ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

BIM-GIS INTEGRATION FOCUSED ON INDOOR NAVIGATION: AUTOMATIC DERIVATION OF NAVIGATION NETWORK

M.Sc. THESIS

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Department of Civil Engineering

Geomatics Engineering Programme

DECEMBER 2019

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İÇ MEKAN NAVİGASYONU AMAÇLI BIM-GIS ENTEGRASYONU: OTOMATİK NAVİGASYON AĞI OLUŞTURULMASI

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To my family and friends,

FOREWORD

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ABBREVIATIONS

BIM **:** Building Information Modelling
FME **:** Feature Manipulation Engine
GIS **:** Geographical Information Systems
IFC **:** Industry Foundation Classes
GML **:** Geography Markup Language

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BIM-GIS INTEGRATION FOCUSED ON INDOOR NAVIGATION: AUTOMATIC DERIVATION OF NAVIGATION NETWORK

SUMMARY

Building Information Modelling is a most recent phenomenon, that has been embraced by the AEC industry as a convenient way to design a structure and manage the construction process. This phenomenon made a positive impact by providing comprehensive data to the side applications, such as indoor navigation. People spend quite a big portion of their lifetimes in indoor spaces. A significant amount of this time may be wasted in a complex building while trying to find a proper route to the destination. Therefore, conducting new approaches to enhance the way of finding a route in indoor spaces is an essential subject. To create an indoor navigation application, it is necessary to extract the indoor space connectivity graph. Extracting this network is straight forward when the process is manual. However, it is quite labor-intensive and time-consuming. Thus, developing a way to automatically extract this network can be an added value to indoor navigation requirements.

In this thesis; the process of network derivation from an Industry Foundation Class (IFC) file of a building has been examined and attempts for creating a generic data pipeline from building model to the indoor spatial space network have been conducted. The Building Information Model of Istanbul Technical University Civil Engineering Faculty has been used as a test building for this purpose. After various geometrical manipulations within FME, six different networks have been obtained from this model. The derived networks have been compared with each other in terms of several aspects such as reliability, performance and efforts to generate. Finally, Medial Axis Transform (MAT) On Unified Polygon Network was chosen to be used in a prototype application that has been developed in a 3D GIS environment with the capability of creating route plans according to user profiles. For the application layer, Cesium JS has been used and all necessary data has been brought to the Cesium environment. With this manner, BIM – GIS integration has been successfully established.

İÇ MEKAN NAVİGASYONU AMAÇLI BIM-GIS ENTEGRASYONU: OTOMATİK NAVİGASYON AĞI OLUŞTURULMASI

ÖZET

Yapı bilgi modellemesi, bir yapının akılcı ve bütüncül bir şekilde tasarlanmasını ve yapım sürecinin iyi bir şekilde yönetilmesini sağlayan, en yeni metodoloji olarak karşımıza çıkmaktadır. Bu metodolojinin sağladığı geniş çaplı dijital veri sayesinde, iç mekan navigasyonu gibi yan uygulamalara da önemli bir altlık oluşturulmuştur. İnsan yaşamının büyük bir kısmını iç mekanlarda geçirmektedir. Özellikle kompleks iç mekanlarda harcanan bu zamanda, yön bulmaya çalışırken ciddi zaman kayıpları oluşmaktadır. Bu nedenle, kompleks yapılar için, iç mekan navigasyonunun yaygın hale gelmesi günümüzde bir ihtiyaç haline gelmiştir. Bir iç mekan navigasyon sistemi yaratmak için öncelikle yapının odaları arasındaki bağlantı ağı çıkartılmalıdır. Bu bilginin manuel olarak çıkartılması uygulama prosedürü bakımından basit olmasına rağmen, iş gücü gerektiren ve oldukça zaman alan bir işlemdir. Bu bağlamda, bu işlemin otomatikleştirilmesi önemli bir katkı sağlayacaktır.

Bu araştırmada; İstanbul Teknik Üniversitesi İnşaat Mühendisliği Fakültesi Yapı Bilgi Modeline ait "Industry Foundation Classes" (IFC) dosyasından, iç mekan navigasyon ağı çıkartılması için kapsamlı olarak kullanılabilecek yöntemler incelenmiştir. İlk olarak Revit yazılımı bünyesinde mevcut bina modelinin, üzerinde çalışılabilecek bir IFC dosyası oluşturulmuştur. Bu anlamda, mevcut bina modelinin birtakım eksiklikleri yine Revit yazılımı kullanılarak giderilmiştir. Bina içerisindeki tüm odalar tanımlanmış ve odaları oluşturan duvarların kapalı birer alan oluşturduğundan emin olunmuştur. Revit'ten çıkartılan bu IFC dosyası "Feature Manipulation Engine" (FME) yazılımında girdi olarak kullanılmıştır. FME bünyesinde uygulanan çeşitli geometrik manipülasyonlar sonucunda, altı adet navigasyon ağı oluşturulmuştur. Bu geometrik manipülasyonların daha kolay bir şekilde uygulanabilmesi adına öncelikle, bina içi odalar üç boyutlu hacimsel verilerden iki boyutlu poligonlara dönüştürülmüştür. Yani, her iki kata ait iki boyutlu kat planı elde edilmiştir. Ardından bu iki boyutlu kat planları "Medial Axis Transform" (MAT) algoritması ve "Grid" sistem olarak iki ana yaklaşım etrafında çeşitli işlemlere tabi tutularak navigasyon ağları elde edilmiştir.

"Medial Axis Transform" algoritması bir poligonun orta eksen çizgisini çıkartmak için kullanılan bir geometrik algoritmadır ve bu çalışma dahilinde iç mekan navigasyon ağını çıkartmak için oldukça elverişli bir yöntem olarak seçilmiştir. Çıkartılan altı adet navigasyon ağından üç tanesi bu algoritmanın bir ürünüdür. Bu üç navigasyon ağından birinde noktalar arasındaki bağlantıyı düzgün bir şekilde kurabilmek için ayrıca FME dahilinde çalışan bir Python programı da yer almaktadır. Bu python programı odalar arası hiyerarşiyi kurarak noktaların doğru bir şekilde bağlanmasını sağlamıştır. Bir diğer MAT navigasyon ağında ise tüm poligonlar tek bir poligon haline getirilerek bu özel poligon üzerinde MAT algoritması uygulanmıştır ve navigasyon ağı elde edilmiştir. Son olarak bir diğer MAT

algoritması kullanılan yaklaşımda, sadece gerekli olan odalara, yani birden fazla kapısı olan odalara MAT algoritması uygulanarak daha elverişli bir navigasyon ağı ortaya çıkarılmıştır.

Grid sistemde ise poligonlar belli genişlikteki alanlara bölünür ve her bir alanın kenarları ve düğüm noktaları navigasyon ağını oluşturur. Grid yöntemi baz alan iki adet navigasyon ağı çıkartılmıştır. Bunlardan ilki, kare ve üçgenlerin kombinasyonu ile oluşturulmuştur. Diğer grid yaklaşımda ise alanlar, hexagon yani altıgen şeklinde gridlere bölünmüştür.

Son olarak Grid ve MAT algoritmasının bir arada kullanıldığı hibrit bir navigasyon ağı oluşturulmuştur. Bu yaklaşımda ise geniş alanlarda grid, dar alanlarda MAT algoritması uygulanarak her iki yaklaşımın avantajlarından faydalanılmaya çalışılmıştır.

Oluşturulan bu navigasyon ağları, mesafe hassasiyeti, indoorGML dosya boyutu, FME içerisinde kullanılan modül sayısı ve yine FME programı dahilinde oluşturulma süreleri açısından karşılaştırmaya sokulmuştur ve prototip uygulama için kullanılabilecek en uygun navigasyon ağı seçilmiştir.

Mesafe hassasiyetlerini ölçmek amacıyla her bir navigasyon ağı için aynı iki nokta kullanılarak en kısa rota oluşturulmuştur. Oluşturulan bu rotaların uzunluğu, bir insanın yürüyerek kat edeceği gerçek mesafe ile karşılaştırılmıştır.

Bu karşılaştırmaya ek olarak, navigasyon ağlarının veri boyutları da önem arz ettiği için her bir navigasyon ağının indoorGML dosyaları oluşturularak bu indoorGML dosyalarının boyutları da değerlendirilmeye sokulmuştur.

FME kapsamında uygulanan çözümlerde kullanılan modül sayısı özellikle bir navigasyon ağının elde edilmesinde harcanan eforu özetlediği için önemli bir belirleyici unsur olmaktadır.

Son olarak FME dahilinde her bir navigasyon ağının oluşturulma süreleri karşılaştırılmıştır. Bu değerlendirmede aynı bilgisayar kullanılmış olup, navigasyon ağlarını oluşturmak için bilgisayar tarafından uygulanması gereken işlem hacmini görmek amaçlanmıştır.

Tüm bu değerlendirmeler dahilinde seçilen navigasyon ağı, “Cesium JS” Javascript kütüphanesi ile oluşturulan uygulamada kullanılmıştır. Uygulamanın web üzerinden tarayıcı aracılığıyla kullanıcıya ulaşabilen ve üç boyutlu veri ile çalışabilen bir kütüphane olması Cesium JS in seçilmesinde önemli nedenler arasındadır. Cesium JS ortamına bina modeli, seçilmiş navigasyon ağı ve oda bilgileri aktarılmıştır. Bu bilgiler Python programlama dilinde “Pyramid” web kütüphanesi kullanılarak geliştirilen bir web sunucuya yapılan HTTP istekleri ile aktarılmaktadır. Oda bilgileri ve navigasyon ağı FME aracılığıyla direkt olarak çalışma bağlamında kullanılan PostGIS veri tabanına kaydedilerek, Cesium’dan web sunucusuna yapılan HTTP isteği sonucunda veri tabanından sorgulanarak Cesium’a aktarılmaktadır. Bina modeli direkt olarak Cesium ortamına alınamadığı için, IFC dosyası aracılığıyla, “3D Tiles” formatına dönüştürülmüştür. Son olarak, seçilen iki oda arasındaki en kısa yol PostGIS içerisinde çalışan “Pgrouting” yazılımı aracılığıyla “Dijkstra” algoritması kullanılarak oluşturulup, Cesium JS içerisinde çizdirilmektedir. Uygulamada ayrıca kullanıcı profiline göre rota planlama değişimlerini göstermek amacıyla örnek olarak bir tekerlekli sandalye kullanıcısı için farklı rota hesaplanması durumu gösterilmiştir.

Bu çalışmanın daha geniş anlamda bir diğer amacı ise BIM-GIS entegrasyonuna örnek sağlamaktır. BIM ve GIS endüstri içerisinde yaygın olarak benimsenmiş olgulardır. Farklı kullanım alanları olan bu iki olgu arasında karşılıklı bir ilişki sağlanması durumunda, her iki tarafın açıkları kapatılarak daha elverişli uygulamalar geliştirilebilmektedir. BIM-GIS entegrasyonuna dair detaylı bir literatür taraması da yapılmış olup çalışmada çeşitli kullanım alanları belirtilmiştir. Ayrıca iç mekan navigasyonu özelinde kullanım alanları ve getirdiği çözümler de özetlenmiştir. Çalışma başlangıcında tezin amacını daha iyi lanse etmek üzere çeşitli araştırma soruları sorulmuş olup bu sorular tezin sonunda cevaplanmıştır.

1. INTRODUCTION

1.1 Statement of the Problem

In a growing modern society, people spend a large portion of their life in indoor spaces. According to a survey by Neil Edward Klepeis and Wayne Ott (2001) this portion is 87% on average in the United States of America. Contrary to this, a large portion of sources in the geospatial industry is used for outdoor applications, especially in outdoor positioning. The big progress of outdoor positioning technologies developed in the last decades and the necessity for indoor navigation applications is growing in different fields. As the intense urbanization growing expeditiously, the necessity of applications and solutions for indoor spaces in the GIS community going to increase in the next several years. (Diakité et al. 2017) United Nations estimating that 66% of the world's population is going to be urban in 2050. (Nations, 2014) This might lead to the construction of more and more complex buildings in the future.

Airports, train stations, hospitals, shopping malls are instances of complex buildings. Their ultimate aim is to provide service to the people. Finding a route inside these kinds of complex buildings could be a tedious and time-consuming experience. Especially, if you are unfamiliar with the building. To avoid this, wayfinding signs have been used to provide information about where a certain room or space located in the building. However, signs are not explanatory enough every time. There are examples; signs in buildings providing vague information by pointing ambiguous directions and creating confusion. This leads to inefficiency. Moreover, the functionality of a room can be changed at a point in time and results in invalid information. In this case, signs must be changed accordingly to provide the correct information. This process can be even more overwhelming if the functionality of a room is changing periodically. With an indoor navigation application, a lot more value can be created over this method. As it is digital, any change can be modified easily through the application and the information stay valid.

In a facility, there may certain sections that can only be accessed with granted authorization. With an indoor navigation system, it is possible to guide a user and generate a route, according to their granted authorization. This is also applicable to an impaired user of an indoor navigation system. According to the profile of a user, a route can be generated through an elevator instead of stairs. Another aspect can be time-dependent route generation. Ascertain parts of the structure could only be accessed within a period in a day, the route generation can be blocked for certain parts of the building between certain times. As a result, an indoor navigation system can generate optimized routes depends on parameters.

In the definition of an indoor navigation system, a user needs to be located inside of a building and routed to the best way as desired. To be routed properly, the navigation network of a building has to be generated. This network is based on graph theory and it contains the connectivity information of the indoor spaces. Building Information Modelling provided us to combine all information in the model technically and semantically to generate useful information such as a connectivity graph of spaces. This information can be used to automatically generate the navigation network of the building. In this manner, the time consumption and labor can be decreased.

1.2 Thesis Objectives

There are two objectives of this thesis. In a broader aspect, one of the objectives is to create an integration example of BIM and GIS technology in the subject of indoor navigation. More specifically, the second objective is automatic extraction of indoor navigation network. Thus, the methods of extracting the space connectivity information from the IFC file of a building and automatically generate the indoor navigation network by using this information are examined.

The objectives emerged below questions that might be an inquiry at the start point of this study. These questions also provide a better indication and description of the thesis objectives. In below, the most essential questions have been asked and they will be answered throughout the thesis:

- What kind of BIM-GIS integration use cases are available in the literature and where indoor navigation states in this list?
- What are the indoor navigation application areas?

- What kind of algorithms can be used to derive the indoor space connectivity network as geometrical operations?
- What kind of opportunities does the IFC file provide to generate an indoor navigation network?
- How reasonable to use Feature Manipulation Engine (FME) to derive the indoor navigation network of a building?
- What kind of operations should be done in a BIM environment before exporting the IFC file from a BIM model?
- What kind of operations and manipulations could be done to make the navigation network reliable?
- What are the positive and negative parts of indoor navigation applications in three-dimensional space?

1.3 Thesis Outline

In Chapter II, the BIM, GIS and CAD phenomenon, the integration use cases of BIM & GIS and finally indoor navigation application areas are introduced with a literature review. In Chapter III, the data and methodology are explained. Then in Chapter IV, the implementation of indoor navigation application processed and described in detail. Finally, in Chapter V, the study has been concluded with remarks that are indicated in the beginning.

2. RELATED WORK

2.1 The Relation of CAD, BIM and GIS

Architecture Engineering Construction (AEC) industry has advanced with CAD (Computer-Aided Design) for several years. However, in time, construction projects have become so large and complex that CAD was not qualified to manage and design them efficiently. Due to the difficulty of following the revisions and manual work, Building Information Modelling has emerged for better handling with complex and greater projects. "Building information modeling (BIM) is a set of interacting policies, processes, and technologies that generates 'a methodology to manage the essential building design and project data in digital format throughout the building's life cycle". (Wang et al. 2013, p. 37) BIM is a substantial way to design a building or facility. However, it is inadequate in terms of integration with the surroundings. As Zhu et al. (2018) stated; "Due to the limited extent of buildings, the spatial scope of BIM is relatively small, and a local planar coordinate system (Cartesian coordinate system) is usually adopted." (p. 3) At this point, GIS is essential to understand the surroundings of a building in the real world, which could affect the design. From the spatial aspect, it is obvious that if GIS and BIM can be integrated, the design will become more productive and sustainable accordingly. Karan et al. (2016) supported this idea in their work:

> "BIM-GIS integration indicates the presence of a gap in analyzing and processing spatial data within a BIM system, it also indicates the potential value of an integrated BIM-GIS model that can be used to enhance the current practice of data sharing between the tools used in the procurement and construction processes. (p. 1)."

2.2 BIM and GIS Integration Use Cases

There are plenty of related works in BIM-GIS integration so far and it is in increasing trend. Figure 2.1 shows the citations regarding the BIM-GIS integrations from 2009 to 2017. Taken from Zhu et al. (2018) work.

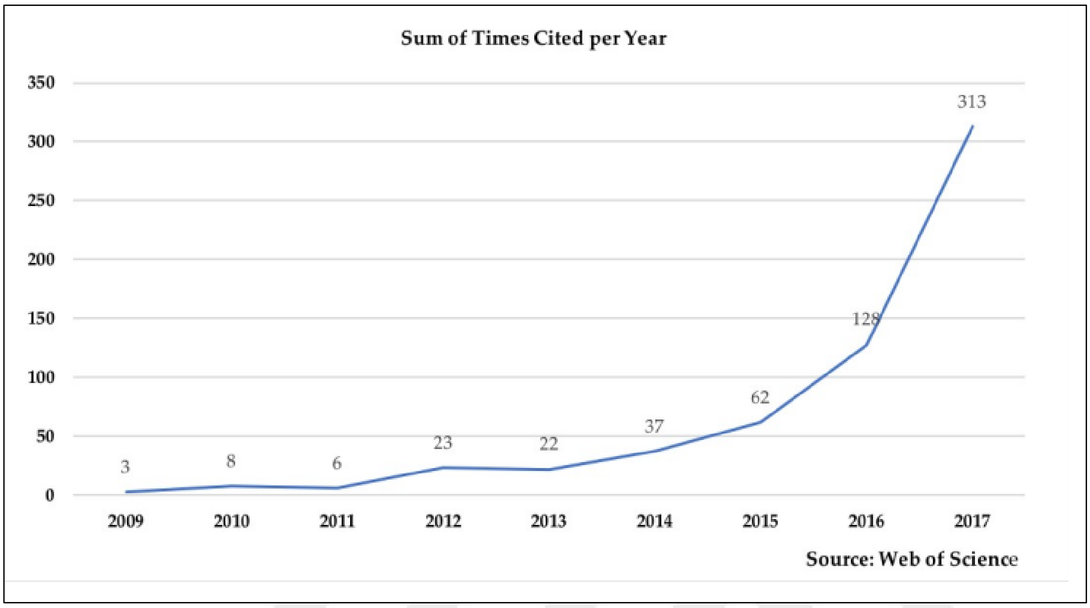

Figure 2.1 : Sum of times cited per year (Zhu et al. 2018).

Also, Song et al. (2017) have published a paper that involves deeply researched information about the related work in BIM-GIS integration from the application aspect.

Isikdag et al. (2008) proposed a site selection and fire management method with integrating BIM and GIS. Site selection for a building could be done effectively with the integration of two systems. BIM has been used for geometry and GIS has been used to find the proper site for that building's characteristics. The research also explains how fire management could be done with the integration of BIM into the GIS environment. While fire brigade approaching to the burning building, a second team in command center can get information about the building and its geospatial environment like; where is the main entrance of building and how to reach there in road network or directs the fire brigade personnel by informing them about the opening directions of doors or materials of building elements.

Irizarry et al. (2013) implemented a construction supply chain management method by integrating two systems. Supply chain management is a process that every construction needs to perform effectively to save money and time. BIM provides rich semantic information about construction materials. Besides, the construction schedule can be integrated with BIM. Combining this information with GIS makes it possible to find a proper manufacturer nearby, ordering supplies at the right time and monitoring the status of materials and inventory.

Another trending topic of BIM-GIS integration is indoor navigation. While BIM provides the geometry of navigable space and space semantics, GIS provides the navigation through, creating a network between rooms and spaces by defining nodes and edges. Some research focused on generating the network topology model of a building automatically from BIM data with GIS techniques. (W.Y. Lin et al., 2017) This is highly time-consuming and needs a lot of labor when the process is manual. Besides the geometric approach, Pereira et al. (2015) proposed an indoor navigation system adapted to users with motor disabilities. Another approach is combining indoor/outdoor which is effective in path planning on large campuses. (Teo and Cho 2016) Moreover, Tashakkori et al. (2015) implemented an indoor/outdoor spatial model for indoor emergency.

As can be seen from Figure 2.2; Song et al. (2017) developed a table of BIM-GIS integration studies ranging from 2008 to 2017 in different application areas. These application areas include; site selection, supply chain management, 3D cities, indoor navigation.

2.3 Indoor Navigation Application Areas

Indoor navigation is mainly using for positioning and navigation. However, it is not limited to that and there are many branches wrapped around this phenomenon. Chow et al. (2018) summarized some examples about the necessity of indoor navigation other than finding a route in the indoor environment, which includes;

1. Finding the nearest exit during emergency events by taking into consideration the obstacles on the ground,
2. Continuous georeferencing both in outdoor and indoor environments to receive seamless location-based information,

Application Object		Building				City
Construction Phase		Planning and Design	Construction	Operation and Maintenance	Demolition	
Year	2008	Site selection [72].		Fire response [72]; Web service [73]; Disaster scenarios [73].		3D city [99].
	2009	Climate adaptation [24].				Urban renewal projects [110].
	2010		Urban renewal projects [82].			Urban facility management [28,102] (e.g., road maintenance [111]); urban design [112].
	2011	Construction safety planning [85]; construction space planning [113].	Visualization of construction time control [114].	Existing buildings maintenance [83].		
	2012		Highway construction management [115].	Emergency response [61].		Urban crisis response [103]; human activity and land use [116].
	2013	Site selection of solar panels [84].	Visualization of construction supply chain management (CSCM) [15].	Indoor navigation [92]; heritage protection [93].		Urban representation [100,101].
	2014			Fire simulation and response [74]; heritage protection [94]; large building operation [98].		Urban facility management [117] (e.g., traffic planning [104]).
	2015	Building design and preconstruction operations [86,87]; building energy design [89,90].		Facility management [118]; indoor emergency response [75]; heritage protection [95,96].	Construction waste processing [119].	Tunnel modelling [120]; energy assessment and management [107–109]; district modelling [121].
	2016	Building design [88].	Urban renewal projects [122].	Flood damage assessment and visualization [76–78]; indoor emergency response and route planning [16–18]; hazard identification and prevention [79–81]; heritage protection [22,23]; ecological assessment [25].		Traffic noise analysis [105]; walkability evaluation of urban routes [106]; energy assessment and management [19–21]; utility compliance checking [123].
	2017	Lift planning of disassembling offshore oil and gas platform [91].	Resilient construction supply chain management (CSCM) [97].	Management of property interests [124].		Energy assessment and management [10].

Figure 2.2 : BIM-GIS integration use cases by the years (Song et al. 2017).

3. Tracking people and goods for surveillance purposes,
4. Monitoring the customer's behaviors to determine better marketing strategies,
5. Assisting people with disabilities.

Indoor navigation systems can be implemented to any buildings; moreover, it is beneficial and reasonable to be implemented in such facilities given below;

- Shopping Malls
- Transport Infrastructures: such as airports, ports, underground stations etc.
- Industrial buildings & Factories
- Hospitals
- Trade fairs & Congresses
- Campuses

In the marketing industry, customer behaviors play an active role to determine marketing strategies. In a large store, implementation of indoor navigation/tracking system monitoring the customers could assist gathering information about customer behaviors. For example, questions like 'How much time a customer spends to investigate a specific product?' or 'Which part of the store is most attractive according to navigation traffic?' can be answered and these kinds of analytical information can allow decision-makers to arrange better store layout or product design (Yaeli et al. 2014, p. 3).

Furthermore, indoor navigation can be used efficiently in transportation infrastructures, such as train stations, airports or coach stations. These kinds of buildings have many partitions and it could be difficult to find your way even there are signs around the environment. Also, too much time is being wasted while trying to find the exact gates or platforms (Czogalla 2015, p. 233).

Indoor navigation can be implemented in temporary fairs or congresses to make customers get to know the place quickly.

Moreover, hospitals are very good examples of indoor navigation applications. Visitors can use an application with their smartphones to find services or staff for their patients. Hospital management can track moveable important devices or personnel in hospitals and decide quickly what to do when something urgent happened (Yang et al. 2015).

Besides only navigating people in the building, indoor navigation can also be used to achieve a specific process in a building. An application can track your movements and lead you systematically to where you should go in order to fulfill that process. For example, an application can be developed for a university to support newcomer student's enrollment process by leading them in the application with seamless indoor/outdoor combined navigation.

There still exists several challenges that has to be solved in such applications. One of them is geo-localization which should be performed to produce valuable information. Usually, the wireless network of the building is being used for calculation of location in the building. Although, it is a straight forward process, there are plenty of problems to be solved to calculate the user's location precisely. Typically, there is more than one wireless network in the building which creates conflictions and causing errors in calculation. (Tisler, 2017) Another challenge to establish an indoor navigation application is generating the space connectivity network of the building. If there is no digital model, this may require survey from the building which makes it even more time-consuming and labor-intensive.

2.4 Industry Foundation Classes (IFC)

Industry Foundation Classes is a data model developed by buildingSMART to support working collaboratively for all departments and disciplines in the Architecture, Engineering and Construction industry. It yields to exchange designs between departments in efficient and optimized way. The IFC specification is registered by International Organization for Standardization (ISO) in ISO 16739-1:2018. It is more than a 3D model, which is also using for facilitating the construction process from beginning to end. It provides an in-detail information model of the building in a lightweight file. Basically, the IFC schema provides the standardization of the building in terms of several aspects. The identity and semantic features of the building, its characteristic, the relationships between entities can be defined and even abstract concepts like performance or costs can be included. Beside the design, it is also possible to define the process and people in the concept of the IFC schema (Building Smart, 2019).

In AEC (Architecture Engineering Construction) industry, it is a important to have a well-organized interoperability between disciplines. It is always a challenge and not an easy task to fulfil. One of the ideas behind IFC is creating a common ground for every different software that has been used as a design tool in the industry.

3. DATA AND METHODOLOGY

3.1 Data

The data that has been used for this study is one of the blocks of the Istanbul Technical University Civil Engineering Faculty Building. This data consists of two different elements, which are:

- Revit file of the building
- Point cloud data of corridor of the building

This data has been collected under the study of Akin et al. (2018) According to the study, a 3D point cloud of the building's inner space has been collected by 3D scanners in 2016 and the building model has been created by 2D drawings from 2006 as Revit file. The purpose of the study is recognizing the changes in the building among the years by comparing the building model and point cloud with the help of a software algorithm that is developed within the study.

3.2 Methodology

As the data has been examined and recognized, the necessary processes to fulfill our goal is defined and divided into four parts in terms of this study:

1. Validation and fusion of the data
2. Exporting reliable IFC file from the BIM model
3. Transformations and operations on IFC file using FME to derive the indoor network
4. Implementation of a prototype indoor navigation application in 3D GIS with the capability of route generation according to a user profile.

These steps can be seen in Figure 3.2, as ordered sections of BIM, IFC, FME and GIS which are explained in the following lines in detail.

First, valid BIM data has been ensured by utilizing the fusion of all the data. To do this, the Revit 2018 software has been used. Revit is one of the Autodesk software family members and it has been using for especially within BIM oriented projects. Revit handles the objects in a parametric approach, which provides a convenient way rather than using just vector graphics. This is a typical feature of BIM software. (Autodesk 2018) The Revit file of the building was partly missing and to complete this BIM model, the point cloud data has been superposed with BIM model and in this manner, the Revit model of the building has been completed manually.

Secondly, it is investigated what kind of information is needed to be focused while exporting the IFC file from Revit, which can be used for space network extraction. Exporting an IFC file is an essential process in order to get reliable data to process for indoor navigation.

Third part consist of approaches for extracting space network geometry with various algorithms within FME software. FME stands for Feature Manipulation Engine and it is a tool to provide ETL (Extract, Transfer, Load) operations on the data. (Safe 2019) FME works as a pipeline creation tool to convert certain data type into another.

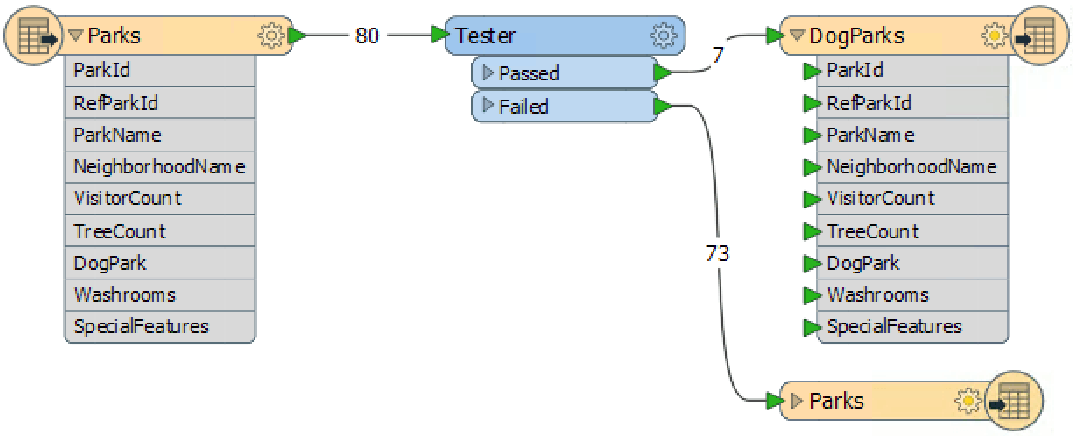

Figure 3.1 : FME workspace example.

In Figure 3.1, it can be seen the basic FME workspace, consist of one reader, one transformer and two writers. In the example; “Dog Parks” are extracted from the “Parks” data with the “Tester” transformer according to some condition.

The IFC file has been examined with FME software and comparison between different methods and approaches to populate the nodes and edges of the network has been conducted. Additionally, it is investigated what kind of processes can be done to make the network more reliable and rational. In the end of this section a proper network has been chosen to be used in the GIS section.

For the last part, a prototype of indoor navigation application has been created with capability of generating routes according to user profile. For this purpose, Cesium JS has been used. Cesium JS is a powerful JavaScript library for creating custom applications in 3D environment with several visualization possibilities of data (Cesium JS, 2019). In other words, it can be considered as 3D GIS environment as it is indicated in the GIS section of the Figure 3.2.

Finally, the questions that have been asked in the introduction part have been discussed according to experiences.

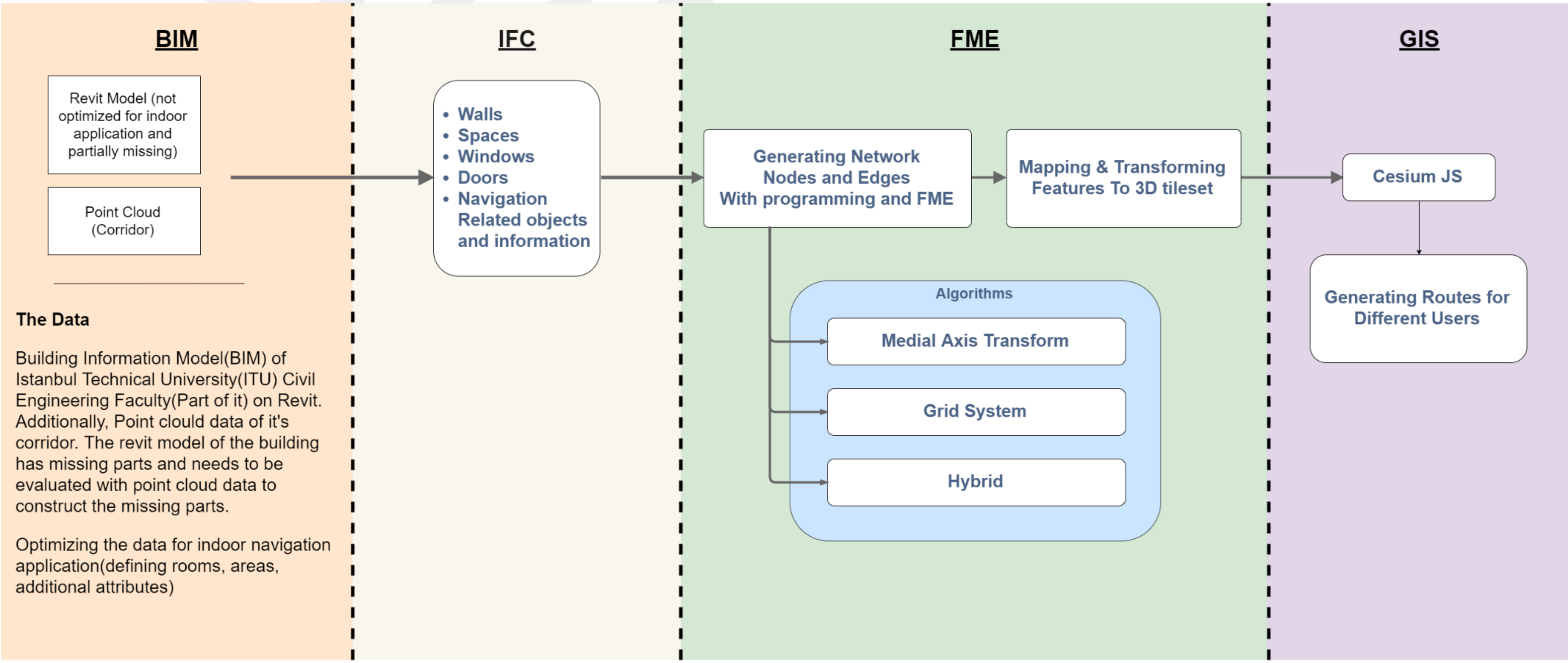

Figure 3.2 : The workflow of the thesis.

4. IMPLEMENTATION

4.1 Completing the Revit Model

As mentioned in the BIM section of Figure 3.2, the Revit model of the building had some missing parts and needed to be completed before further processes. The observations on the data showed that the missing parts of the building can be completed by superposing the point cloud data of the corridor. In the Revit model, the corridor of the building was mostly missing so the point cloud data was a great complement on that subject. Since point cloud data is superposed with the building model, further steps are straight forward, where the missing elements of the building could be detected (Figure 4.1).

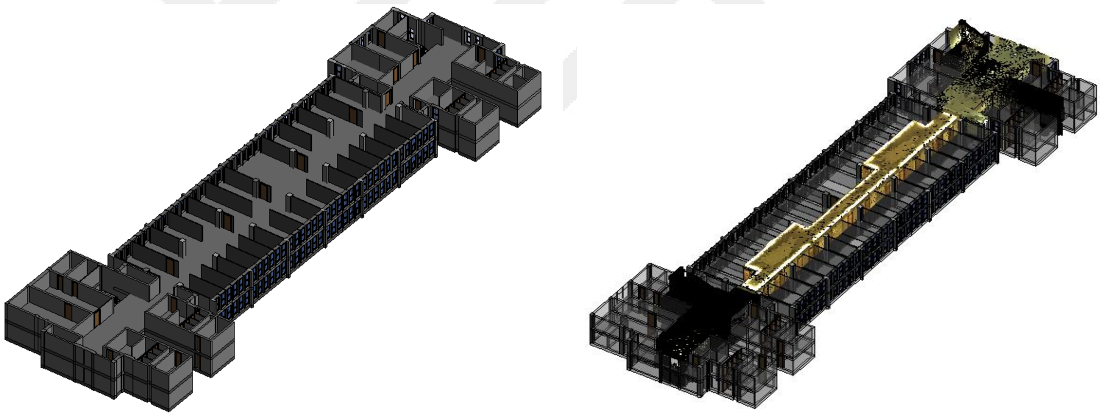

Figure 4.1 : Revit model of ITU (Left), superposed with point cloud data (Right).

As can be seen in Figure 4.2 wall elements have been placed with support of point cloud data. This was necessary to define the rooms, as they need a closed area to be defined. After placing the walls and doors, room spaces have been defined. (Figure 4.3) Space (room) definition functionality of Revit is smart enough to automatically detecting the closed boundaries of a space, which made the process quicker.

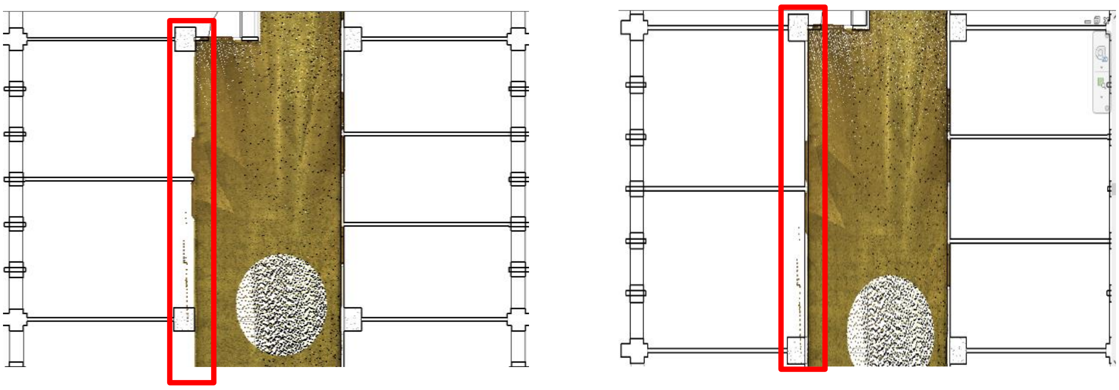

Figure 4.2 : Creating wall objects according to point cloud data.

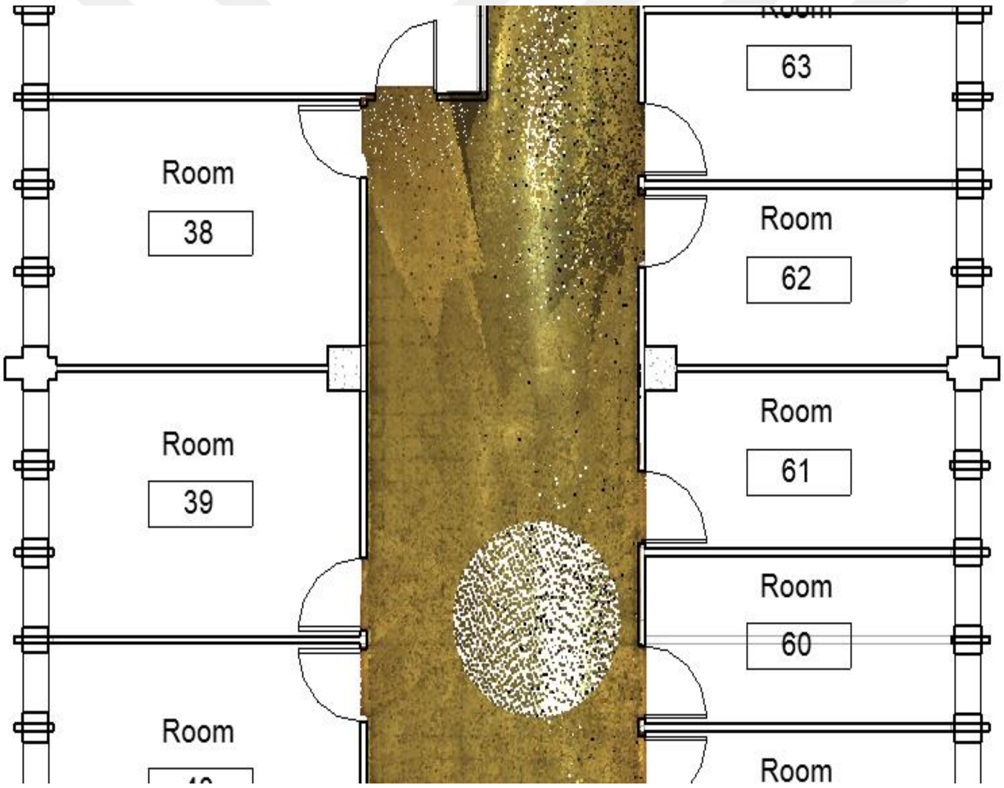

Figure 4.3 : Completed Revit model.

4.2 Exporting the IFC File From Revit

Exporting the IFC file from Revit Software requires some configuration to make the IFC file useful for indoor navigation network extraction. First, all spaces must be defined and properly named, the areas must be drawn and geometrically closed.

In Revit 2018, the IFC export tool (Figure 4.4) provides some configurations to adjust the IFC file. One of the important parts is the “Space boundaries” option. Boyes et al. (2015) mentioned in their study about space boundaries. The first level represents the space boundaries of the room and the second level represents the boundaries of the object behind the room. The visual explanation is in Figure 4.5.

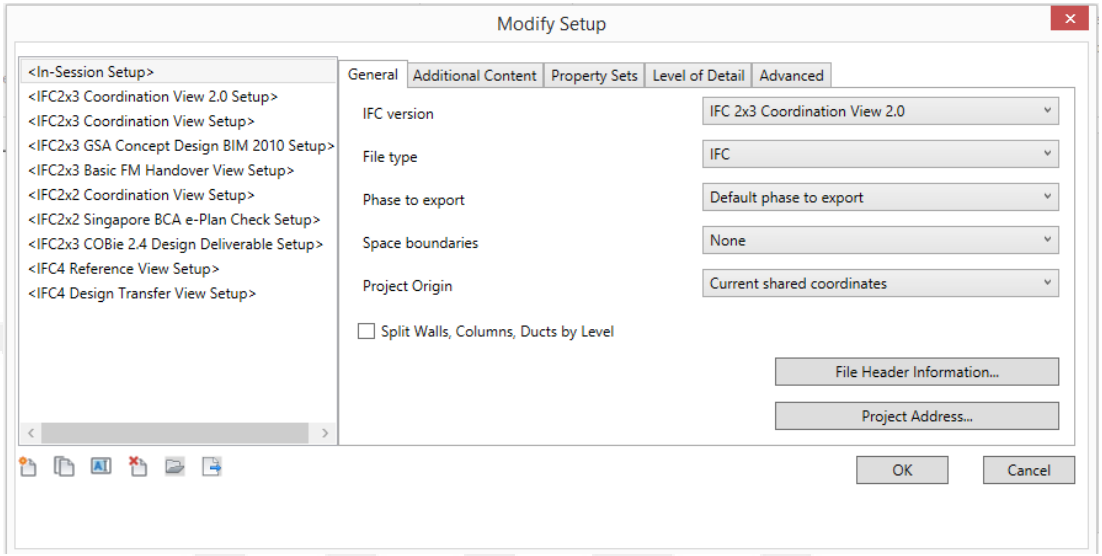

Figure 4.4 : Ifc export tool.

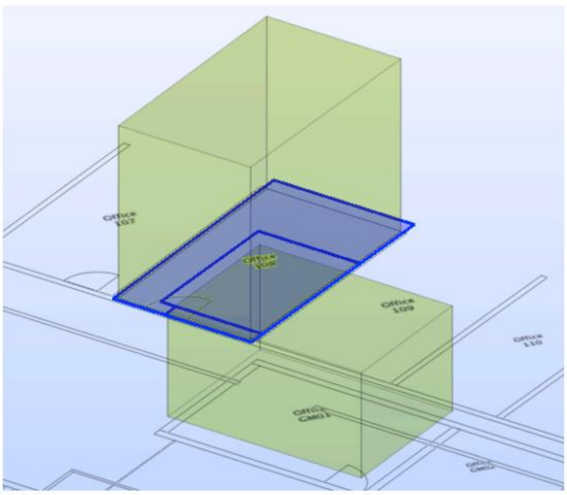

Figure 4.5 : Space boundary representation (Boyes et al., 2015).

As the attempt is for getting valuable information for indoor navigation, it is necessary to export the door’s opening spaces. Thus, the 2D Plan-view elements should be exported accordingly (Figure 4.6). This configuration will bring the opening spaces of doors, which is going to be valuable in order to get the information about the door exact location.

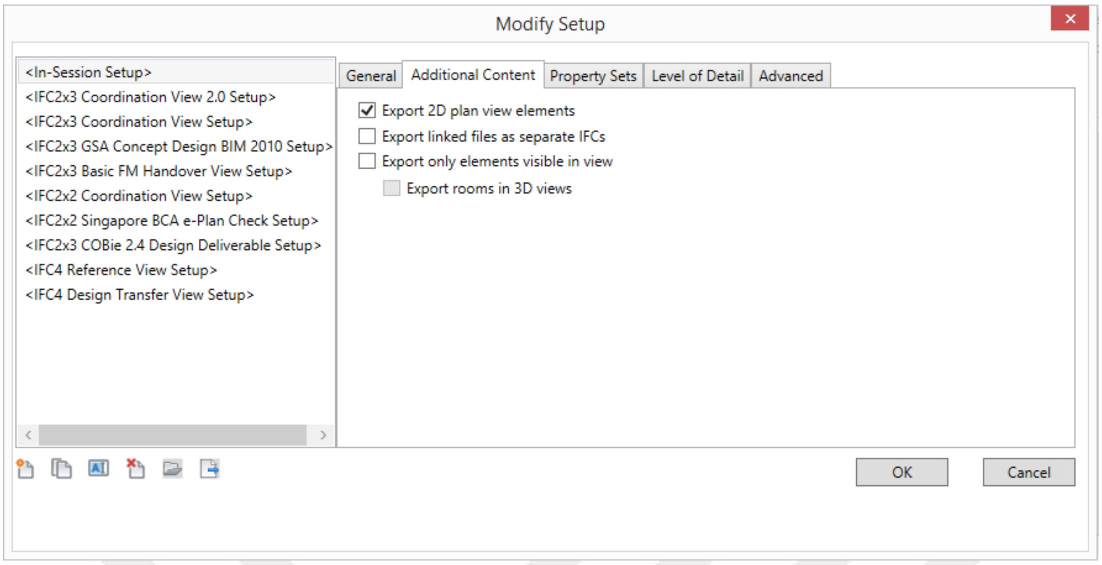

Figure 4.6 : Option for obtaining the door opening spaces.

Lastly, the next tab contains options for property sets (Figure 4.7). As mentioned before in the chapter of the industry foundation class, there are property sets for each object type by default in IFC definition. In this case, when exporting from Revit, custom property sets can also be included in the file when exporting from Rev. In this study, this option has not been selected because exporting the IFC file with custom definitions would make the data noisy and it is not a good practice if the intention is making the data globally compatible for exchange. For indoor navigation purposes, default IFC property sets would be enough.

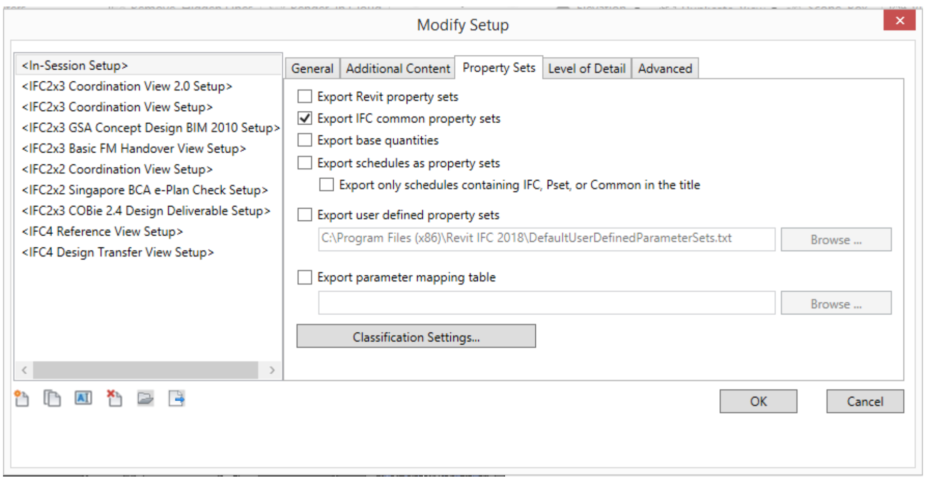

Figure 4.7 : Options for property sets.

4.3 Automatic Spatial Network Derivation Process

4.3.1 Extracting the indoor navigation network in FME

In this part, the actual process of network derivation will be explained in detail. First, the algorithms that have been used for this purpose are defined in section 4.3.1.1 The experiments that have been done through this study will be expressed and the problems that have been encountered will be described with the solutions developed for them. At the end of this section, six different navigation networks have been extracted by using FME. The workflow and the extracted networks can be seen in Figure 4.8.

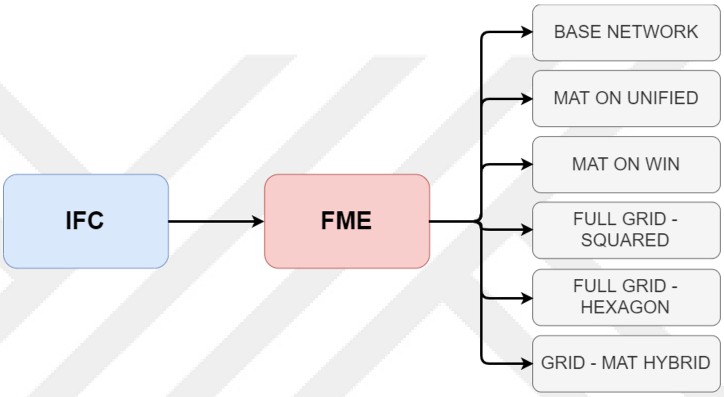

Figure 4.8 : Extracted networks.

4.3.1.1 Computational geometry background information

Medial Axis Transform (MAT)

The main purpose of this algorithm is obtaining the skeleton of a shape (Figure 4.9). It is introduced by Blum (1967) and it is being used widely in computational geometry since then. Lee (1982) described the Medial Axis in his work;

> "Given an object represented, say by a simple polygon G, the medial axis M(G) is the set of points {q} internal to G such that there are at least two points on the object's boundary that are equidistant from {q} and are closest to {q}. Because of its shape, the medial axis of a figure is also called the skeleton or the symmetric axis of the figure. Associated with the medial axis is a radius function R, which defines for each point on the axis its distance to the boundary of the object. With the axis and the radius function one can reconstruct the figure by taking the union of all circles centered on the points comprising the axis, each with a radius given by the radius function."

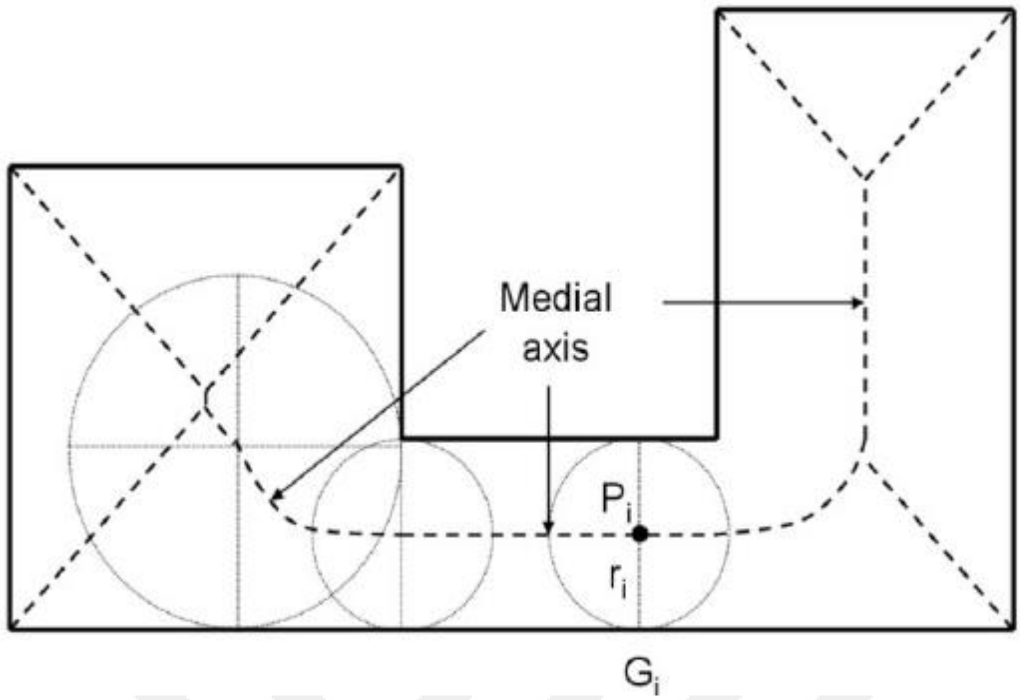

Figure 4.9 : Medial Axis Transform visualization (K. Subburaj et al. 2006).

The MAT has numerous applications in visualization (Pizer et al. 1999), computer vision (Siddiqi et al. 1998). It is still one of the best algorithms to describe a shape. Besides 2D polygons, the 3D object's axis can be extracted with this algorithm. (Tagliasacchi 2013).

Regular Grid

Grid methods are good solutions if precise localization is needed. They are easy to produce, and they provide a complete subdivision of spaces. There are studies in robotics to use hexagon or squared grids to direct the robot in an indoor environment. (Figure 4.10) "Grids allow incremental movement (and speed control), which facilitates drive, collision detection, and maneuvering."(Zlatanova, S. et al. 2014).

4.3.1.2 Generating nodes and edges

The basic idea in this process, generating just enough amounts of nodes and edges to use as a network for successfully create a route for a specific user. A sufficient number of nodes depends on the network type. For example, a network that is adequate for a robotic application could not be optimized for human navigation applications as it may contain unnecessarily too many nodes. Contrary to this, grid networks are reliable enough to get the actual walk distance to the target point.

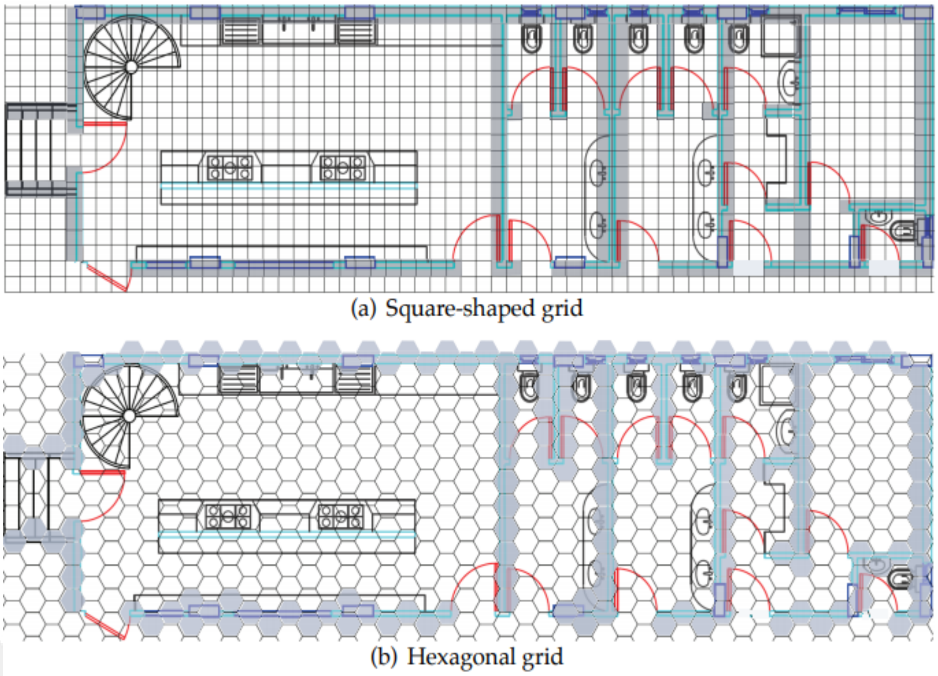

Figure 4.10 : Squared and hexagonal grid examples (Afyouni et al. 2012).

First, the IFC file imported to the FME. As can be seen in Figure 4.11, it is a complete model with all the spaces defined as solids.

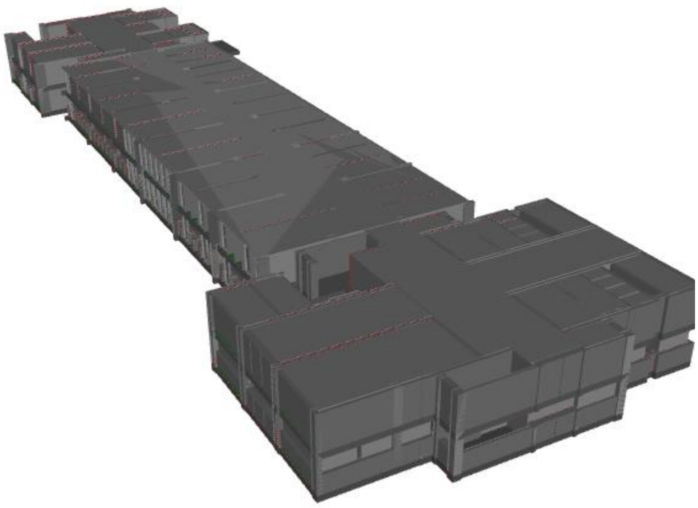

Figure 4.11 : Ifc version of the data from FME data inspector.

For the sake of simplicity and to work with the data easier, the solids have been converted to polygons and points. In this way, the geometrical manipulations become less challenging. After various efforts and interactions in FME, the data has been converted to polygons and points. (Figure 4.12);

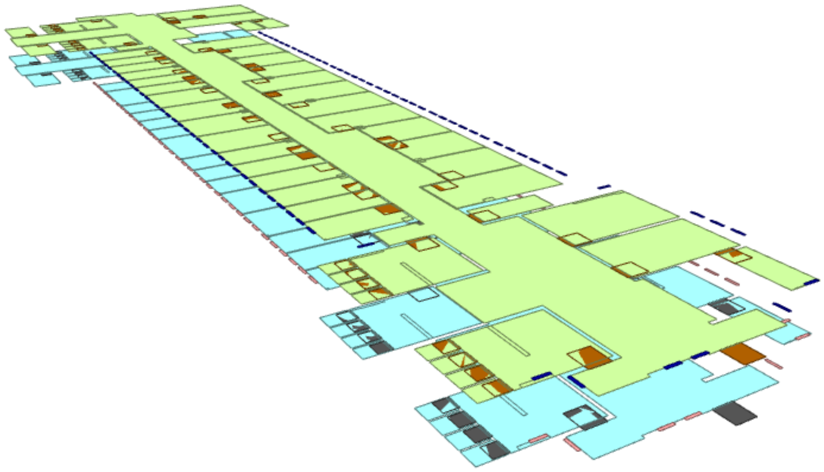

Figure 4.12 : Converted 2D version of spaces.

This approach is interacting with each floor individually in 2D, but in fact; it is a 3D approach in terms of the complete model. Floors will be connected from certain nodes, such as stairs or elevators. (Zlatanova, S. et al. 2014)

By definition of the buildings, corridors usually connect one space to another in a building. So, corridors can be considered as the main road of the network. As it is connecting too many rooms and spaces it needs to be subdivided efficiently so that our network will become powerful to create optimized routes. In that case, the axis of the corridor needs to be extracted. After extracting the corridors axis, room spaces will be connected to that axis.

First, the Medial Axis Transform algorithm has been implemented. As FME works with transformers, the CenterLineReplacer transformer is used to apply the MAT algorithm to a given corridor polygon. In the end, the axis of the polygon is obtained. This can be seen in Figure 4.13. The connections to the second floor are also displayed as blue circles for stairs, green circle for the elevator.

For the next step, the room spaces connected to the corridor axis. FME provides a transformer, which finds the closest point on a given axis from a given point. In this case, it was suitable to use this transformer to connect the doors to the corridor line (Figure 4.14).

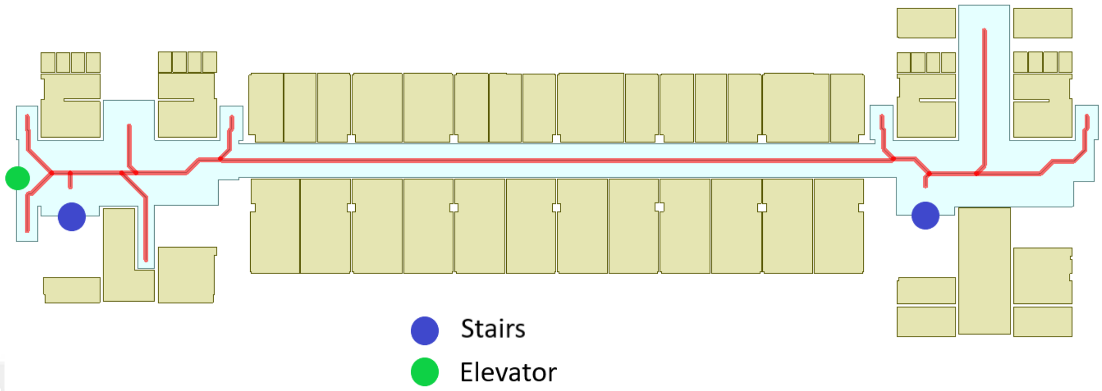

Figure 4.13 : Generating corridor axis.

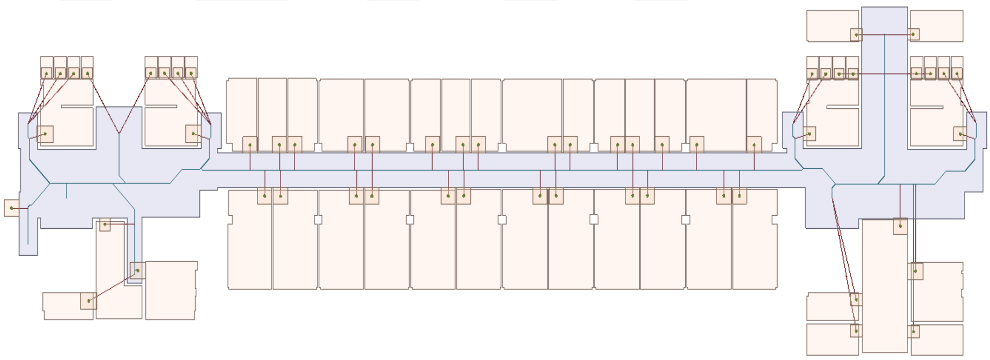

Figure 4.14 : Space nodes catching the nearest corridor axis point.

Even though it seems a good practice, it is not working perfectly. As can be seen in Figure 4.15, there are mistakes in the way of connections to the corridor axis. The mistakes illustrated in red lines and the green lines refer to the correct connection.

Implementing the connectivity between spaces

It can be seen from Figure 4.15, room numbers 68 and 73 have multiple subspaces and the hierarchical order of spaces needs to be considered. Fortunately, this information is available in the IFC file. The ifcSpace class has a subclass named ifcRelSpaceBoundaries. This class provides the information of neighbor spaces of the given space. (Teo and Yu 2017) have used this information to generate a network from an IFC file. The basic schematic can be seen in Figure 4.16.

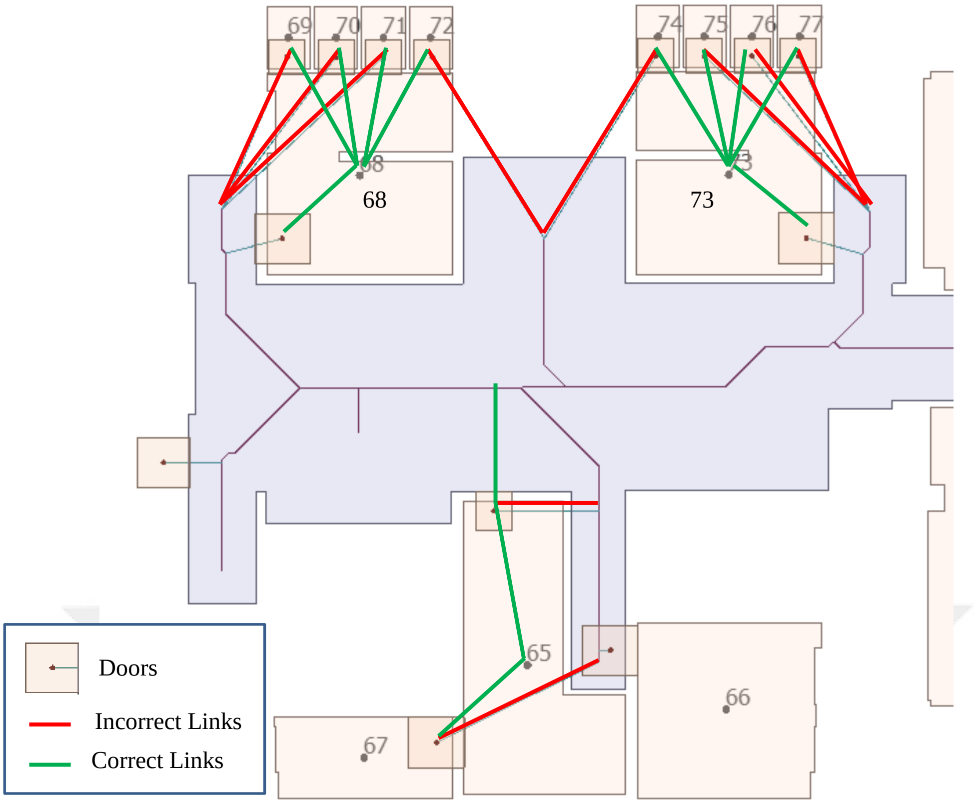

Figure 4.15 : Incorrect links in red, correct links in green lines.

Throughout this connection, the hierarchical order of the spaces can be obtained. It can be considered that each space and door objects are nodes and those nodes connected by edges.

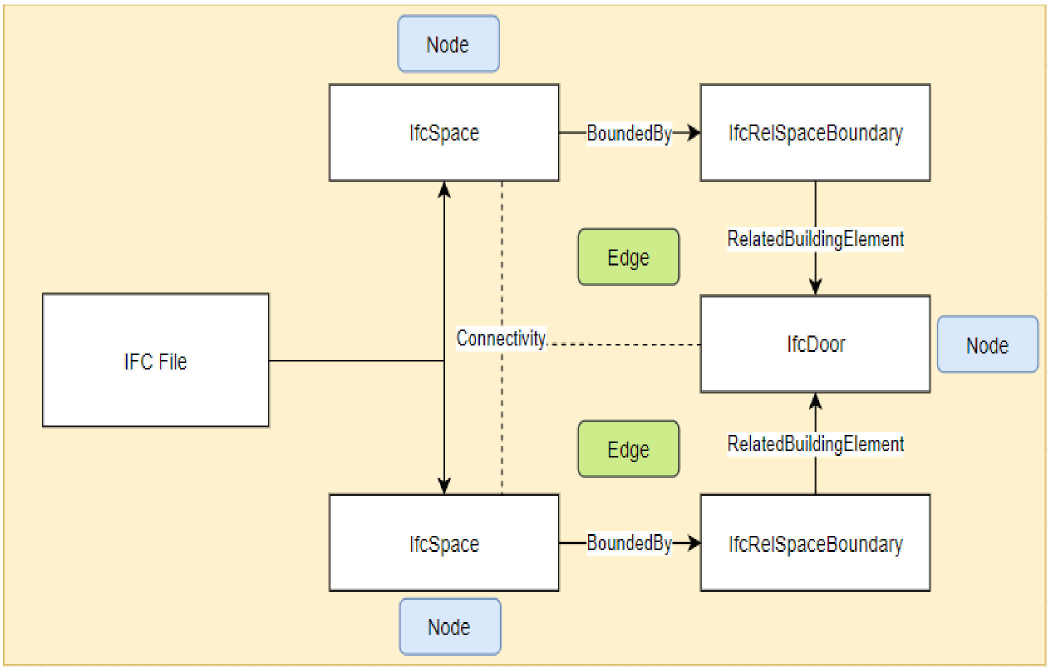

Figure 4.16 : IfcSpace connectivity information (Teo and Yu, 2017).

Developing python script to obtain space hierarchy

IfcRelSpaceBoundary information cannot be extracted in FME with regular transformers. However, the pythoncaller transformer can be used to read the IFC file and get the data to use inside of the FME workspace. IfcOpenShell library has been used to interact with the IFC file through the python script. IfcOpenShell is an open source (LGPL) software library that helps users and software developers to work with the IFC file format. (IfcOpenShell) In order to import this library into the FME's pythonCaller, it needs to be placed inside the directory of FME in your computer.

PythonCaller works as a script tool, which manipulates each feature, that coming to the transformer according to code that has been written. Basically, the developed python code is getting the information of the doors that each space connected. (the developed python code could be found in the section Annex A.) This information is merged to the space objects via their Ids. The result can be seen in Figure 4.17.

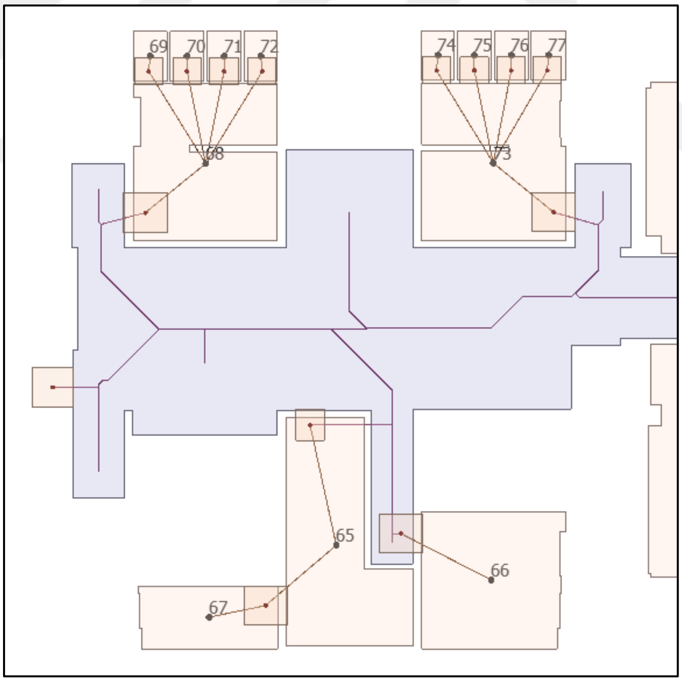

Figure 4.17 : Connected network.

As it is illustrated in the Figure 4.17, hierarchical order has been successfully established. However, room 65 still has an incorrect connection with the corridor axis. The additional transformer, using for connecting the corridor axis, seeking for the closest point on the corridor axis and it seems that the wrong connection is much closer to the axis. To solve this issue, the corridor axis needs to get closer to the doors. Mortari et al. (2014) implemented an inward polygon in his work to make the network more reliable and rational. The same principle has been followed in this study to get the corridor axis closer to the doors. It is the process of offsetting the polygon inward with a specific distance to create an island inside of the corridor polygon. This island in the center creates sub corridors and after the implementation of the MAT algorithm to these sub-corridors, the whole network becomes more rational. In addition, as the corridor axis becomes closer to the doors, the algorithm to find the closest point of the corridor axis works properly.

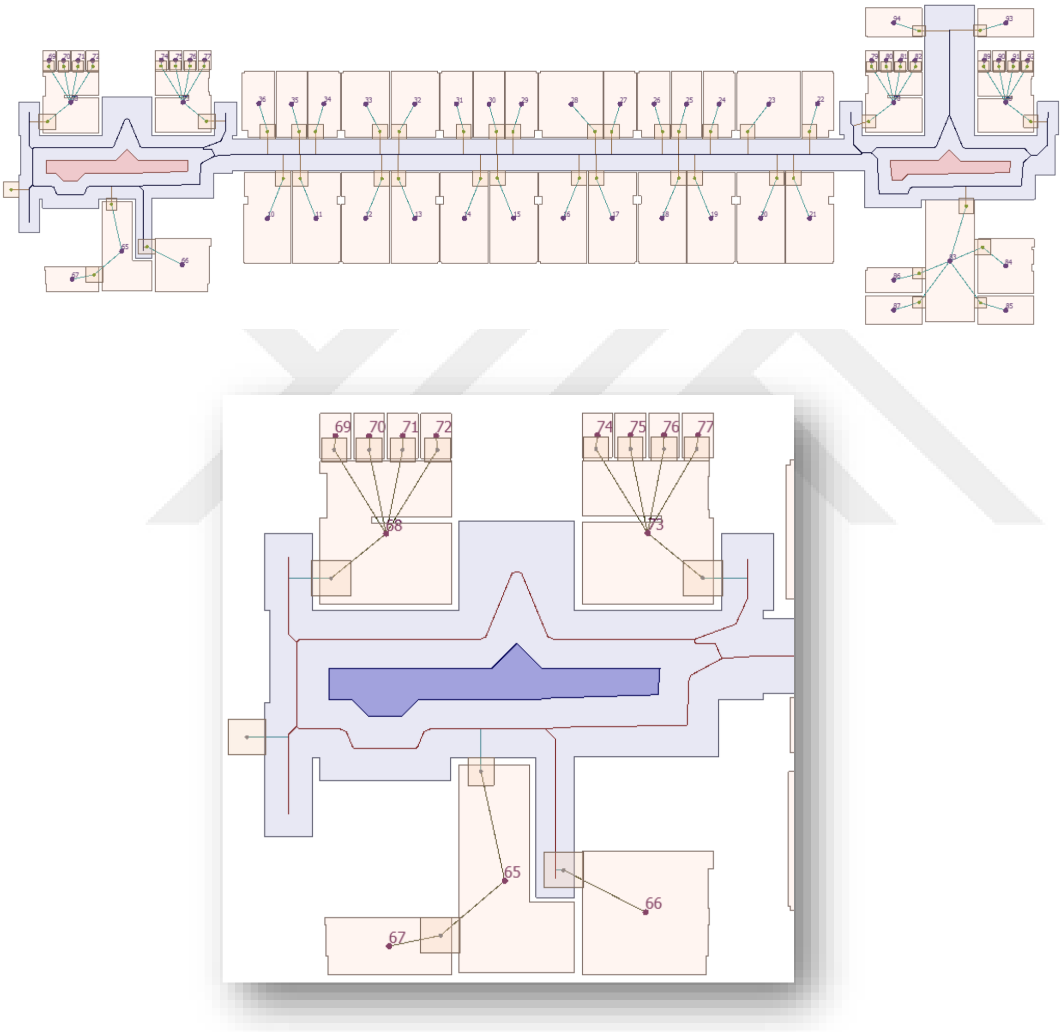

Figure 4.18 : Properly connected network.

The result that has been obtained this far, can be considered as enough to build a basic indoor navigation application. Nevertheless, there are still inaccuracies that can be seen in the network. Awkward connections do exist, and it would be much better if further solutions provided to make it more rational. For example, a route like this in the Figure 4.19 with red color can lead to miscalculated travel distances.

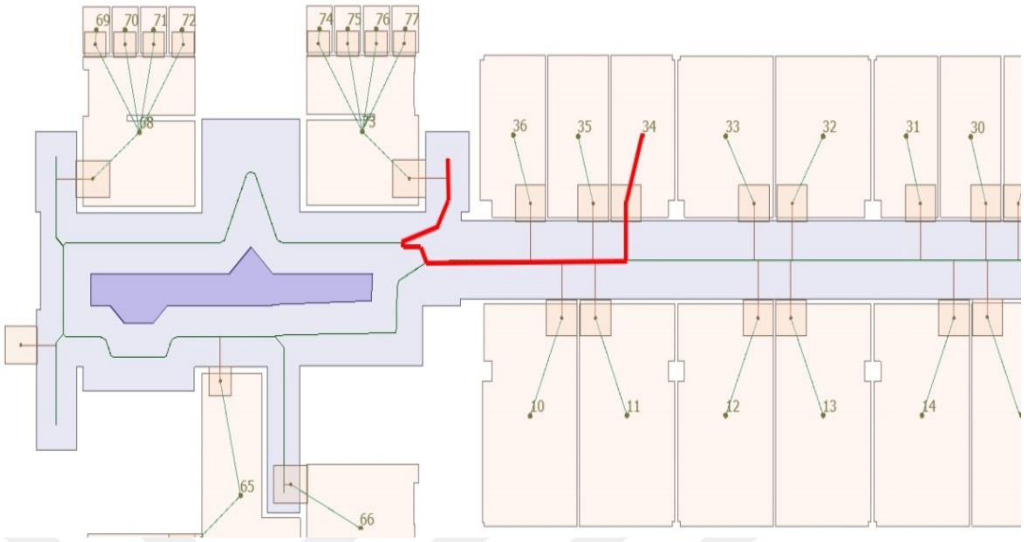

Figure 4.19 : Inaccurate planned path.

Another example, as it is presented in the Figure 4.19, rooms 68 and 73 have irregular shapes and inherited subspaces. The connection with their subspaces intersects with non-navigable space, which is incorrect. Instead of directly connecting to the center point, it would be better to generate an axis of the polygon. Thus, it is needed to determine a way to identify them as a polygon that needs an additional MAT algorithm to be run, similar to what is applied to the corridors. With this particular method, 168 nodes and 164 edges have been generated and the computation took 4.7 seconds in FME.

The second approach was merging all the spaces into one space and running MAT algorithm on this unique polygon. In this way, it is assumed to obtain all possible connections in one MAT algorithm. As can be seen in the Figure 4.20, the skeleton of the unique polygon has been obtained. One of the disadvantages of this method is neglecting the doors of the spaces. Wallgrün (2005) has used the same method and they proposed manually annotating the door spaces. However, it is possible to include the door spaces as constraints in the topology, which needs some post process to do in FME. In this network, 186 nodes and 185 edges have been generated and the computation took 5.0 seconds in FME.

The third approach (Figure 4.21) is a derivation of the base network. The principle of this network is applying MAT algorithm to the room polygons with more than one door. If a room has more than one door, it can be evaluated as it has a subspace. Thus, there should be a walking path inside of it, like an axis. The medial axis transform is providing to obtain such an axis inside the room. This way, the subspaces of any room have been connected to their parent spaces easily and more rationally.

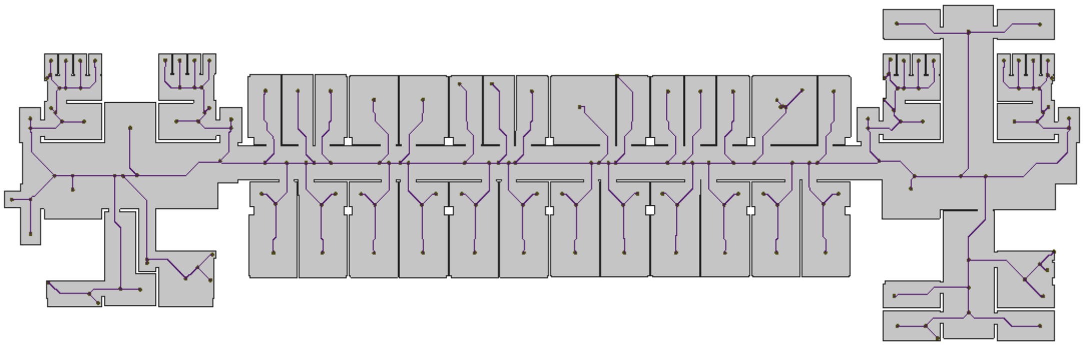

Figure 4.20 : The network by running MAT algorithm on the unified polygon.

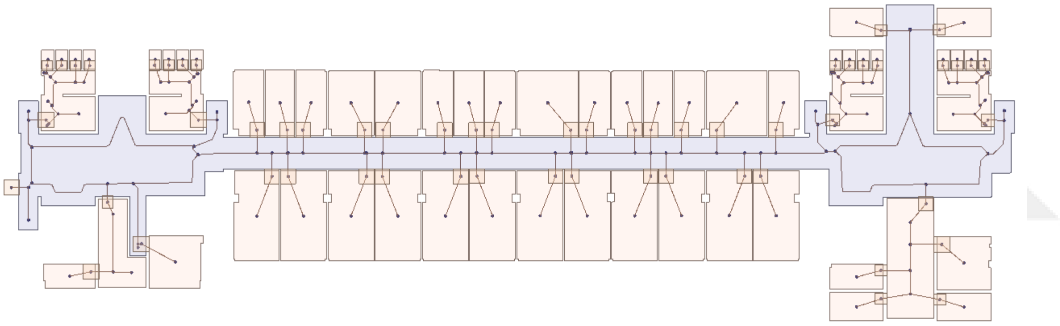

Figure 4.21 : MAT on where it needs (WIN) network.

As can be seen in Figure 4.22, room number 68, 73 and 65 connecting with their subspaces more logically. With this method, 215 nodes and 206 edges have been generated and the computation took 4.7 seconds in FME.

This method has some disadvantages of reliability from some aspects but, there is no doubt it is efficient and inexpensive in terms of the nodes and edges amount and computation time.

The next network is a grid approach. Square and triangle combination has been used for better direction resolution (Figure 4.23). It is important to mention that the grid size is a very essential part of this approach and it needs to be carefully selected. It can make a big impact on the number of nodes and edges also to the computation time.

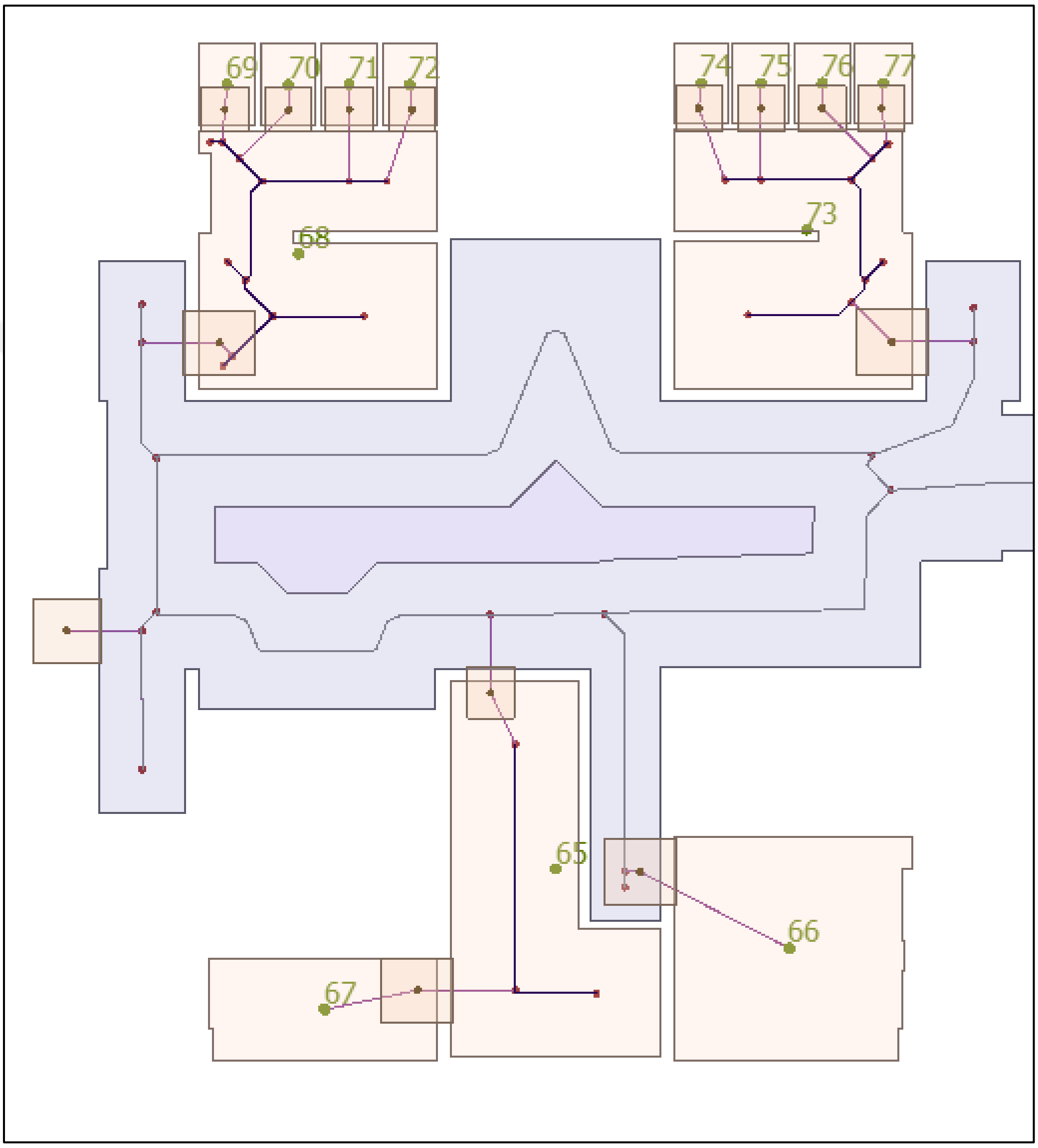

Figure 4.22 : Rooms 68,73 and 65 connection.

The grid size selected as $0.5m^2$, which is a reasonable step distance for a human. Moreover, from each node, there are eight directions available for better routing. With this method, 2423 nodes and 15088 edges have been generated and the computation took 9.9 seconds in FME.

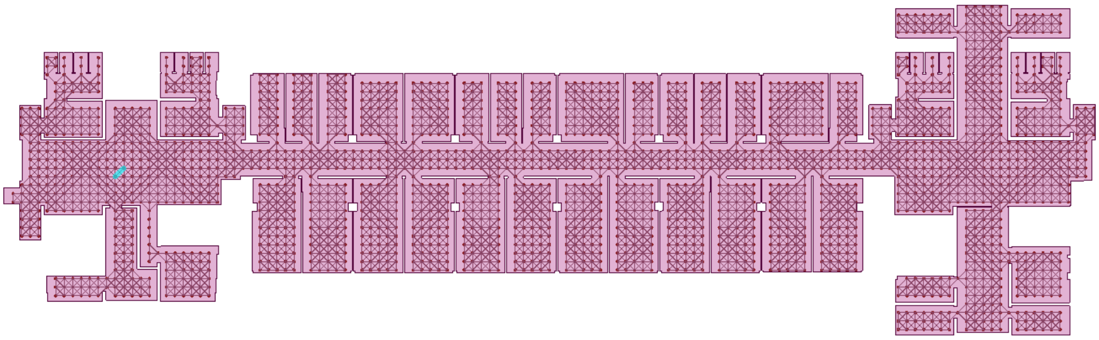

Figure 4.23 : Squared grid network.

Another grid approach is using hexagons for the partition. Full Grid - Hexagon method probably the most powerful one among the other methods but it is the most expensive one in terms of memory usage. Hexagon shape provides the same distance to every neighbor cell, which is useful for routing to irregular angles other than vertical or horizontal. In this example, a user can be directed to twelve different directions from a cell, which results in more capable route planning (Figure 4.24). Also, the pattern of the network can be seen in Figure 4.25. With this method, 4132 nodes, 23237 edges have been generated and the computation took 1 minute 15 seconds in FME.

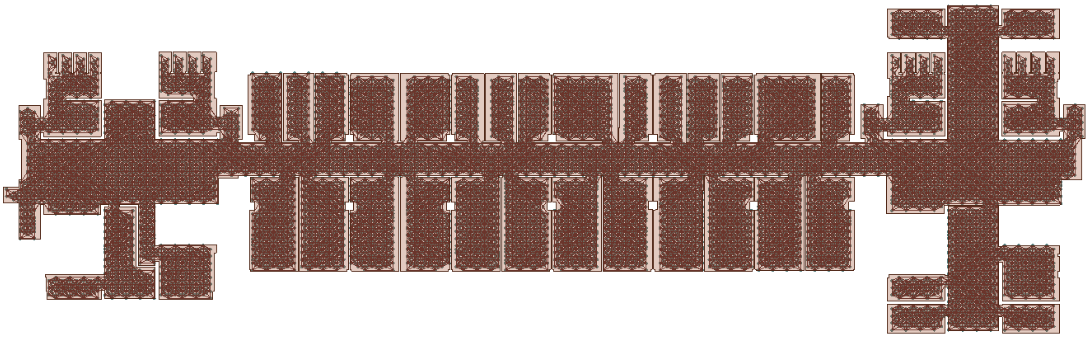

Figure 4.24 : Hexagon grid network.

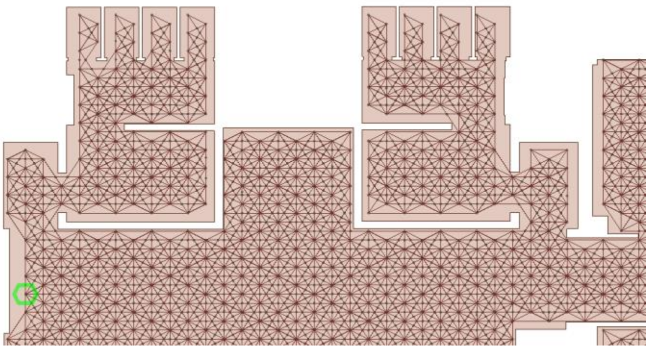

Figure 4.25 : The pattern of the network.

Another approach is a hybrid solution that uses Grid and MAT algorithms. It consists of applying different methods in certain areas to gain the advantages of each method. In the data, there are two large areas, connected with a narrow corridor in the middle. As it is known, the regular grid is a decent solution in larger areas. It provides complete subdivision in large areas, which supplies reliable travel distances and accurate route plans. In addition, the MAT algorithm is efficient in narrow and long spaces. A possible hybrid solution could be beneficial in terms of the reliability of the network. The intention of the attempt was using the grid solution in the large areas and the MAT in the narrow space of the corridor (Figure 4.26). With this method, 1506 nodes and 3855 edges have been generated, the computation took 8.0 seconds in FME.

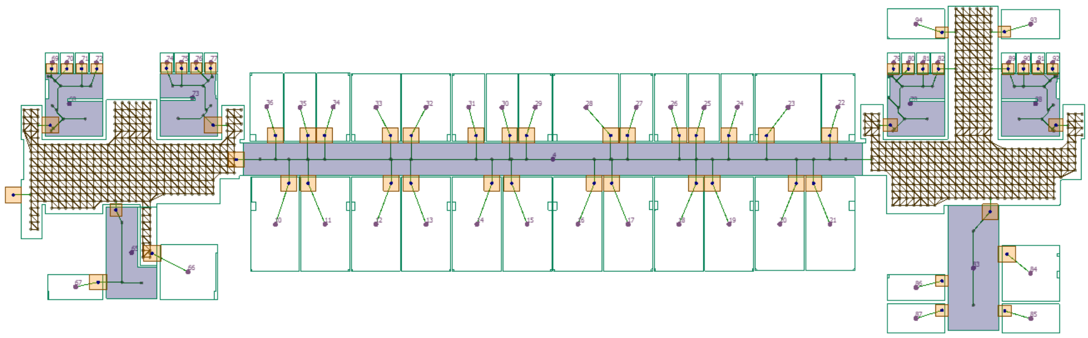

Figure 4.26 : Grid and MAT hybrid network.

One of the disadvantages of this method, that it requires defining the large and narrow areas of the corridor polygon in the BIM environment before exporting the IFC file. Since it is not easy to detect the large or narrow areas programmatically, redrawing and explicitly defining the corridor areas as large or small in BIM software is one option. The second option is running some algorithms on corridor polygon to define the large or narrow parts of the polygon. Pole of inaccessibility algorithms might be useful in this case. Eventually, the first option has been applied in this study.

4.3.2 Network generation results and choosing the network for application

The results that have been acquired are showing that not all the networks are suitable for every application. Full Grid – Hexagon looks like the most powerful network, but it lacks simplicity and has an enormous file size. Similarly; the base network is a lightweight solution however, it lacks complexity. This situation also affects file sizes. IndoorGML files have been produced for each network. IndoorGML standard has created by Open Geospatial Consortium and it provides indoor spatial information of a building with a data model. (Open Geospatial Consortium, 2015) The motivation behind it is creating a global standard to be used in indoor applications such as indoor navigation. This file format is used because it provides a data model of an indoor navigation network and a good representation of the size of the data. The file sizes are essential because in any developed application the data flow is important. If the IndoorGML file is small, the response will be faster in the application. If a more precise and accurate network is necessary, then one of the Full-Grid methods can be used. You can see the brief information about the networks in Table 4.1;

Table 4.1 : The number of elements with computation time and number of transformers used in FME.

Network	Nodes	Edges	Computation Time (seconds)	Quantity of Transformers in FME
Base Network	168	164	4.7	43
MAT on Unified Polygon	186	185	5	28
MAT on where it Needs	215	206	4.7	53
Full Grid – Square	2423	15088	9.9	34
Full Grid – Hexagon	4132	23237	75	34
Grid & MAT Hybrid	1506	3855	8	61

The number of transformers that have been used to produce each network is presented within the Table 4.1. This indicates how much effort has been given and how difficult to acquire a network within FME. All these networks obtained with some series of interactions and these interactions have been made by all individual transformers in a workspace. Fewer transformers mean a simpler solution to acquire the demanded network. In terms of the workspace simplicity, the winner is “MAT on Unified polygon”. It requires fewer transformers and it takes less effort to produce such a network. A more optimized workspace leads to a more adequate solution. All workspaces to generate these networks have carefully created by one same user and it is ensured that there is no waste of memory with unnecessary processes other than extracting the network. Such as visualizing extra parts or reading another file in the workspace. They are pure FME workspaces with only built-in transformers.

Another fact; the computation time depends on the computer's CPU and features. For this study, Lenovo Ideapad z510 with 8 GB RAM and Intel i7 2.20 GHz CPU has been used to produce all the networks.

Next, a route has been specified to test on each network to get a better idea about them. The test route starts from room 72 and ends up in room 89. This route was selected because the intention was to compare all the networks with a challenging task. The actual distance has been measured manually from the CAD drawings by imitating a real human behavior of walking as 88.89m. In the end, each result has been compared with the actual distance. The results for each network can be seen in Figures 4.27 to 4.32.

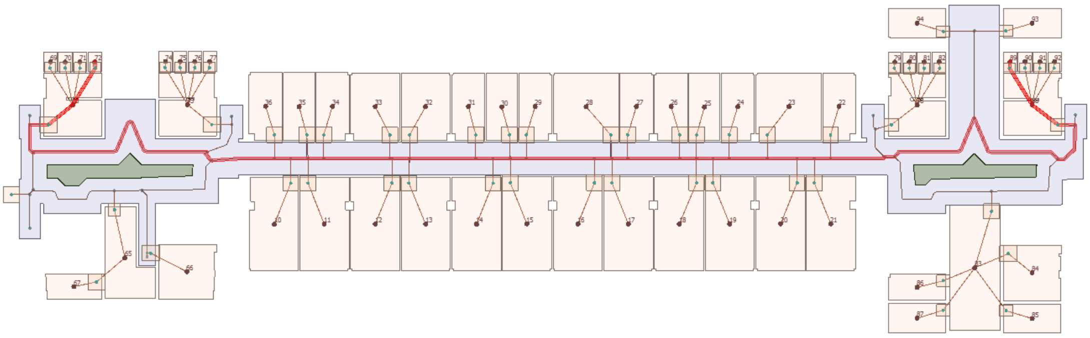

Figure 4.27 : Base network; length: 99.02m, number of segments: 38.

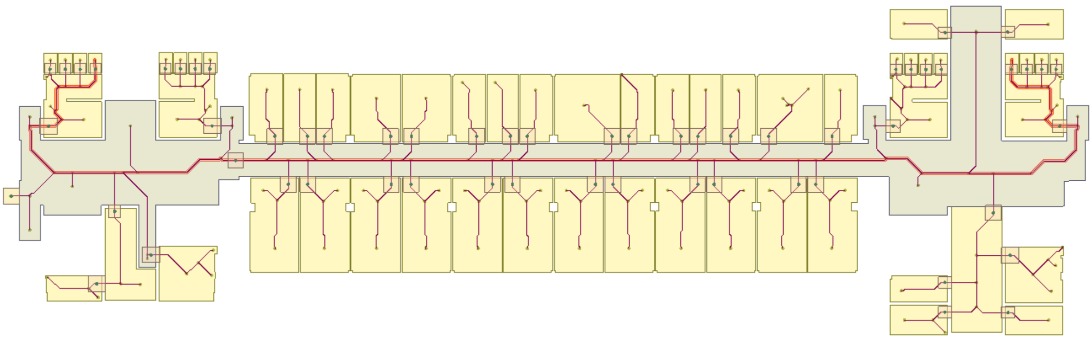

Figure 4.28 : MAT on Unified; length: 98.55, number of segments: 50.

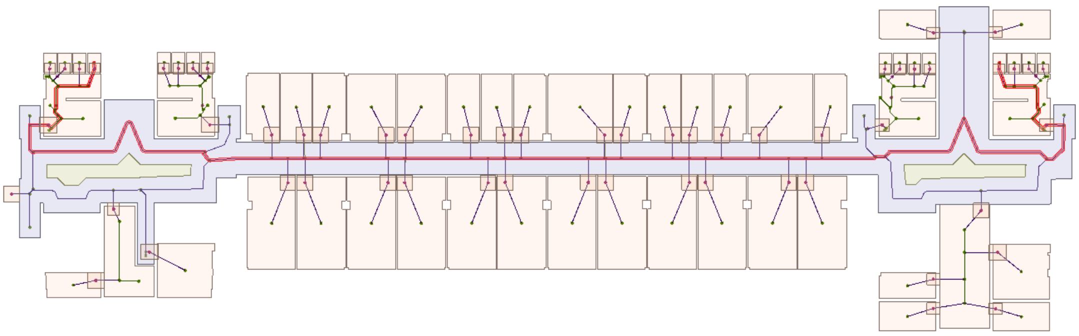

Figure 4.29 : MAT on WIN; length:103.26, number of segments: 51.

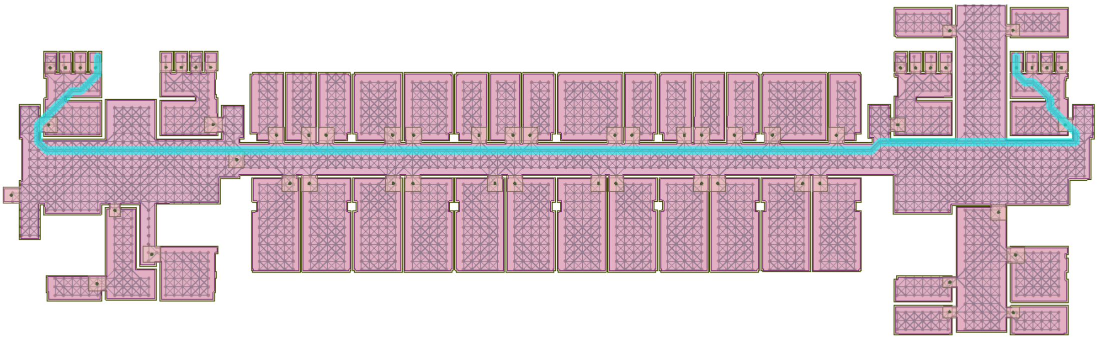

Figure 4.30 : Full Grid – Squared; Length: 89.88, Number of Segments: 144.

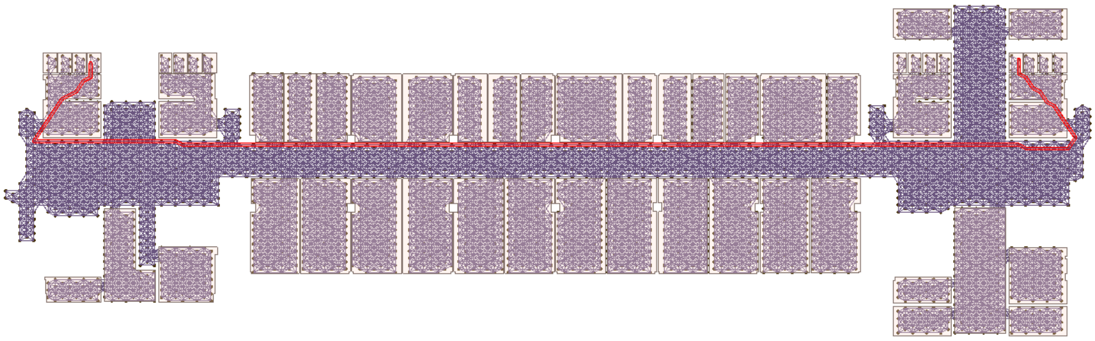

Figure 4.31 : Full Grid – Hexagon; Length: 88.39, Number of Segments: 93.

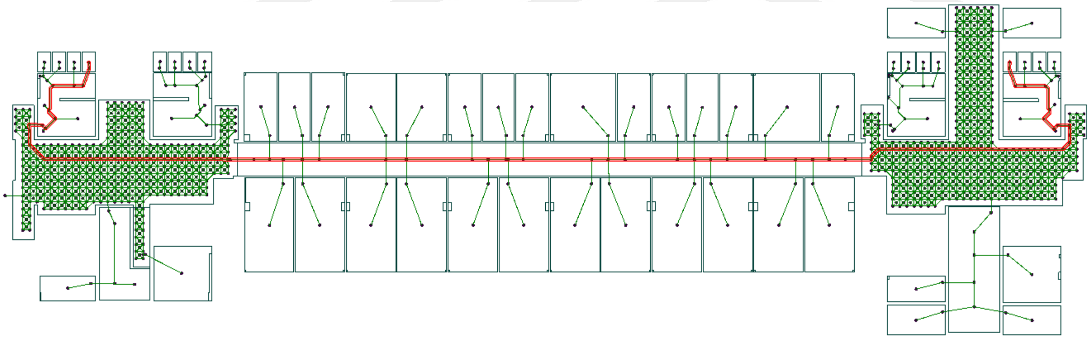

Figure 4.32 : Grid and MAT; Length: 94.70, Number of Segments: 110.

As can be seen from the Table 4.2, the most reliable method in terms of the distance is “Full Grid – Hexagon”. Contrary to this, it has the biggest file size. In the simplicity and effortless aspect, “MAT on Unified Polygon” is one step further, the number of transformers and nodes in a respectable ratio. It could be an efficient solution for human navigation. Grid and MAT Hybrid solution needs too much effort to obtain. It has the highest number of transformers and at the same time, large and narrow areas must be defined in the BIM model explicitly before the process, which is one more step to successfully implement this approach.

Table 4.2 : Length results of test route.

Network	Length of Path (m)	Number of Segments	Difference from actual distance (m)
Base Network	99.02	38	10.13
MAT on Unified Polygon	98.55	50	9.66
MAT on Where it Needs	103.26	51	14.37
Full Grid – Square	89.88	144	0.99
Full Grid – Hexagon	88.39	93	0.5
Grid & MAT Hybrid	94.70	110	5.81

In Table 4.3, it is presented another results table in a more comprehensive aspect. It is denoted that which the main algorithm has been used and which processes have been applied to each network model. Space connectivity script is the python script that is developed for obtaining the connectivity information between spaces. Polygon unification is the process of unifying all polygons on one floor. Thanks to this approach it is possible to have space connectivity by running the MAT algorithm in one unified polygon. As it can be deducted from the table, with this approach there is no need to use connectivity script as it automatically obtains space connectivity. The inward polygon process provides a more rational network when space connectivity script is being used. Lastly, the “Modification in BIM” column determines, whether a network needed extra pre-modification in the BIM environment.

Table 4.3 : Results table.

Network	Main Algorithm		Additional Processes				Results			
	MAT	GRID	Space Connectivity Script	Polygon Unification	Inward Polygon	Modification in BIM	Number of Transformers in FME	File Size (kb)	Difference from actual distance (m)	Computation time in FME (seconds)
Base Network	✓		✓		✓		43	149	10.13	4.7
MAT on Unified Polygon	✓			✓			28	200	9.66	5
MAT on WIN	✓		✓		✓		53	202	14.37	4.7
Full Grid – Squad		✓		✓			34	8,6	0.99	9.9
Full Grid – Hexagon		✓		✓			34	13,5	0.5	75
Grid & MAT Hybrid	✓	✓		✓		✓	61	2,5	5.81	8

For the indoor navigation application step, “MAT on Unified Polygon” network has chosen to be used, as it is simple and adequate for human-level navigation. This network loaded into a PostGIS database and built-in Dijkstra algorithm has been used to retrieve the shortest path between chosen points.

4.4 Creating the Indoor Navigation Application

Cesium JS has been chosen for the application environment. Since it provides WebGL technology and can run on the browser, it was the perfect solution to render 3D content such as BIM and interact with it. In this prototype application, 3D tiles data format has been used, which is developed by Cesium team.

4.4.1 Cesium JS 3D tiles background information

3D tiles format has been developed by Cesium and its general idea is reducing the rendering load of 3D geometry when a user interacting with it. The principle is almost the same as Web Map Service tiles. 3D geometry divided into smaller pieces and it loads certain pieces according to the user’s interaction. The specification is available on the GitHub under the Analytical Graphics Inc repository. (Analytical Graphics Inc) Moreover, 3D Tiles format has become a community standard in February 2019. (Open Geospatial Consortium 2019) One of the application areas of 3D Tiles is city models. City models have big data sizes and it is always a challenge to handle this amount of data in the browser. Chaturvedi et al (2015) created a 3D city model in Cesium JS and they implemented 3D tiles in their work which provided efficient user experience in the browser.

4.4.2 Bringing the data to cesium

The data that is going to be used in Cesium environment consists of four parts. The first one is building model, as the mainframe of the application. The second will be the chosen navigation network. The third will be the space information labels. Lastly, the fourth will be the queried route. The queried route will be updated as new queries occur.

To successfully bring the BIM data inside the cesium, Chen et al. (2018) work have been followed and the software that they provided is modified according to our model. In their paper, the proposed conversion approach consists of four steps: (1)

Decomposition of the IFC file, (2) IFC to OBJ conversion, (3) OBJ to glTF conversion and (4) glTF to b3dm (batched 3d model, defined file format as 3D tile) conversion.

In the first step, the BIM server has been installed and the IFC file uploaded to it. The reason for uploading the IFC file to the BIM server is keeping the data available upon the request as it will lose information while converting to the OBJ file. After converting to the OBJ file, in the third step, the data is retrieved from the BIM server and it is pushed inside the glTF file. Since the glTF file is capable of store texture and material information the texture defined in the BIM environment becomes available in the Cesium JS environment too. Finally, the glTF file converted into a b3dm file in the fourth step. B3dm file has an additional "tileset.json" file which, works as a configuration of the b3dm file. Within this file, it is possible to configure the tile set according to several options.

After successfully bringing the data in Cesium the next challenge was georeferencing it. Since the application does not need precise location awareness, the georeferencing of the model has been done at approximate levels (Figure 4.33).

Figure 4.33 : BIM model of ITU in Cesium JS.

The indoor navigation network that is going to be used has been added to the cesium through a web server. A Python Pyramid Web framework is used to run the webserver. Before exporting the network from FME to Postgis, certain attributes are explicitly defined to the important edges that are going to affect the route generation according to a user; such as stairs and elevators. For different purposes, different parameters can be given to the specific edges to control the route generation. The spatial network has been precisely overlaid on the building model (Figure 4.34, Figure 4.35).

Figure 4.34 : The derived network in Cesium JS.

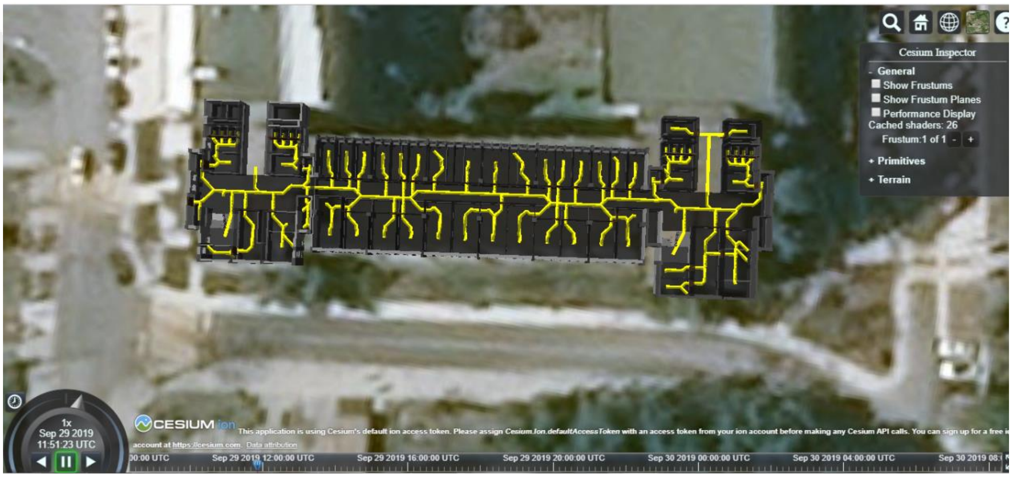

Figure 4.35 : The derived network in Cesium JS from top.

It is also possible to interact with the building elements, such as changing the visual of the model. Since all the entities has been added to Cesium individually, it is possible to move, edit and get information about each entity within the building model. In Figure 4.36, the slab of the building displayed translucent.

The last part of the application is the route generation. For this part, a query tool with enable/disable wheelchair option added to the user interface. The intention was providing more useful information for impaired users.

For the test, a route has been chosen between rooms 110 and 21. Room 110 is on the second floor and room 21 is on the first floor. Both rooms are located close to the stairs. When a user clicks to the “Get Route” button with the wheelchair option checked, a route is being generated through the elevator, even though the stairs are closer. As can be seen in Figure 4.37 and Figure 4.38.

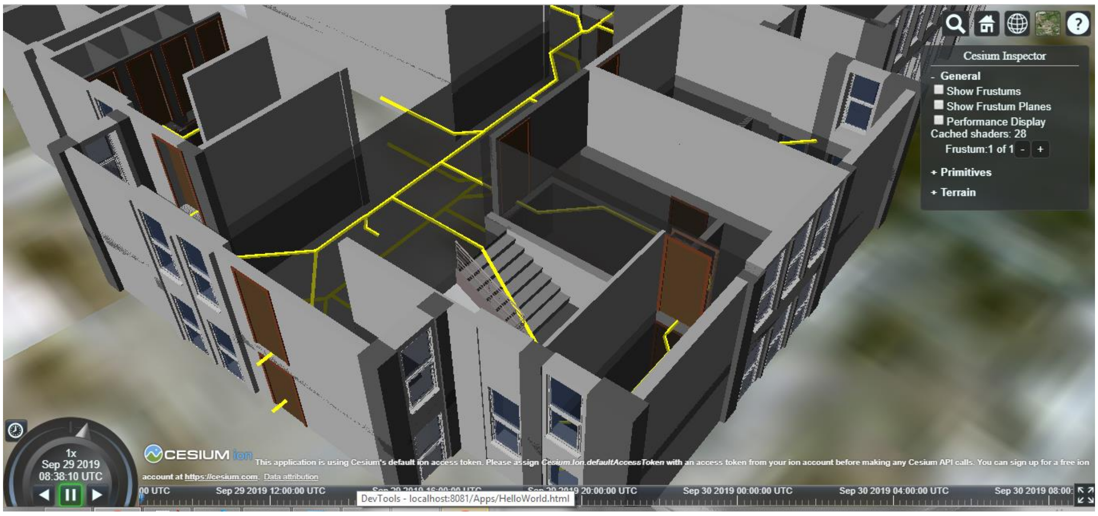

Figure 4.36 : Translucent slab.

User can also review the route by investigating through the inside of the building model (Figure 4.39).

Figure 4.37 : Generated route when wheelchair option enabled.

Figure 4.38 : The route leads to the elevator when wheelchair option enabled.

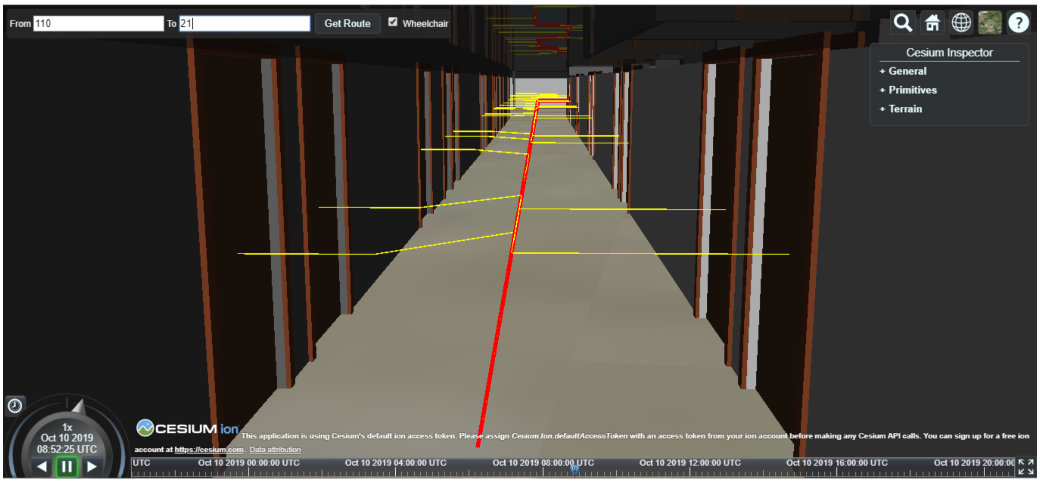

Figure 4.39 : View from inside of the building.

In the second route, the wheelchair option is unchecked so, the route has been generated by using stairs, as it is the shortest way (Figure 4.42, Figure 4.41, Figure 4.42).

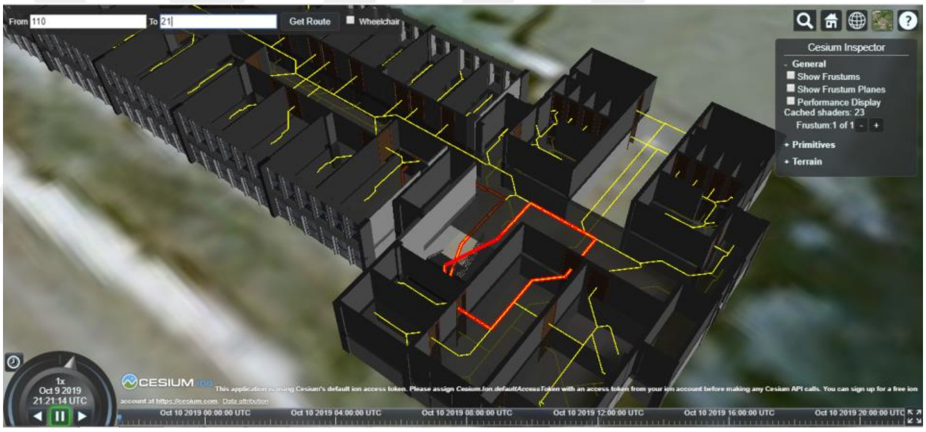

Figure 4.40 : Generated route when wheelchair option disabled.

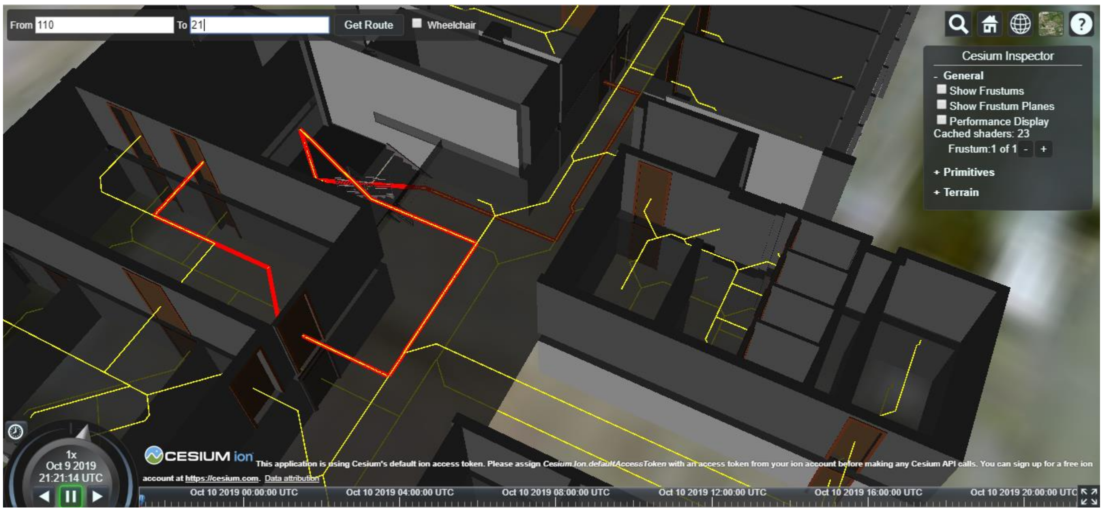

Figure 4.41 : Another view of route.

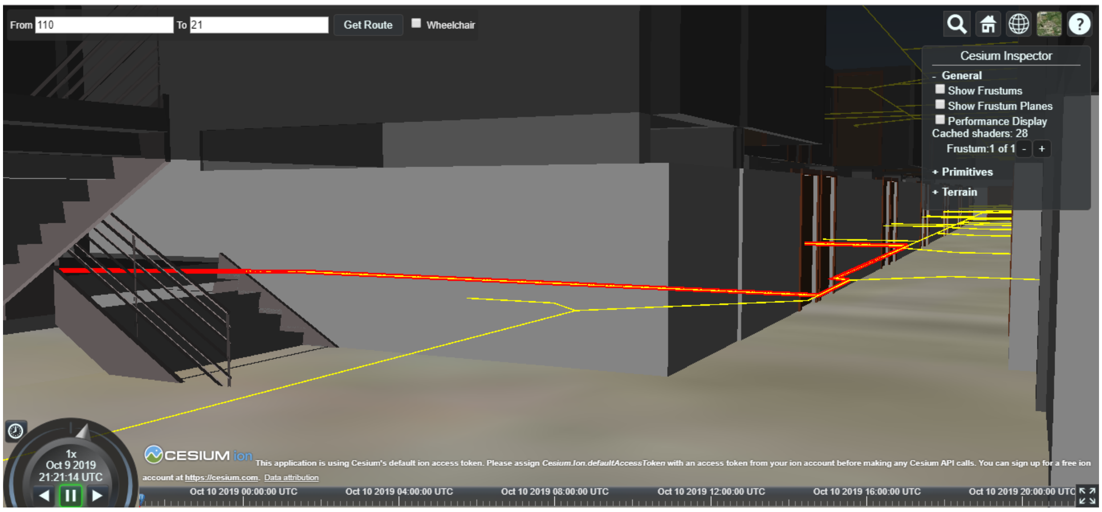

Figure 4.42 : View from inside of the building.

Six different navigation networks have been derived successfully from the BIM model. The approaches to extract the spatial network of the building have been explained with the good and downsides of them. Each network compared by its reliability, network connectivity, generation time, file sizes and the number of transformers in FME to produce them. Finally, one of them has been chosen to be used in the prototype application which, also has been tested in terms of the route generation depending on the user profile. In Figure 4.43, the more comprehensive thesis workflow has presented.

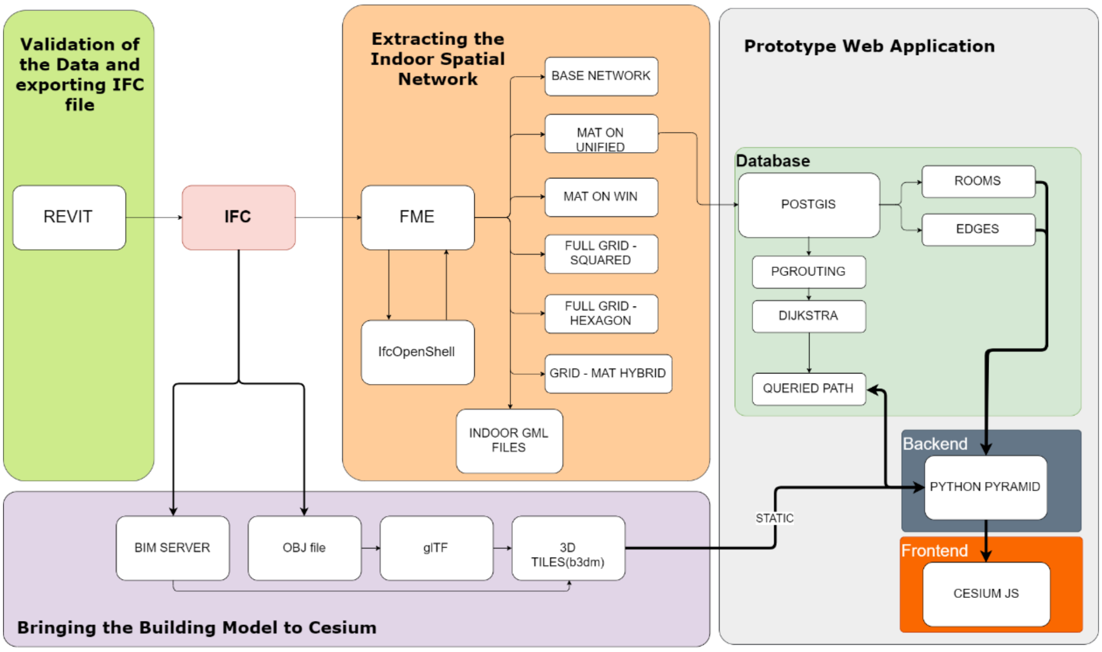

Figure 4.43 : Comprehensive thesis workflow.

It should be noted that the application is a prototype and needs more work to make it available for the client level. However, the result looks promising as it is a simple solution for such an application.

The data that is used consists of only one building. The processes that are developed so far were intended to be generic ways to create such an application but in fact; these approaches need to be tested with more data to confirm it is truly a generic way. According to these further studies, it is possible to standardize the design of a building or make the IFC data model more relevant for indoor navigation applications.

The actual building in the physical world consists of four floors. However, the Building Model has two floors. Since our approaches are for two separate floors, the challenges that are tackled would be similar if it had four floors in the BIM model in the first place. Therefore, this fact can be ignored. Since the implementation contains two separate floors, it is adequate to experience the challenges of this implementation.

The localization of a user inside of the building is beneficial for an indoor navigation application. This study does not contain a solution to this problem. However, it provides the infrastructure for a fully capable indoor navigation application. A localization system can be added to this study to create a fully capable application.

Cesium JS has been used for the application's client-side and the result was promising. Especially with 3D Tiles, it is possible to render a big amount of data in the browser flawlessly. The model was approximately 100 MB and cesium handled it well. Cesium is not specialized only for BIM or indoor navigation. Therefore, the user experience of an indoor navigation application still needs work. Cesium provides a development environment containing the whole planet and only a very small part of it has been used with this application. Therefore, a more minimalist approach can be conducted, and in this manner, the performance can be increased. In contrast, having a whole planet for the development environment provides interaction between various systems. With this in mind, it is possible to integrate this application with outdoor navigation which results to, end to end navigation. For instance; from a room in a house to a store inside a shopping mall. More specifically, it is possible to determine which entrance would be easier to reach a store in the building. According to that information, one can park his/her car close to that entrance. In Figure 4.44, it is illustrated how indoor and outdoor navigation can be combined as a reference. The indoor navigation network can be integrated with the existing road network by an anchor node that is defined in an indoor navigation network. As every building has an entrance, this anchor node should be the entrance node. This is the same concept defined in the indoorGML standard to connect the indoor spaces with outdoor spaces. (IndoorGML, 2015)

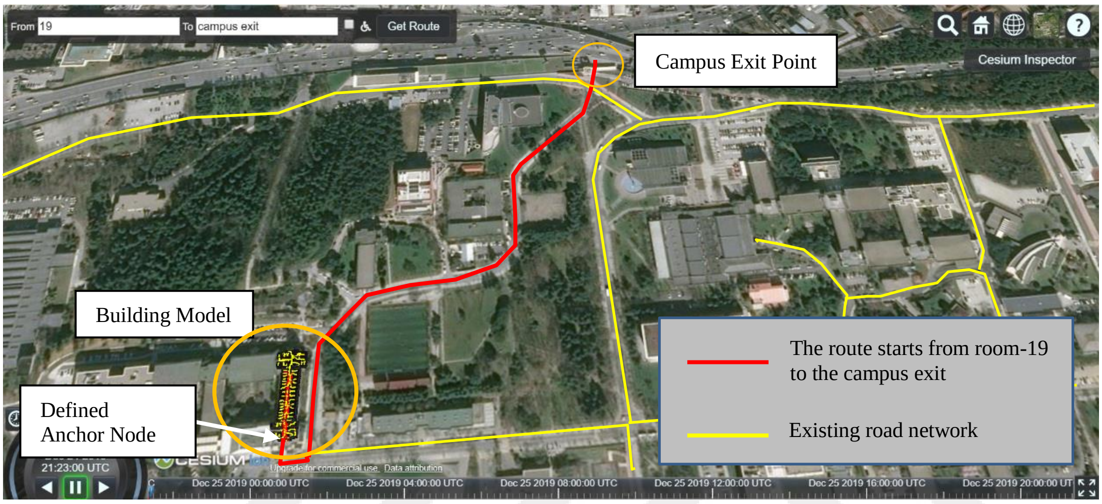

Figure 4.44 : Illustration of connection between indoor and outdoor networks.

5. CONCLUSION

In conclusion, it is confirmed that it is possible to automatically derive an indoor navigation network from an IFC file with FME. Indoor navigation is a challenging task and approaches have been tested to derive the navigation network through this study. The data of the Istanbul Technical Faculty BIM model has been used and approaches were successful for this data. With this study, an integration use case of BIM-GIS has been implemented. As a product, a web application has been developed using one of the spatial networks, in the Cesium JS environment, with the capability to control the route generation according to the user profile.

Below, the questions that have been asked in the introduction part of the study are answered:

- What kind of algorithms can be used to derive the indoor space connectivity network as geometrical operations?

There are plenty of algorithms; some of them are Medial Axis Transform, Delaunay Triangulation, Voronoi Diagrams, Visibility Graphs. These algorithms are for subdividing the space partly. Another approach is focused on a complete subdivision of spaces, which is a grid subdivision. For partly subdivision, we focused on manipulations and processes rather than the main algorithm. However, complete subdivisions, which are grid methods, slightly giving better results and decent coverage of spaces as expected. It should be used if it is important to cover all the areas in the indoor space or the actual distance is important and has to be precise. Nevertheless, for human navigation purposes, it may be better to use more lightweight solutions.

- What kind of opportunities does the IFC file provide to generate an indoor navigation network?

IFC file provides numerous data that can be used effectively. In one method, we have used the IFC class relation to extract the space connectivity information that is needed. Besides, it is possible to get the material information of building elements to create a more sophisticated indoor navigation system with emergency response. These are possible with IFC data.

- How reasonable to use Feature Manipulation Engine (FME) to derive an indoor navigation network of a building?

In the progress of this thesis, FME was one of the main tools. Plenty of different file types available to read and write with it. One of the advantages of it was the ability to read an IFC file and write an IndoorGML file. It is a flexible tool, but this availability of options makes it complex. However, this gap is closed by detailed documentation. In addition, it has a supportive community; it can be found lots of information through forum posts and videos on the official site. Several transformers made it easy to handle the issues that have been encountered in this study. Nevertheless, just a simple task can make your workspace incomprehensible. The ability to include Python script inside the workspace is a real benefit. Overall, it was adequate to use for generating an indoor navigation network.

- What kind of operations should be done before exporting the IFC file from a BIM model?

It is essential to define the room spaces and areas with just enough amount of vertex. Needless vertexes that do not influence indoor navigation should be avoided to make space polygons more suitable to run the MAT algorithm.

- What kind of operations and manipulations could be done to make the navigation network reliable?

In the implementation section, all the manipulations and operations have been explained. These operations are limitless. The aim behind these manipulations and operations was making maximum impact with the minimum effort.

- What are the positive and negative parts of indoor navigation application in three-dimensional space?

For human navigation, a 3D system provides more explanatory interface. However, it is expensive in terms of memory and CPU. With current technology, visualizing an indoor navigation application through a web browser seems not an option that every time has to be taken, especially for human navigation. Generally, 2D is a selected option for most outdoor navigation systems and it is usually enough to deliver the information as quickly as possible. Nonetheless, 2D systems have downsides in visualizing elevation differences between edges. In a 2D visualization, these edges look like they are intersecting which, results misreading in user level. For example, it becomes difficult to interpret a route from a 2D map when a route goes from a tunnel or a similar element in the traffic.

REFERENCES

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

Akın, Ö., Mert, B., Eroğlu, O., Arslan, M., Şeker, D., Demirel, H. (2018): The Role of Spatial Data in Building Information Modelling, *Journal of the Institute of Science and Technology*, 8(3), 137-143

Analytical Graphics Inc (2019): AnalyticalGraphicsInc/3d-tiles. Available online at https://github.com/AnalyticalGraphicsInc/3d-tiles/tree/master/specification, checked on 10/12/2019.

Autodesk Revit (Version 2018) [computer software]

Blum, H. (1967): A Transformation for Extracting New Descriptors of Shape, *Models for the Perception of Speech and Visual Form*, 362-380.

Boyes, G., Thomson, C., Ellul, C. (2015): Integrating BIM and GIS Exploring the use of IFC Space Objects and Boundaries, *Conference: GISRUK 2015*

BuildingSmart (t.y.): What is IFC?, Retrieved from: technical.buildingsmart.org/standards/ifc/ Checked on: 12/27/2019

Chaturvedi, K., Kolbe, T., Yao, Z. (2015): Web-based Exploration of and Interaction with Large and Deeply Structured Semantic 3D City Models, *Conference: Bridging Scales - Skalenübergreifende Nah- und Fernerkundungsmethoden*

Chen, Y., Shooraj, E., Rajabifard, A., Sabri, S., (2018): From IFC to 3D Tiles: An Integrated Open-Source Solution for Visualising BIMs on Cesium, *International Journal of Geo-Information*, 7(10):393

Chow, C. K. J., Peter, M., Scaioni, M., Al-Durgham, M., (2018): Indoor Tracking, Mapping, and Navigation: Algorithms, Technologies, and Applications, *Journal of Sensors* 2018, 1–3.

Czogalla, O. (2015): Smart phone based indoor navigation for guidance in public transport facilities, *IFAC-PapersOnLine*, 48(10), 233–239

Diakité, A. A., Zlatanova, S., Li, K.-J. (2017): About the Subdivision of Indoor Spaces In IndoorGML, *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 41–48

IfcOpenShell (2019) [Computer Software] Version v0.3.0.

Irizarry, J., Karan, E. P., Jalaei, F. (2013): Integrating BIM and GIS to improve the visual monitoring of construction supply chain management, *Automation in Construction*, 241–254.

Isikdag, U., Underwood, J., Aouad, G. (2008): An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes, *Advanced Engineering Informatics*, 22(4), 504–519

Klepeis, E. N., Ott W. William, C. N., Robinson, P. J. (2001): The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants, *Journal of Exposure Analysis and Environmental Epidemiology*,11, 231-232

Lee, D. T. (1982): Medial Axis Transformation of a Planar Shape, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 4(4), 363–369

Mortari, F., Zlatanova, S., Liu, L., Clementini, E. (2014): "Improved Geometric Network Model" (IGNM): a novel approach for deriving Connectivity Graphs for Indoor Navigation. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci. II-4*, 45–51

Open Geospatial Consortium (2015): IndoorGML. Version: 1.0.3 Retrieved from: http://docs.opengeospatial.org/is/14-005r5/14-005r5.html.

Open Geospatial Consortium (2019): 3D Tiles Specification 1.0. Retrieved from: http://docs.opengeospatial.org/cs/18-053r2/18-053r2.html.

Pereira, C., Sousa, A., Filipe, V. (2015): Open-Source Indoor Navigation System Adapted to Users with Motor Disabilities. *Procedia Computer Science* 67, 38–47.

Pizer, S. M., Fritsch, D. S., Yushkevich, P. A., Johnson, V. E., Chaney, E. L. (1999): Segmentation, registration, and measurement of shape variation via image object shape. *IEEE Trans. Med. Imaging*, 18 (10), 851–865

Safe (2019): FME. Version 2019: [Computer software].

Siddiqi, K., Shokoufandeh, A., Dickenson, S. J., Zucker, S. W. (1998): Shock graphs and shape matching. *Conference Sixth International Conference on Computer Vision (IEEE Cat. No.98CH36271). IEEE 6th International Conference on Computer Vision. Bombay, India, 4-7 Jan. 1998: Narosa Publishing House*, 222–229.

Song, Y., Wang, X., Tan, Y., Wu, P., Sutrisna, M., Cheng, J., Hampson, K., (2017): Trends and Opportunities of BIM-GIS Integration in the Architecture, Engineering and Construction Industry: A Review from a Spatio-Temporal Statistical Perspective. *IJGI*, 6 (12), 397.

Subburaj, K., Patil, S., Ravi, B. (2006): Voxel-based Thickness Analysis of Intricate Objects 6, pp. 105–115.

Tagliasacchi, A. (2013): Skeletal Representations and Applications. Retrieved from: http://arxiv.org/pdf/1301.6809v2.

Tashakkori, H., Rajabifard, A., Kalantari, M., (2015): A new 3D indoor/outdoor spatial model for indoor emergency response facilitation. *Building and Environment*, 89, 170–182

Teo, T.-A., Yu, S.-C. (2017): The Extraction of Indoor Building Information from BIM to OGC IndoorGML. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLII-4/W2*, 167–170

Teo, Tee-Ann; Cho, Kuan-Hsun (2016): BIM-oriented indoor network model for indoor and outdoor combined route planning. *Advanced Engineering Informatics*, 30 (3), 268–282

Tisler, M. (2017, 6, 5): Indoor Location Detection using Wifi | Marko Tisler | WLPC EU Budapest 2016 [Video file]. Retrieved from https://www.youtube.com/watch?v=vtfnlgTj_-A, checked on 3/11/2019.

Wallgrün, J. O. (2005): Autonomous Construction of Hierarchical Voronoi-Based Route Graph Representations. *Freksa C., Knauff M., Krieg-Brückner B., Nebel B., Barkowsky T. (eds) Spatial Cognition IV. Reasoning, Action, Interaction. Spatial Cognition 2004*. Lecture Notes in Computer Science, vol 3343. Springer, Berlin, Heidelberg, 413–433.

Yaeli, A., Bak, P., Feigenblat, G., Nadler, S., Roitman, H., Saadoun, G. et al. (2014): Understanding customer behavior using indoor location analysis and visualization. *IBM J. Res. & Dev.* 58 (5/6), 3:1-3:12.

Yang, J., Wang, Z., Zhang, X., (2015): An iBeacon-based Indoor Positioning Systems for Hospitals. *IJSH* 9 (7), 161–168.

Zhu, J., Wright, G., Wang, J., Wang, X., (2018): A Critical Review of the Integration of Geographic Information System and Building Information Modelling at the Data Level. *IJGI* 7 (2), 66.

Zlatanova, S., Liu L., Sithole G., Zhao, J., Mortari, F., (2014): Space subdivision for indoor applications. (GISt Report No. 66)

APPENDICES

APPENDIX A: Python Code
APPENDIX B: Derived Networks

APPENDIX A

Python code to extract door information of each space:

```python
import fme
import fmeobjects
import ifcopenshell
import ifcopenshell.geom
# Template Function interface:
# When using this function, make sure its name is set as the value of
# the 'Class or Function to Process Features' transformer parameter
def processFeature(feature):
    pass
# Template Class Interface:
# When using this class, make sure its name is set as the value of
# the 'Class or Function to Process Features' transformer parameter
class Space():
    def __init__(self, spaceId):
        self.spaceId = spaceId

class FeatureProcessor(object):
    def __init__(self):
        self.space_objects = []
    def input(self,feature):
        ifc_file = ifcopenshell.open("C:\Autodesk\ProjelerBirlesik_withPointCloud_Edited_SeperatedAreas.ifc")
        spaces = ifc_file.by_type("IfcSpace")
        for space in spaces:
            #space = fmeobjects.FMEFeature()
            #self.space_objects.append(space)

            space_object = fmeobjects.FMEFeature()
            space_object.setAttribute("GlobalId", space.GlobalId)
            rel_space_boundaries = space.BoundedBy
            for i in range(len(rel_space_boundaries)):
                obje = rel_space_boundaries[i].RelatedBuildingElement
                if obje is not None and obje.is_a("IfcDoor"):
                    space_object.setAttribute("doors{"+ str(i) +"}", obje.GlobalId)
                else:
                    space_object.setAttribute("doors{"+ str(i) +"}", 0)

            self.space_objects.append(space_object)
    def close(self):
        for feature in self.space_objects:
            self.pyoutput(feature)
```

APPENDIX B:

Derived networks:

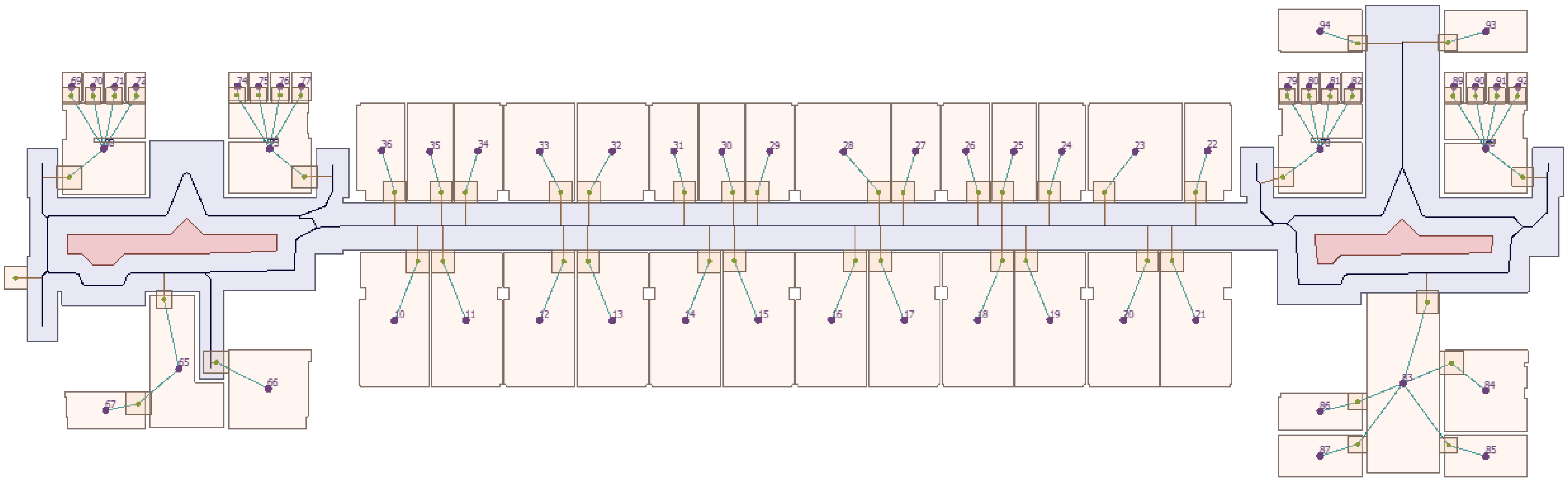

Figure B.1 : Base network

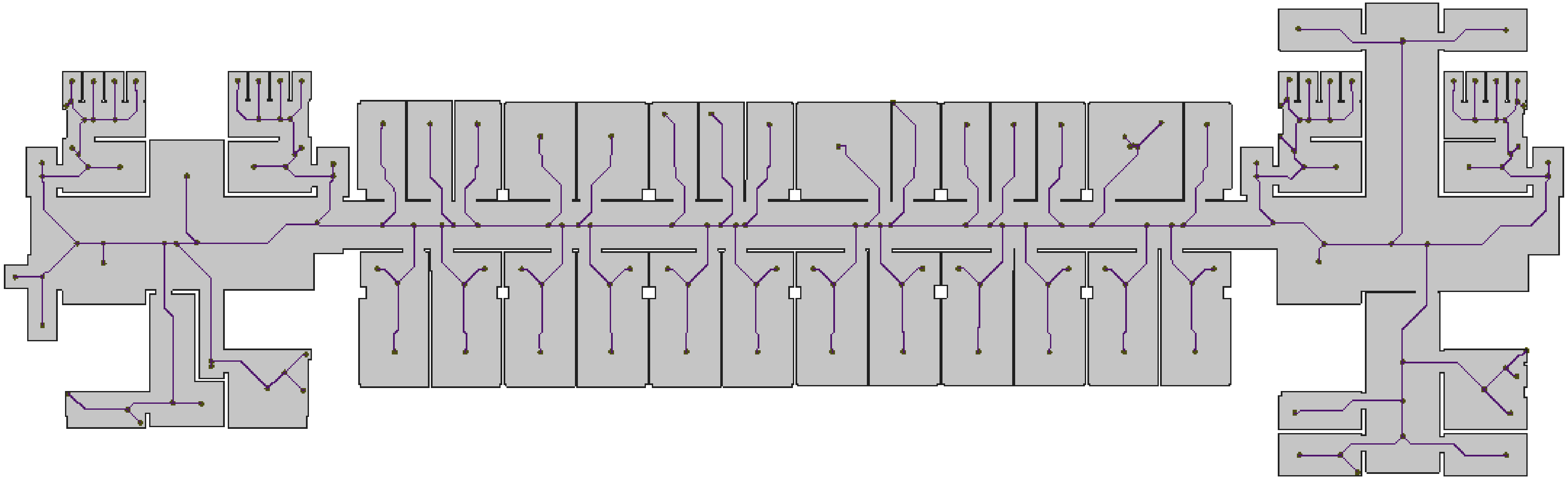

Figure B.2 : MAT on unified polygon network

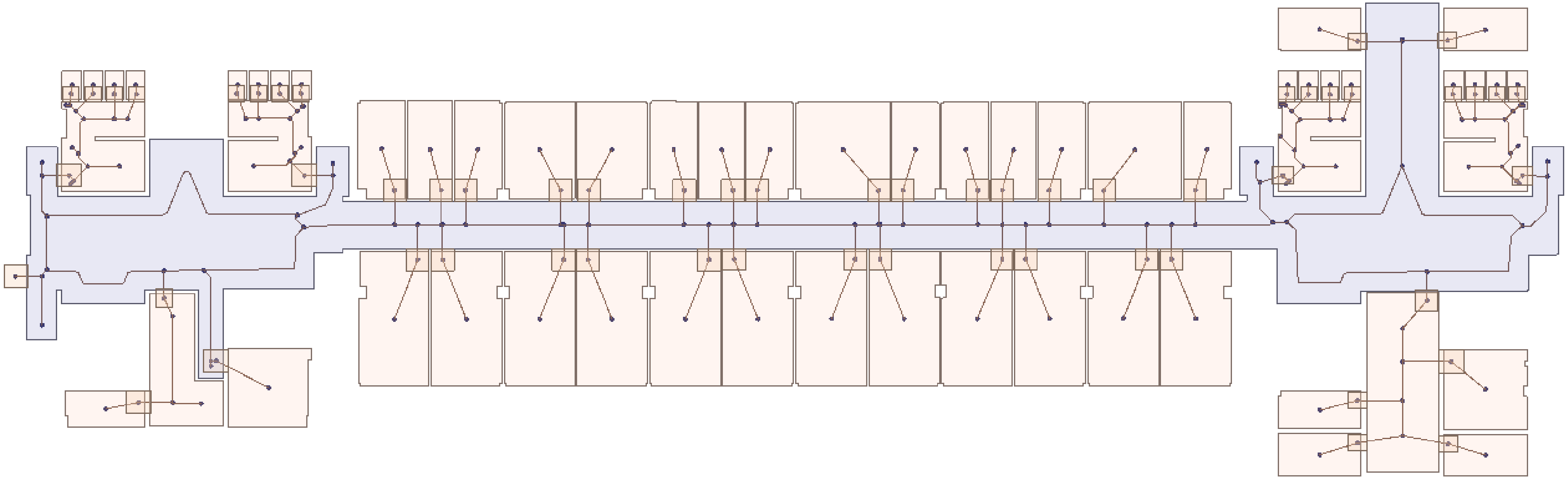

Figure B.3 : MAT on where it needs network

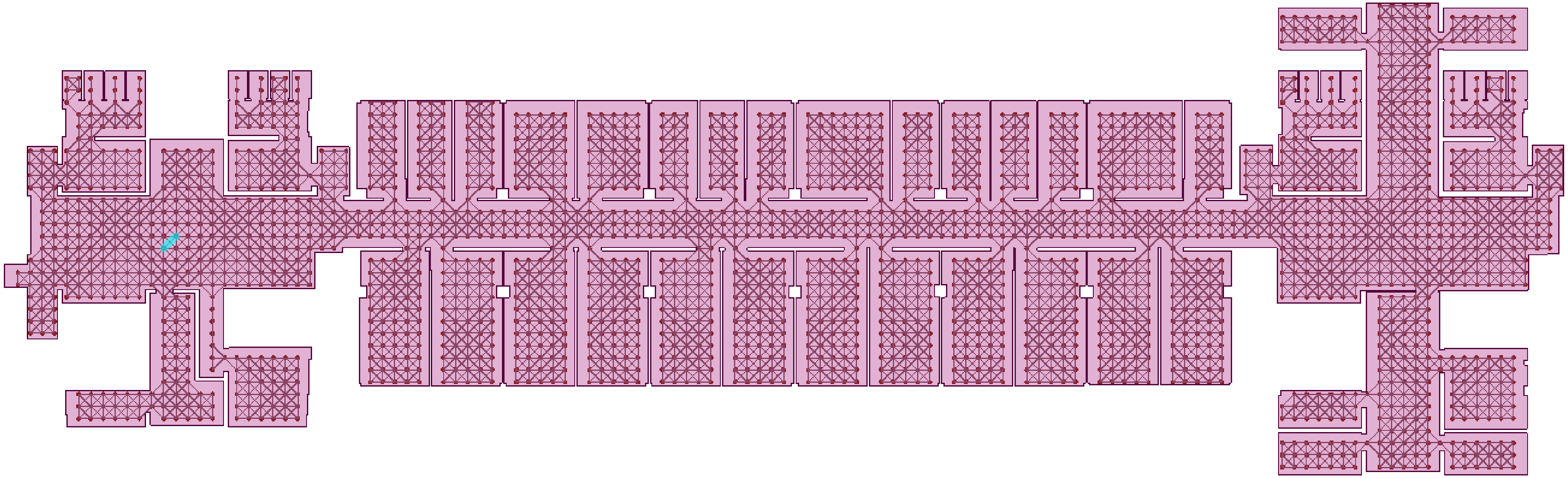

Figure B.4 : Full grid- squared network

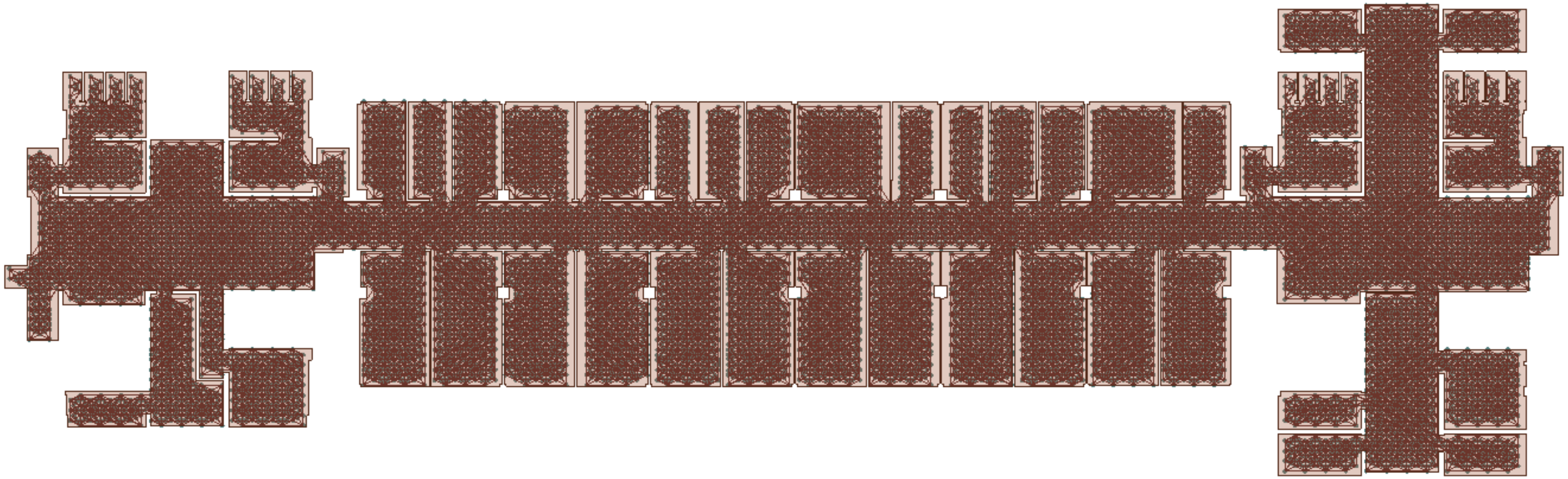

Figure B.5 : Full grid – Hexagon network

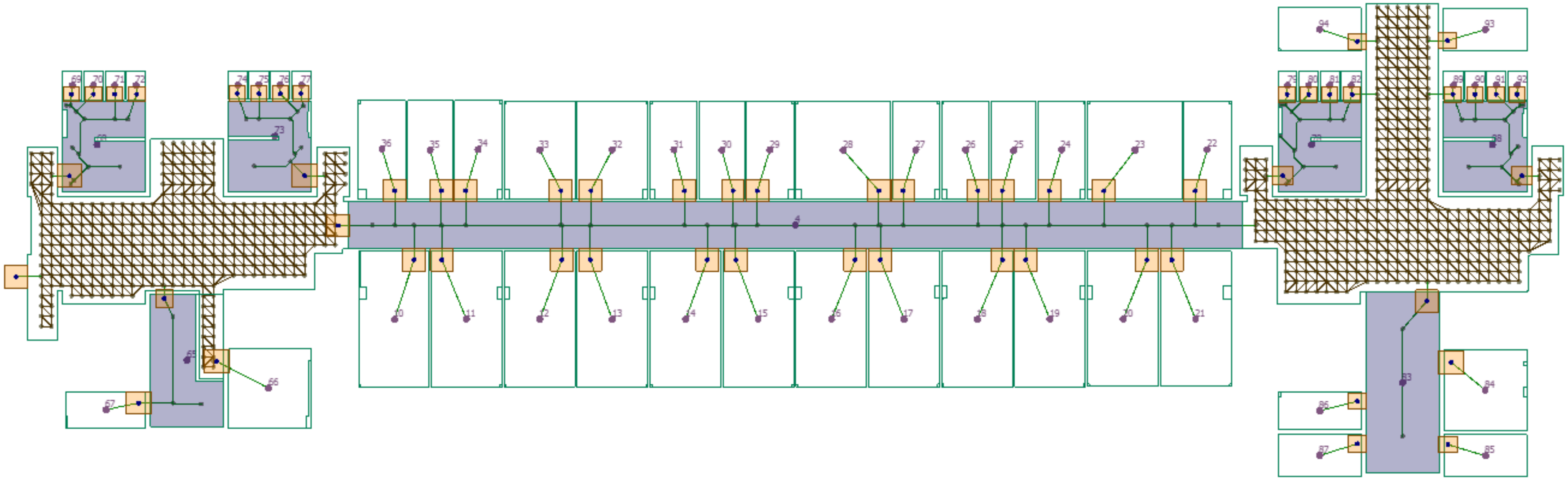

Figure B.6 : Grid and MAT hybrid network

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