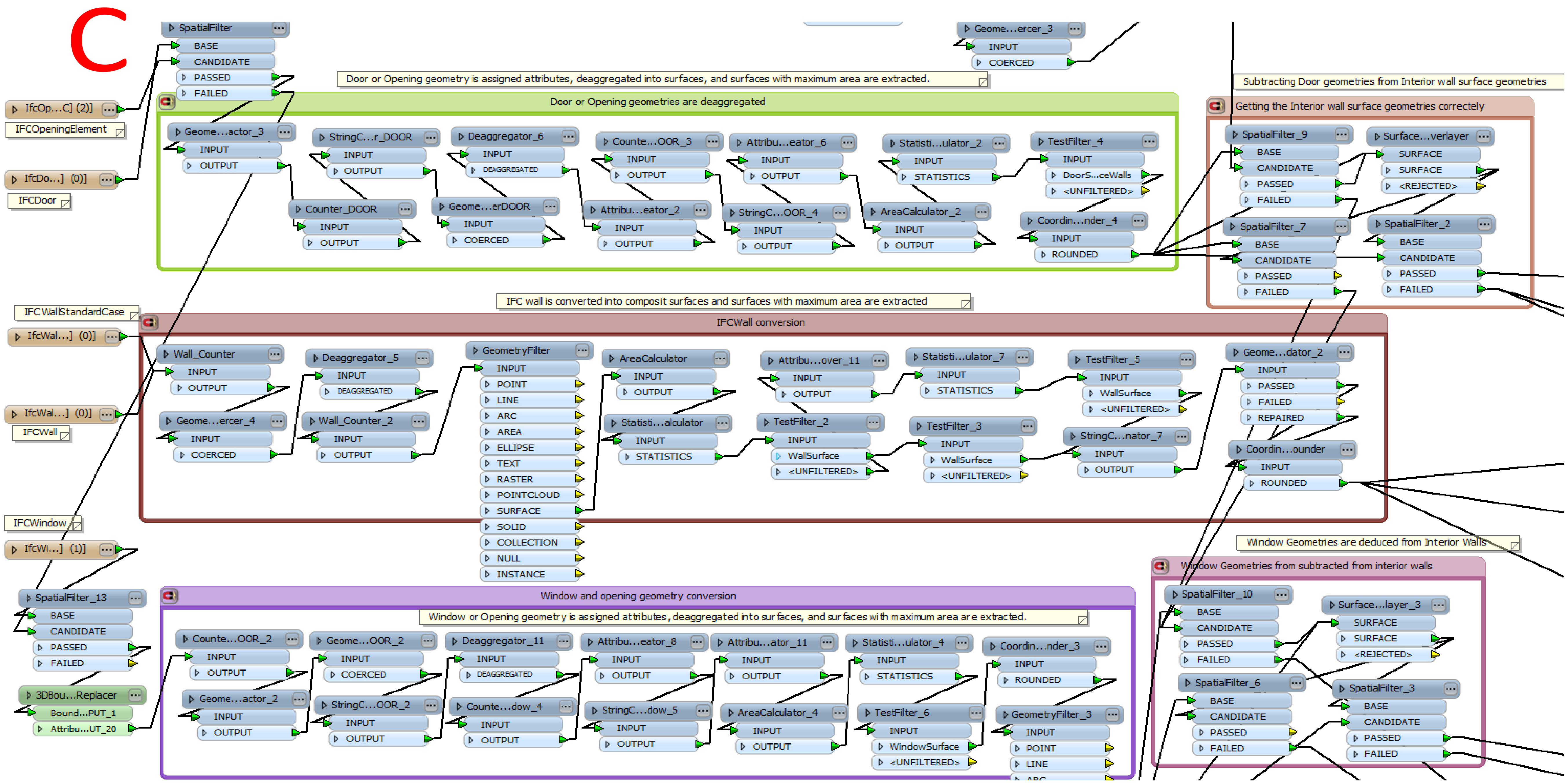

Fig. A.6 The FME Workbench transformation from IFC to CityGML, detail view of portion C from figure A.1.

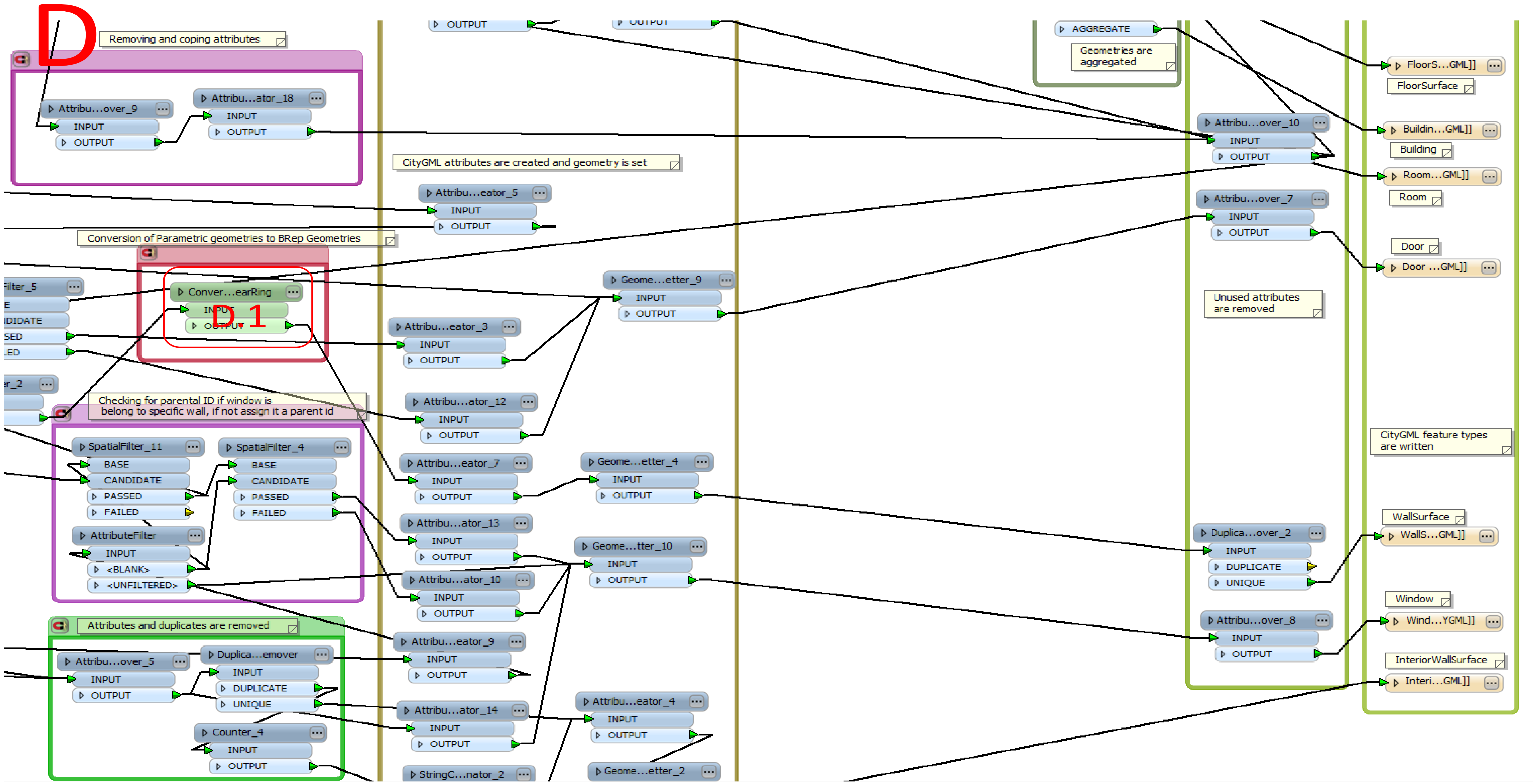

Fig. A.7 The FME Workbench transformation from IFC to CityGML, detail view of portion D from figure A.1.

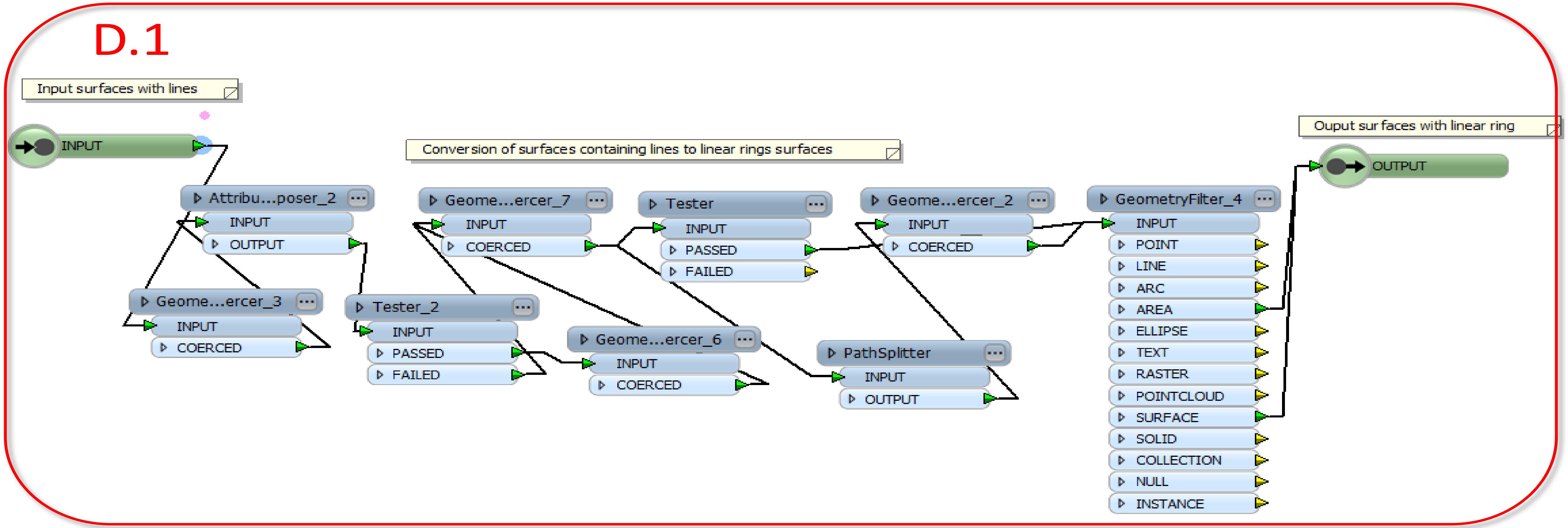

Fig. A.8 The FME Workbench transformation from IFC to CityGML, detail view of transformer D.1 shown in figure A.7.

Appendix B

Transformation from CityGML to IndoorGML

B.1 Transformation program from CityGML to IndoorGML

The main steps and functions of the program to transform 3-dimensional building datasets from CityGML to IndoorGML database are presented in the following.

```
public class MainOper {
  public static void main(String[] args) throws Exception {
       Operations dboper=new Operations();
       /*
       * Method dbConnect to connect with the CityGML and IndoorGML databases
       * @param url servername, port name, sid
       * username username
       * password password
       */
    Connection conCityGML=dboper.dbConnect( url, username, password);
    Connection conIndoorGML=dboper.dbConnect( url, username, password);
    // Step 1:
    /*
    * Method to inserts space layers names and ids in space layers table in
       IndoorGML database
    * @param conCityGML connection object with database
    */
    insertSpaceLayers(conCityGML);
    int[] roomList = null;
    // Step 2:
    /*
    * Method to take the room id list from CityGML database
    * @param room name of table
    * @ LoD4_Geometry_ID to access all LoD4 geometries related with room
       object
    * @param conCityGML connection object with database
    */
    roomList=dboper.getGeometryIDList("room","LOD4_GEOMETRY_ID",conCityGML);
```

```
for(int i=0;i < roomList.length;i++){
   Statement sIndoorGML =
       conCityGML.createStatement(ResultSet.TYPE_SCROLL_INSENSITIVE,
   ResultSet.CONCUR_UPDATABLE);// creating query statement to insert
       indoor objects
   String insertQry = "INSERT INTO IDML_INDOOR_OBJECT (id) values
       ("+roomList[i]+")";
   sIndoorGML.executeQuery(insertQry); //Inserts Indoor_Object
   /*
    * Method insertSolidByID to take the room objects from
      CityGML database and inserting into IndoorGML
      database as space objects
    * @param layerid space layer id
    * @param conCityGML connection object with CityGML database
    * @param conIndoorGML connection object with IndoorGML database
    */
    dboper.insertSolidByID(eleArr[i],layerid , conCityGML, conIndoorGML);

  }

//Step 3: Inserting door and window spaces from CityGml database to
   IndoorGML database

 int[] OpeningIDsList = null; //variable to store opening id list
 String[]openingSurfaceUniqueList=null;// variable to store opening
     surface id list
 String openingSurface="WindowSurfaceID";//in case of window
     WindowSurfaceID in case of door DoorSurfaceID
 String openingSurfaceID="'Window%'";//in case of window...'Window%' and
     in case of door DOOR%
 String openingName= "'Window'";//in case of door....'Window' Door

 /*
  * Method getOpeningSurfaceIDList to get opening geometries id list
  * @param char from CITYOBJECT_GENERICATTRIB table
  * @param char searching column
  * @param opeingSurfaceID variable to store searching term e.g., window
      or door
  * @param conIndoorGML connection object with IndoorGML database
  */
 openingSurfaceUniqueList=dboper.getOpeningSurfaceIDList
 ("CITYOBJECT_GENERICATTRIB","STRVAL",opeingSurfaceID,conCityGML);

 //fetching opening geometries and inserting into IndoorGML database
 for(int i=0;i<openingSurfaceUniqueList.length;i++){
     /*
      * Method insertOpeningSpacesByID inserts Opening spaces into
          IndoorGML database
      * @param char from CITYOBJECT_GENERICATTRIB table
      * @param []list list of opening surfaces
      * @param openingSurface opening surface name e.g., window or door
```

```
     * @param layerid space layer id
     * @param conCityGML connection object with CityGML database
     * @param conIndoorGML connection object with IndoorGML database
     */
     insertOpeningSpacesByID(openingSurfaceUniqueList[i],openingSurface,
        layerid , conCityGML, conIndoorGML);
 }
 //step 4: Generating centroids (state geometries) of space geometries and
    insert into space_state table

 // taking the id list of space objects and computing centroids or state
    geometries in IndoorGML database
 for(int i=0;i<idlist.length;i++){
    /*
     * Method createCentroid computing the centroids of 3-dimensional
        objects
     * @param []list list of space object ID
     * @param conIndoorGML connection object with IndoorGML database
     * @param tab_name Space_state table name in IndoorGML database
     */
     createCentroid(idlist[i],conCityGML,tab_name);
 }
//step 5:Inserts transitions, transition geometries, and boundary
   geometries
/*
* Method insertSpaceBoundary inserts transitions numbers and relations
   based on their 3-dimensional connectivity
* @param []list list of space object ID
* @param layer_id space layer ID
* @param conIndoorGML connection object with IndoorGML database
* @param tab_name Space_state table name in IndoorGML database
*/
insertSpaceBoundary(idlist,layer_id, conIndoorGML,tab_name);
/*
* Method updateSpaceBoundaryGeometry inserts transition geometries (lines)
* @param conIndoorGML connection object with IndoorGML database
*/
updateSpaceBoundaryGeometry(conIndoorGML);
/*
* Method updateSpaceBoundaryTransitionGeometry inserting space boundary
   geometries
* @param conIndoorGML connection object with IndoorGML database
* @param layer_id space layer ID
*/
updateSpaceBoundaryTransitionGeometry(conIndoorGML,layer_id);

/*
 * Method updateSpaceBoundaryTransitionGeometry_withDummySpace Importing
    the interior surfaces from CityGML database to IDML database as
    boundary space geometries for space objects
 * @param conIndoorGML connection object with IndoorGML database
```

```
     * @param conCityGML connection object with CityGML database
     * @param layer_id space layer ID
     */
    updateSpaceBoundaryTransitionGeometry_withDummySpace(conCityGML,conIndoorGML,layer_id);
    }
}
```

Appendix C

Subspacing Algorithm

The main methods of subspacing algorithm are given in the following.

```
// The algroritm to determine navigable and non-navigable subspaces based
    on the constraints of the locomotion type
    Locomotion type = select locomotion  type ;
        3DSpaceObjects UnSafeRegionObjects[];
        3DSpaceObjects NavigableSpaceObjects[];
        While (end of all the Indoor cells){
                obstacle=applyPrimaryConstraints(IndoorCell,
                    FoundationConstraintsTypeofLocomotion[]);
                If (obstacle){
                        UnsafeRegion=obstacleExpansion(obstacle);
                        addToOverAllUnsafeRegion(UnsafeRegion);
                } else{
                        addTonavigbleSpaceObjects(indoorCell);
                  }
        }
        NavigableSpace=subtractUnsafeNavigableSpace( NavigableSpaceObjects
            [], UnSafeRegionObjects[]);
        // subtractUnsafeRegionFromNavigableSpace


//step 1: Extruding the surfaces of obstacles geometries
* Method correctSurfaceOrientation correcting the orientation of boundary
    surfaces
   * @param conIndoorGML connection object with IndoorGML database
   * @param spaceName name of space e.g., 'airspace'
   * @param mainSpace_layer_id space layer ID of main layer
   * @param layer_id_Subspace space layer ID of subspace
   * @param tab_name Space_state table name in IndoorGML database
   */
correctSurfaceOrientation(conCityGML,spaceName,mainSpace_layer_id,layer_id_Subspace);
//step 2: Extruding the obstacles geometries (edges and vertices)
* Method extrudWallSurface extruding the plane surfaces of obstacle
    geometries
   * @param conIndoorGML connection object with IndoorGML database
   * @param spaceName name of space e.g., 'airspace'
   * @param mainSpace_layer_id space layer ID of main layer
```

```
   * @param layer_id_Subspace space layer ID of subspace
   * @param unSafeLength unsafe length of the locomotion type. For example,
      in walking person locomotion type consideration (represented as
      cylinder), the radius is considered as unsafe length, i.e.,0.1m
   */
extrudWallSurface(conIndoorGML,spaceName,mainSpace_layer_id,layer_id_Subspace,
    unSafeLength);
* Method extrudObstacle_EdgesVetrices extruding the edges and vertices of
    obstacle surfaces
   * @param conCityGML connection object with CityGML database
   * @param spaceName name of space e.g., 'airspace'
   * @param mainSpace_layer_id space layer ID of main layer
   * @param layer_id_Subspace space layer ID of subspace
   * @param unSafeLength unsafe length of the locomotion type. For example,
      in walking person locomotion type consideration (represented as
      cylinder) the radius is considered as unsafe length, i.e.,0.1m
   */
extrudObstacle_EdgesVetrices(conCityGML,spaceName,mainSpace_layer_id,layer_id_Subspace,
    unSafeLength);

* Method extrudedGeometryreadingandinserting extruded geometries are read
    and converted into solid and inserted into oracle IndoorGML database
   * @param path path of the geodatabase to read the file
   * @param featureclassname name of feature from geodatabase
   * @param conIndoorGML connection object with IndoorGML database
   * @param layer_id space layer ID
   */
extrudedGeometryreadingandinserting(path,featureclassname,conIndoorGML,layer_id);
//step 3:computing actual navigable space
* Method subspaceNavigable computes navigable space by deducing the obstacle
    geometries from navigable space
   * @param conCityGML connection object with IndoorGML database
   * @param layer_id space layer ID
   */
subspaceNavigable(conIndoorGML,layer_id);

//step 3: Computing the state geometries and transition geometries for new
    subspaces
* Method subspaceAirSpacetGeUpdate updating new subspaces by computing state
    geometries and transition geometries
 * @param conIndoorGML connection object with IndoorGML database
 * @param layer_id space layer ID
 */
subspaceAirSpacetGeUpdate(conCityGML,layer_id); //updating with new
    geometries, c
```

Appendix D

Constraint details for the Subspacing Example

The author considered some constraints examples presented in tables H.1, H.3, and D.3 of different locomotion types to determine their navigable subspaces.

D.1 Locomotion type: Driving (wheelchair)

Geometry representation: 3-dimensional cylinder

D.2 Locomotion type: Walking (walking person)

Geometry representation: 3-dimensional cylinder

D.3 Locomotion type: Flying (UAV)

Geometry representation: 3-dimensional Sphere

Table D.1 Wheelchair's constraints.

Name of Attribute	Requirement for the in-door navigation	Constraint	Constraint Type	Constraint application Procedure
Volume	3D indoor air (free) space volume must be more than volume of locomotion type	3D indoor space cell volume >= Volume of locomotion	Physical-Geometry-Related	- The volume of the 3D indoor space free space cell is considered - The volume of locomotion type is considered - Both volumes are compared, if the constraint result is true, then indoor space cell is navigable, otherwise non-navigable
Cannot-Cross-Through	Cannot navigate through blocked space (e.g. wall)	Cannot-Cross-Through ="Wall-Surface"	Capability-Constraint	- Wall surfaces of the 3D indoor space model are considered and are declared as non-navigable
Ground-Surface-Topology	Always need ground surface to hold the locomotion type	Ground surface of locomotion must be "always connected to" ground surface of indoor space	Topological-Geometry-Related-Constraint	- The indoor air space must always have a navigable ground surface, if true, then the air space is navigable, otherwise nonnavigable. - The topology between GroundSurface of locomotion and navigable GroundSurface is checked, whether it is connected or not.
Slope	Ground Surface must be in range of required slope.	Slope of surface < 4	Capability-Constraint	- The slope of GroundSurface of indoor space is compared with the capability limit of the locomotion type.
Smoothness of plane surface	No stairs, gap or objects with height > 0.5 foot	Two ground surface boundaries must touch (no gap), angle between current surface and next surface must be less than 35 degree.	Capability-Constraint	- If the gap or angle is more than the capability of the locomotion type then the ground Surface/stair is considered as non-navigable.

Table D.2 Walking person's constraints.

Name of Attribute	Requirement for the indoor navigation	Constraint	Constraint Type	Constraint application Procedure
Volume	3D indoor air (free) space volume must be more than volume of locomotion type	3D indoor space cell volume >= Volume of locomotion	Physical-Geometry-Related	- The volume of the 3D indoor space free space cell is considered - The volume of locomotion type is considered - Both volumes are compared, if the constraint result is true, then indoor space cell is navigable, otherwise non-navigable
Cannot-Cross-Through	Cannot navigate through blocked space (e.g. wall)	Cannot-Cross-Through ="Wall-Surface"	Capability-Constraint	- Wall surfaces of the 3D indoor space model are considered and are declared as non-navigable
Slope	The ground surface must be in range of required slope.	Must be surface < 6	Capability Constraint	- The slope of ground surface of indoor space is compared with the capability limit of the locomotion type.
Ground-Surface-Topology	The ground surface needs to hold the locomotion type	The ground surface of locomotion must be "connected to" ground surface of indoor space	Topological-Geometry-Related-Constraint	- The indoor air space must have a navigable ground surface; if true, then the air space is navigable, otherwise non-navigable. - The topology between the ground surface of locomotion and the navigable ground Surface is checked, whether it is connected or not.
Smoothness of plane surface	Gap or objects with height > 3 feet	The distance between two Ground surface boundaries must less than 2 feet (gap with two feet)	Capability-Constraint	- If the gap is more than the capability of the locomotion type, then the ground surface/ stair is considered as non-navigable.

Table D.3 Unmanned Aerial Vehicle's constraints.

Name of Attribute	Requirement for the indoor navigation	Constraint	Constraint Type	Constraint application Procedure
Volume	3D indoor air (free) space volume must be more than volume of locomotion type	3D indoor space cell volume >= Volume of locomotion	Physical-Geometry-Related	- The volume of the 3D indoor space free space cell is considered - The volume of locomotion type is considered - Both volumes are compared, if the constraint result is true, then indoor space cell is navigable, otherwise non-navigable
Cannot-Cross-Through	Cannot navigate through blocked space (e.g. wall)	Cannot-Cross-Through ="Wall-Surface"	Capability-Constraint	- Wall surfaces of the 3D indoor space model are considered and are declared as non-navigable
Ground-Surface-Topology	No need of a ground surface to hold the locomotion type	No need of a connection with the ground surface	Topological-Geometry-related Constraint	-No need to check any topology relation between the locomotion type and the ground surface.

Appendix E

Coupling of IndoorGML with Cloud-based System

E.1 Translation Process

The 3-dimensional building model dataset is translated from IndoorGML to CityGML.The transition and state geometries along their relevant information from IndoorGML are translated into generic objects in CityGML, and then CityGML dataset is transformed into KML file by 3-dimensional City Database Importer/Exporter tool[1] to serve on cloud-based 3-dimensional web client. The transformation process is shown in figure E.1.

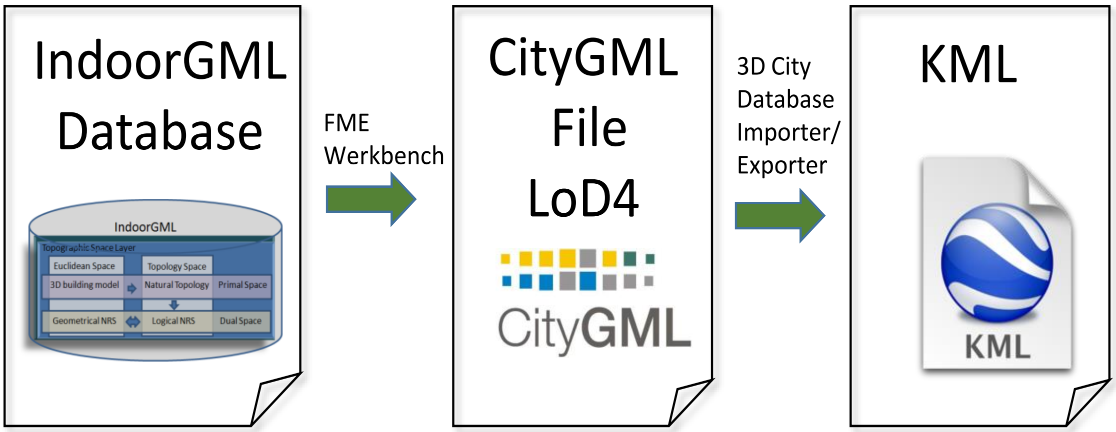

Fig. E.1 The translation of 3-dimensional building model dataset from IndoorGML to KML.

E.2 FME Workbench to Translate Dataset from IndoorGML to CityGML

Through FME Workbench the 3-dimensional building model is translated from IndoorGML to CityGML. The FME Werkbench details are presented in figures E.2 and E.3.

[1]The 3D City Database Importer/Exporter is a Java based front-end for importing and exporting spatial data for a virtual 3D city models (i.e. CityGML, KML, COLLADA). www.3dcitydb.net

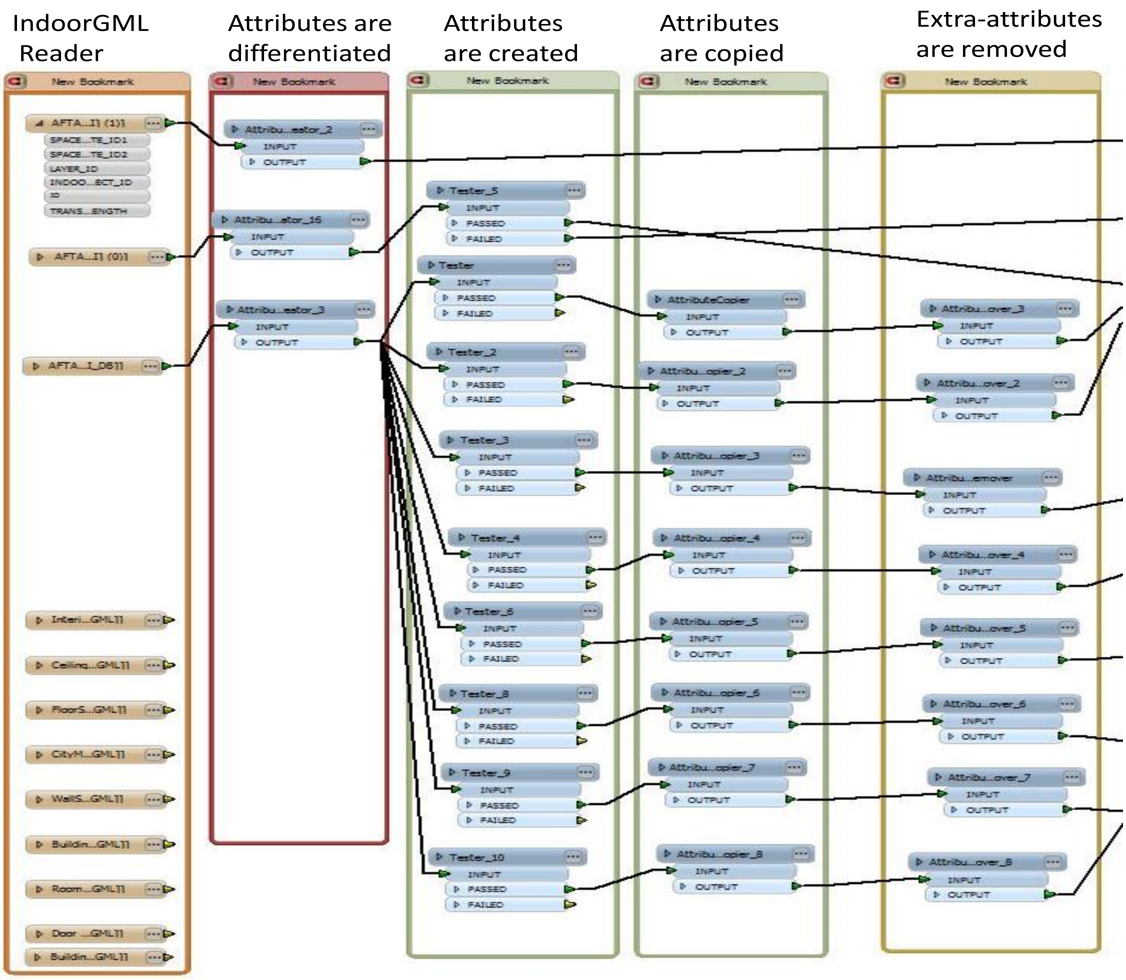

Fig. E.2 The FME Workbench to translate IndoorGML dataset into CityGML (Image continued to the next page).

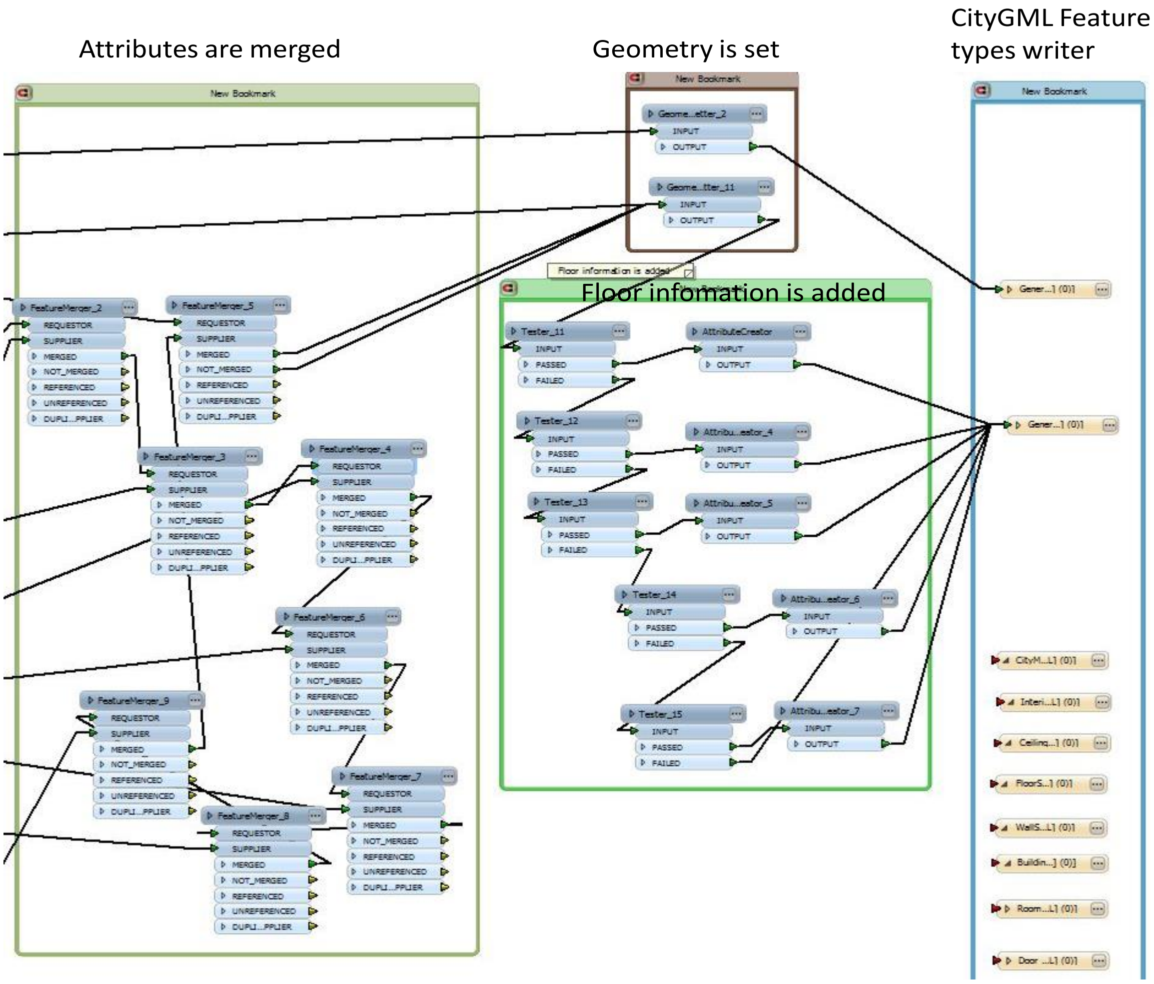

Fig. E.3 The FME Workbench to translate IndoorGML dataset into CityGML (Image continued from the previous page).

Appendix F

IndoorGML Database Schema

The IndoorGML database schema presented in figure F.1 is derived from the IndoorGML's core module. The author of this thesis contributed to this work as a member of team of a master's project that worked at the Technical University of Berlin. The new version of IndoorGML specification contains new modules (e.g., navigation), which are not included in this database schema.

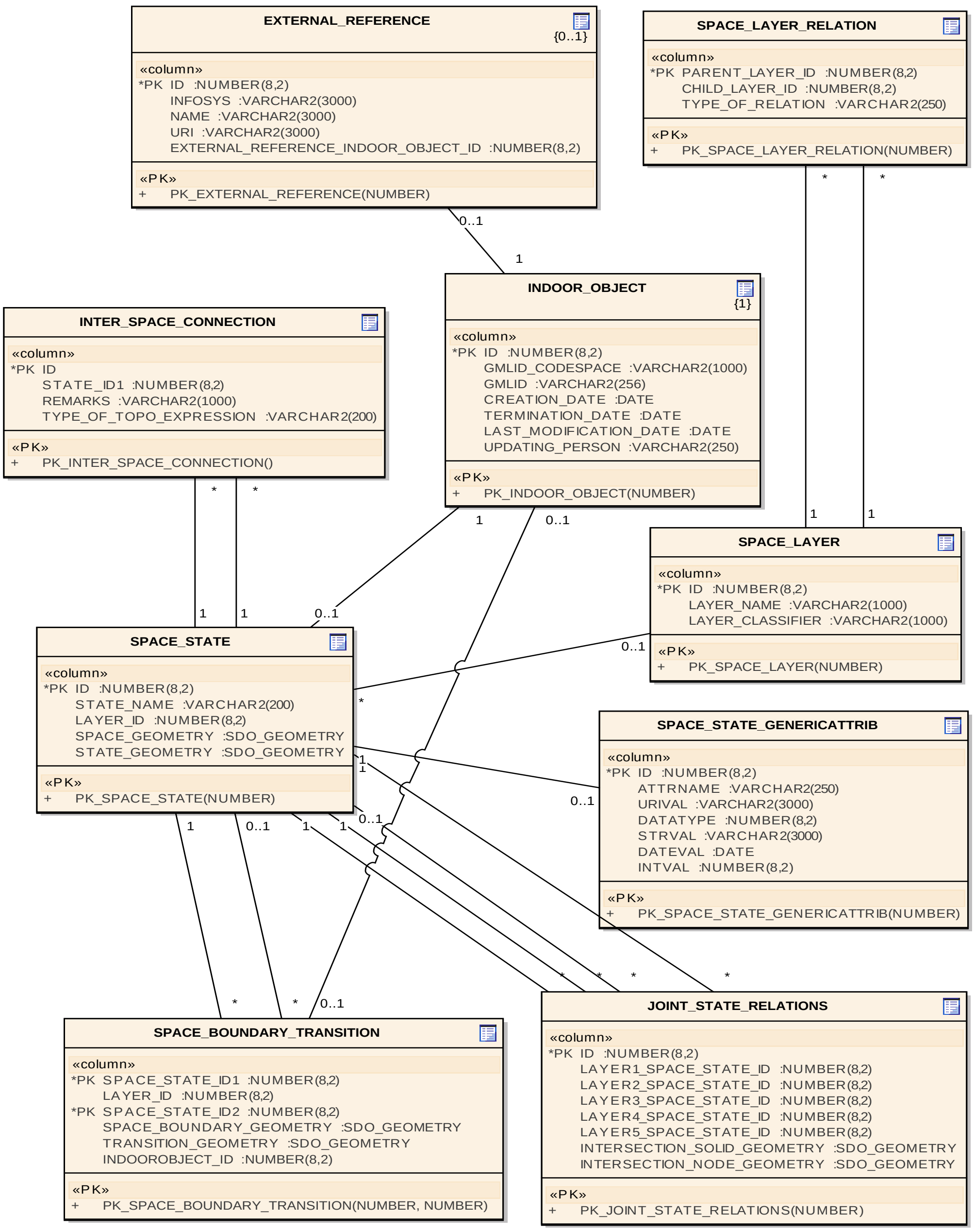

Fig. F.1 The IndoorGML database schema derived from the data model presented in (Becker et al., 2009b).

Appendix G

Subspacing using only Geometric 3-dimensional Building Models

The following work is some initial work to carry out subspacing using only geometric 3-dimensional building models.

A 3-dimensional point cloud model of a room is considered to explore the possibility for subspacing (method presented in chapter 4) using the geometric 3-dimensional building model as shown in figure G.1. To compute navigable subspaces according to different locomotion types for the considered geometric model, the process is divided into two steps. In the first step, the geometric model is enriched with semantic information based on the semantic, geometric, and topological information of the locomotion type by means of its conceptual constraint model. After the 3-dimensional geometric model is enriched with semantic information the navigable subspace for the specific locomotion type is computed.

The whole process is further divided into following steps.

1. Extracting the planes from geometric model and converted into 3-dimensional plane surfaces.

2. The 3-dimensional geometric model (containing plane surfaces) is converted into CityGML 3-dimensional building model to enrich with semantic information. In this conversion process the interpretation of geometric planes is done based on the spatial information of the locomotion type (through constraint model). For example, the constraint model of the walking person provides information about his navigating constraints which include he only walks on the *floorSurface* that should be less than 2 meters height. Based on this information the geometric model is enriched with semantic information that all the planes which are less than the height of 2 meters are *floorSurfaces*. Similarly, constraint model of locomotion type provides information that it can walk *beside wallSurfaces*, thus all the surface which are *beside* locomotion types are classified as *wallSurfaces*.

The interpretation of geometries is done in FME Werkbench based on the assumption that the constraint model information of the locomotion type is in author's pre-knowledge. The planes are detected through a Matlab program and then interpretation and writing of CityGML model is done with FME Werkbench. At the end, the procedure of subspacing is carried out as discussed in chapter 4. The realization of this approach on a simple (still incomplete) model is to demonstrate the method and highlight the direction of a research area that the subspacing indoor model for the 3-dimensional geometric model is possible but still need to be explored.

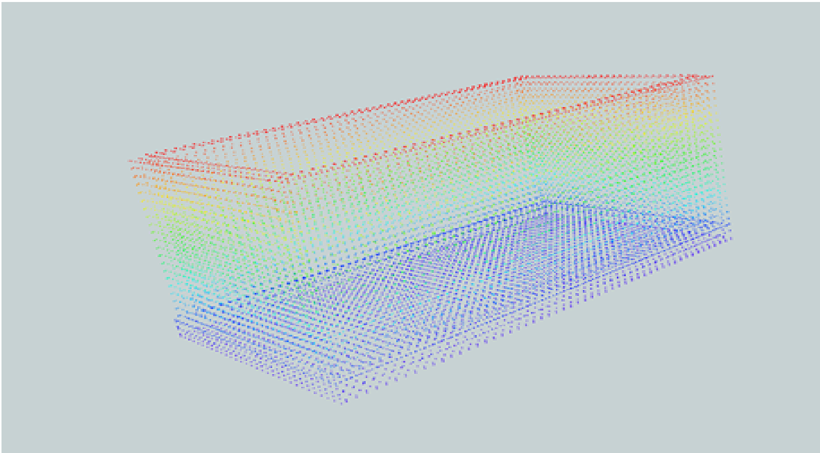

Fig. G.1 A simple 3-dimensional point cloud geometric model representing a room.

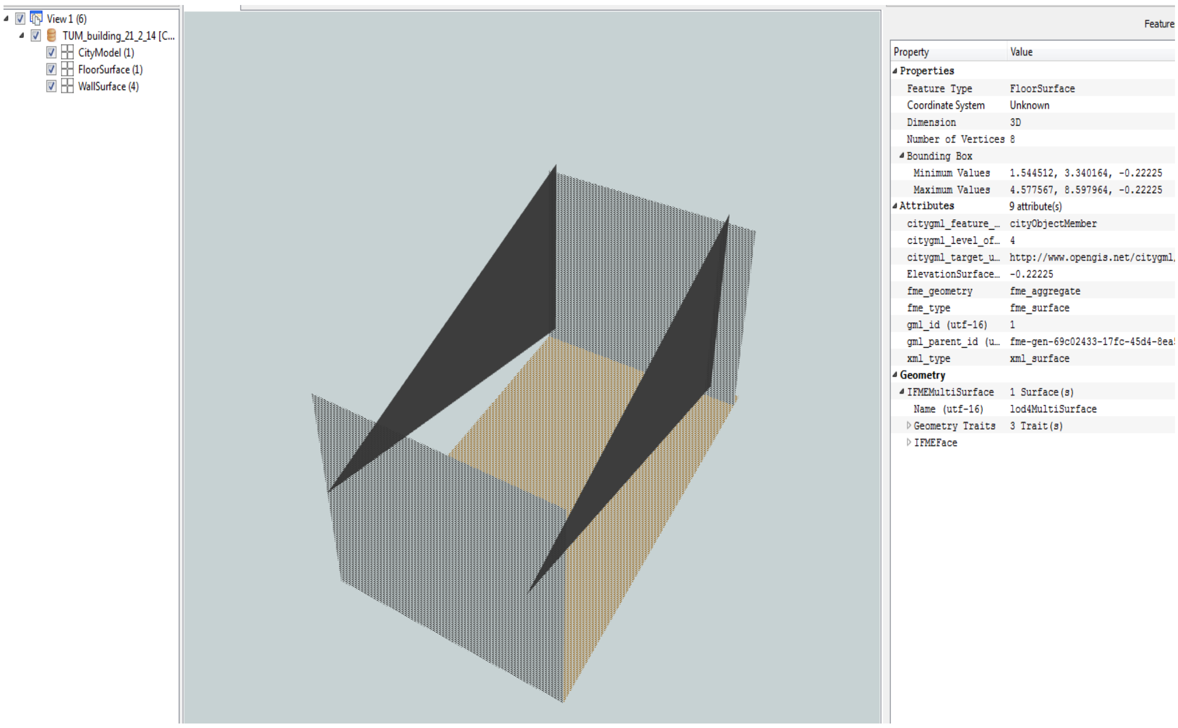

Fig. G.2 The 3-dimensional planes of room are converted into CityGML feature types (*floorSurface* and *wallSurfaces*). (The model is not complete as two *wallSurfaces* are not complete.)

Appendix H

Constraints of Locomotion Types

Some constraints examples presented in table 4.1 of driving locomotion type to determine its navigable subspace. Additional constraints of driving and other locomotion types are given in following tables. These constraints can be further extended based on unique situations.

H.1 Locomotion type: Driving (wheelchair)

Table H.1 Wheelchair's constraints.

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Height	1.5 meter	Fixed Constraint; Geometry Related Constraint	Height of passage must be greater than the height of the navigating body	Foundation Constraint	Height of navigational space
Width	1 meter	Fixed Constraint; Geometry Related Constraint	Width of passage must be greater than the width of the navigating body	Foundation Constraint	Width of navigational space
Length	1 meter	Fixed Constraint; Geometry Related Constraint	Length of passage must be greater than the length of the navigating body	Foundation Constraint	Length of navigational space
Position	On horizontal surface	Fixed Constraint; Capacity constraint	Passage must contain a horizontal surface to support the navigating body	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	Horizontal Floor Surface

Continued on next page

Table H.1 – *Continued from previous page*

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Maximum Speed	40 km/h	Fixed Constraint; Capacity Constraint	Speed must be less than the maximum speed of the navigating body	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	
Jump	1 meter	Fixed Constraint; Capacity Constraint	The navigating body can jump up-to height of 1 meter	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	
Cross Through	0.08 meter	Fixed Constraint; Capability Constraint	The navigating body can cross through a Glass which has less than 0.08 meter thickness or diameter.	Advanced Constraint: (note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position constraint need to be fulfilled)	Measurement of thickness of Glass
Status of Floor Surface	Slippy	Fixed Constraint: Status Constraint	The navigating body cannot navigate on slippery glass floor surface.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	FloorSurface

Continued on next page

Table H.1 – *Continued from previous page*

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Navigating Direction regarding WallSurface	Besides	Direction Constraint	The navigating body can navigate besides WallSurface as it cannot navigate on Wallsurface.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	WallSurface
PassOn	Glass Surface	PassOn Constraint	The navigating body cannot pass on glass surface.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	FloorSurface
Topology	Touch	Topology Geometry Related Constraint	The navigating body's ground surface must be always in touch with floor surface of navigating body's environment.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	FloorSurface

H.2 Locomotion type: Flying Vehicle (Unmanned Aerial Vehicle)

Table H.2 UAV's constraints.

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Volume	1.18 Cubic meter	Scale Geometry Related Constraint	The navigating body's volume must be less than the 3D indoor space cell volume	Foundation Constraint	Volume of navigational space
Position Landing	On a horizontal surface	Fixed Constraint; Capacity constraint	Landing space must contain a horizontal surface to support for the navigating body.	Advanced Constraint	Horizontal Surface
Maximum Speed	22 meters per second	Fixed Constraint; Capacity Constraint	Speed of navigating body must be less than 22 meter per second	Advanced Constraint	3D Space and speed of navigating body
Maximum ascent speed	5 meter per second	Fixed Constraint; Capacity Constraint	Ascent Speed of navigating body must be less than 5 m/s	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	3D Space and speed of navigating body
Maximum descent Speed	4 meter per second	Fixed Constraint; Capacity Constraint	Descent Speed of navigating body must be less than 4 m/s	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	3D Space and speed of navigating body

Continued on next page

Table H.2 – *Continued from previous page*

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Cross Through	Cannot cross through a glass	Fixed Constraint; Capacity Constraint	The navigating body cannot cross through a glass	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	Feature Type of entity
Status of Floor Surface in Landing Position	Normal floor surface	Fixed Constraint; Capacity Constraint	The navigating body can land on only normal surface. It cannot land on slippery surface.	Advanced Constraint: (note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position constraint need to be fulfilled)	FloorSurface
Navigating Direction regarding WallSurface	Besides	Direction Constraint	The navigating body can navigate besides WallSurface as it cannot navigate on Wallsurface.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	WallSurface
Navigating Topology regarding 3D space	Within	Topology Geometry related Constraint	The navigating body will navigate within 3D free space.	Foundation Space	3D Space

Continued on next page

Table H.2 – *Continued from previous page*

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Navigating Topology regarding Ceiling Surface	Below	Topology Geometry Related Constraint	The navigating body's ground surface must be always in touch with floor surface of navigating body's environment.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	Ceiling Surface

H.3 Locomotion type: Walking (walking person)

Table H.3 Walking person's constraints.

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Height	1.5 meter	Scale Geometry Related Constraint	Height of passage must be greater than the height of the navigating body	Foundation Constraint	Height of navigational space
Width	0.5 meter	Scale Geometry related Constraint	Width of passage must be greater than the Width of the navigating body	Foundation Constraint	Width of navigational space
Navigational direction regarding Floor Surface	Above	Direction Geometry related Constraint	Navigating body can navigate on FloorSurface	Advanced Constraint	FloorSurface
Navigational Direction regarding CeilingSurface	Below	Direction Geometry related Constraint	Navigating body can navigate below Ceiling Surface	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	Ceiling Surface

Continued on next page

Table H.3 – *Continued from previous page*

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Navigational Direction regarding WallSurface	Besides	Direction Geometry related Constraint	Navigating body can navigate besides WallSurface	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	WallSurface
Topology regarding free space	Within	Topology Geometry related Constraint	Navigating body must navigate within free 3D space	Advanced Constraint (note: before fulfilling this constraint there must be empty space to navigate for the navigating body)	3D Space
Topology regarding FloorSurface	Touch	Topology Geometry related Constraint	Navigating body must touch FloorSurface during navigation	Advanced Constraint: (note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position constraint need to be fulfilled)	FloorSurface
Navigating Direction regarding WallSurface	Touch	Topology Geometry related Constraint	The navigating body can touch WallSurface during navigation.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	WallSurface
PassOn	Glass Floor	Capability Constraint	Navigating body can navigate on Glass floor	Advanced Constraint	Feature type of FloorSurface

Continued on next page

Table H.3 – *Continued from previous page*

Attribute of navigating body	**Value**	**Constraint type**	**Requirement for the smooth passage of navigating body**	**Constraint type category**	**Entity of navigational space**
Cross Through	Free Space	Capability Constraint	Navigating body can cross through free space	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	Feature type (Status) of 3D space
Maneuver Type	Jump	Capability Constraint	Navigating body can jump up to height of 2 meters	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	
IndoorSpace Status	Normal	Status Constraint	Navigating body can only navigate in normal indoor space conditions. It cannot navigate in smoky conditions.	Advanced Constraint:(note: before fulfilling this constraint there must be empty space to navigate for the navigating body and also Position Constraint need to be fulfilled)	Status of 3D space
List of unconsidered feature types for navigation	Window, Ceiling-Surface, WallSurface	UnConsidered List Constraint	Navigating body cannot navigate through/ on windows, ceiling surfaces, and wallsurfaces.	Advanced Constraint	Feature type of indoor space entity

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