A BIM-BASED COLLABORATION SYSTEM IN DESIGN PHASE OF METRO PROJECTS IN TURKISH AEC INDUSTRY

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ABSTRACT

A BIM-BASED COLLABORATION SYSTEM IN DESIGN PHASE OF METRO PROJECTS IN TURKISH AEC INDUSTRY

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A Building Information Model is a digital representation of physical and functional characteristics of a facility. It is a three-dimensional model that contains both geometric and non-geometric information. This comprehensive data enables Building Information Modeling (BIM) to be used for many different purposes during various phases of the projects. However, the quality and completeness of the data generated during the design phase are essential for supporting all other uses of BIM. Therefore, it could be considered that the more effectively the design authoring process can be managed, the more favorable it will be for all BIM processes. Nowadays, BIM processes are described in technical specifications of metro projects, which have an important place in infrastructure investments. With the fact that building information modeling becoming compulsory in these projects, a need for adoption of new approaches for design collaboration arises. Therefore, in this study, a BIM-based design collaboration system is developed for metro projects that are tendered with the Design-Bid-Build delivery method in the Turkish Architecture, Engineering, and Construction (AEC) industry. The proposed system covers the main issues related to design collaboration, design automation, and information management. The automation and standardization of these processes constitute the main structure of the system. As a case study, the proposed system is used in a real-life metro design project where design documents are generated for tendering purposes. The data obtained from the case study have been analyzed and compared with another metro project that was previously completed by the same design firm, in terms of time, cost, the number of documents produced in the BIM environment, and file sharing process. In this context, the benefits and limitations of the proposed system are identified. According to the results of the study, there is a significant increase in the number of information models generated and the number of design documents produced from the models within a comparable amount of time. The case study findings demonstrate the advantages of the proposed system and its potential for aiding fully benefiting from BIM-based design for the design firms in the Turkish AEC industry.

Keywords: Building Information Modeling, Design Collaboration, Metro Systems

ÖZ

TÜRKİYE İNŞAAT ENDÜSTRİSİNDE METRO PROJELERİNİN TASARIM SÜRECİNDE BIM TABANLI BİR İŞBİRLİĞİ SİSTEMİ

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Yapı Bilgi Modeli, bir tesisin fiziksel ve fonksiyonel özelliklerinin dijital bir temsilidir. Hem geometrik hem de geometrik olmayan bilgiler içeren üç boyutlu bir modeldir. Bu kapsamlı veri, Yapı Bilgi Modellemesi'nin (YBM), projelerin çeşitli aşamalarında birçok farklı amaç için kullanılmasını sağlar. Bununla birlikte, tasarım aşamasında üretilen verilerin kalitesi ve eksiksizliği BIM'in diğer tüm kullanımlarını desteklemek için gereklidir. Bu nedenle, tasarım sürecinin daha etkin bir şekilde yürütülmesi, diğer bütün BIM süreçleri açısından fayda sağlayacaktır. Günümüzde, altyapı yatırımlarında önemli yeri olan metro projelerinin teknik şartnamelerinde YBM süreçleri tanımlanmaktadır. YBM'nin zorunlu hale gelmesi ile bu projelerde tasarım işbirliği için yeni yaklaşımlara ihtiyaç doğmuştur. Bu nedenle, bu çalışmada, Türk Mimarlık, Mühendislik ve İnşaat sektöründe geleneksel proje teslim yöntemiyle ihale edilen metro projeleri için BIM tabanlı bir tasarım işbirliği sistemi geliştirilmiştir. Önerilen sistem, tasarım işbirliği, tasarım otomasyonu ve bilgi yönetimi ile ilgili ana konuları kapsamaktadır. Bu süreçlerin otomatize ve standardize edilmesi sistemin ana kurgusunu oluşturmaktadır. Önerilen sistem, bir tasarım firmasında gerçek bir metro projesinin ihaleye yönelik tasarım belgelerini hazırlamak için vaka çalışmasında kullanılmıştır. Vaka çalışmasından elde edilen veriler analiz edilerek, aynı tasarım firması tarafından daha önce tamamlanan başka bir metro projesi ile zaman, maliyet, YBM ortamında üretilen doküman sayısı ve dosya paylaşım süreci açısından karşılaştırılmıştır. Bu kapsamda önerilen sistemin faydaları ve sınırlamaları belirlenmiştir. Çalışmanın sonuçlarına göre, karşılaştırılabilir bir sürede üretilen bilgi modellerinde ve modellerden üretilen tasarım belgesi sayısında önemli bir artış olmaktadır. Vaka çalışması bulguları, önerilen sistemin faydalarını ve Türk Mimarlık, Mühendislik ve İnşaat sektöründeki tasarım firmaları için YBM bazlı tasarımdan tam olarak yararlanmaya yardımcı olma potansiyelini göstermektedir.

Anahtar Kelimeler: Yapı Bilgi Modellemesi, Tasarım İşbirliği, Metro Sistemleri

To My Beloved Family…

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I would like to thank all the designers who participated in the design process of the project used in case study.

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AAD	Algorithms-Aided Design
AIA	American Institute of Architects
AEC	Architecture-Engineering-Construction
API	Application Programming Interface
BEP	BIM Execution Plan
BIM	Building Information Modeling/Model (Multiple Meaning)
BS	British Standards
CAD	Computer-Aided Design
CCTV	Closed-Circuit Television Camera
CDE	Common Data Environment
CFD	Computational Fluid Dynamics
CIC	Construction Industry Council
COBie	Construction Operations Building Information Exchange
DBB	Design-Bid-Build
EN	European Norm
EKAP	Electronic Public Procurement Platform
EUU	Existing Underground Utilities
FM	Facility Management

GIS	Geographic Information System
HVAC	Heating, Ventilation and Air Conditioning
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
KM	Kilometer/Kilometers
LEED	Leadership in Energy and Environmental Design
LOD	Level of Development
MENA	Middle East and North Africa
MEP	Mechanical-Electrical-Plumbing
METU	Middle East Technical University
NATM	New Austrian Tunneling Method
NATSPEC	National Building Specification
PAS	Publicly Available Specification
RDS	Room Data Sheet
TBM	Tunnel Boring Machine
UAV	Unmanned Aerial Vehicle
US	United States
VR	Virtual Reality
WIP	Work-In-Progress

CHAPTER 1

INTRODUCTION

1.1. Definition of the Problem

In all developed and developing countries, the construction industry has a strategic role. Because of the size of the construction industry, productivity trends in this industry have significant impacts on the national productivity and economy (Allmon et al. 2000). Despite its great impact on the economy, the productivity problems in the construction sector are higher than in almost all other sectors. It was the only non-agricultural sector that experienced a steady decline in productivity from 1964 to 2004 (Teicholz 2004). One of the major factors contributing to this situation has been the traditional and inefficient approaches used in the industry.

Collaboration problems are often identified as one of the main factors affecting low productivity and inefficiency in the construction sector. Due to increasing complexity of the projects, more integrated approaches are needed for generating design of a construction (Codinhoto and Formoso 2005). Innovative approaches used in the design phase can help solving the collaboration problems.

In the last decade, technological developments and innovative approaches have started to be adopted into the construction industry as in other sectors. One of the major advancements is the utilization of Building Information Modeling (BIM) in Architecture, Engineering and Construction industry. With the demands of employers and available technological opportunities, BIM started to be preferred over traditional methods in the design process. The increase in productivity that BIM can provide has made it sought for project stakeholders (Arayici et al. 2009). Within the architecture, engineering and construction industry, Building Information Modeling is now considered as one of the most promising developments.

According to Kensek (2014), the building industry has changed from its ground and the growing acceptance of BIM is the acknowledgment of that. The three-dimensional information model has taken the place of paper-based two-dimensional drawings. Building Information Model is a three-dimensional model that contains both geometric and non-geometric data. This comprehensive data enables BIM to be used for many different purposes during various phases of the projects, such as for structural and energy analysis, cost estimation, constructability evaluation, clash detection between different systems and maintenance-operation support. Nevertheless, BIM is not only a set of software solutions, it is a process that helps enhancing collaboration and data sharing. It is an inclusive process that involves a large group of stakeholders from design and construction to operation and maintenance.

BIM, first proposed for superstructure projects, has now been requested by the employers in many major infrastructure investment projects such as railways, roads, treatment plants and power plants, etc. Bradley et al. (2016) state that BIM serves a much wider area than the planned impact area and the integration of BIM processes into infrastructure projects has provided many challenges. It is suggested that BIM processes in longitudinal infrastructure projects should differ from building projects in some respects. Since design techniques require separate expertise for longitudinal infrastructure projects, it is needed that the BIM system to be used for these projects should also be specific to project requirements.

After the advantages of BIM have been globally noticed especially in large and costly projects, almost all metro projects, one of the costliest infrastructure investments, have BIM mandate. Turkish AEC Industry also followed this approach. Government and municipalities have been working systematically to increase the scope of BIM-mandated metro projects in the country since 2015. BIM covers the whole life-cycle of a project which includes Design, Construction and Operation, among others. It has been determined that the use of BIM has positive effects on the construction and operation phases (Eastman et al. 2008). BIM use was added to the project specifications particularly by considering the advantages that BIM provides to contractors during the construction phase and the employers during the operation phase, since these phases cover almost all of the investment costs (Dodge Data and Analytics 2017). The quality and completeness of the data generated during the design phase is essential for supporting all other uses of BIM. Therefore, it could be considered that the more effectively design authoring process can be managed, the more favorable it will be for all BIM processes.

The project delivery method has always been Design-Bid-Build (DBB) for metro projects in Turkey. It is foreseen that this will continue in the near future for legal and technical reasons. As a result of this, the importance of design in the project increases to efficiently manage tendering, construction, and operation stages. The design phase should be well executed so that the employer can effectively manage the bidding phase and the contractor does not have to start modeling from scratch in the construction phase.

Although BIM system has been used instead of traditional methods in the design process of metro projects, due to the complex nature of metro projects and the necessity of working on a wide area by depending on many variables, the desired efficiency for the design phase could not be achieved. In the design of these projects, especially involving many different design disciplines that are using different software systems/packages and techniques, there is a need for a system where interdisciplinary dialogue is at the forefront. In some cases, even the smallest revisions can have a huge impact on all the other disciplines' studies. For example, traffic displacement studies that are not even needed in some projects may need a revision and this situation may cause the change of the layout of the station. Then, this may lead to changes in underground utility and route projects. Along with the changes made in the layout, route, and underground utilities, it may cause revisions in MEP systems. Many examples can be given for the necessity of revisions in the main disciplines, depending on the auxiliary discipline studies. Instead of a BIM system in which only the main disciplines are actively involved, a system in which all disciplines are actively involved is needed to be used for these projects.

Therefore, there is a need for a system which integrates 10+ different disciplines into BIM environment, including Architectural, Structural, HVAC, Plumbing, Electrical, Electronic, Fire Protection and Detection, Underground Utilities, Geotechnical, Route, Traffic, Survey, etc., so that all disciplines can easily access information, compare versions of disciplinary studies, and communicate their opinions and comments in an easy and correct way. To achieve these, there is a necessity to standardize the interdisciplinary data sharing and exchange processes.

In addition, the number of repetitive works is very high in these projects. In some projects, it is required to update all similar stations according to a change request or to re-arrange the tunnel structures due to changes in route of the metro system. All possible processes should be automated to decrease project design duration and prevent design flaws.

The metro projects necessitate data acquisition from 100+ different institutions for the planned, on-going, and completed projects. Since the information about these projects are not managed on a common database, all these data need to be superposed and examined together. Occasionally, human-induced errors can occur in the superposing process. In some cases, when a field trip is done or construction work starts, it may be revealed that the transmitted data do not represent the current status of the field. Even for projects that have been studied for months, these situations can arise. Problems in the data acquisition process can cause major revisions in the projects. The system should be designed considering the revision needs that may occur during the data acquisition process.

Although several firms and employers in the Turkish AEC Industry have already begun to make good use of BIM for the design of metro projects, there is still a need for an integrated collaboration system supporting information management, design automation, and engineering analysis processes to overcome various barriers in fully benefiting from this promising BIM-based design approach.

1.2. Goals of the Study

The main objective of this study is to develop a BIM-based design collaboration system for one of the costliest infrastructure investments, metro projects. It aims to make the design process more efficient through the use of the proposed system, since the lack of collaboration is a main contributor in low productivity and inefficiency. The aspects in which the design process is expected to become more effective are listed below:

- Increasing collaboration between design disciplines.
- Increasing the number of documents produced in the BIM environment.
- Reducing total duration for the generation of design documents.
- Reducing project revisions.
- Reducing the number of disputes between design disciplines.
- Reducing man-month costs incurred in the project.
- Enabling easy access to reference documents shared by other disciplines.
- Minimizing errors in file sharing.

In this study, the main concerns are improving the content of design documents to avoid problems encountered during the construction stage, transferring a more accurate design to the construction stage, and managing the design process more effectively.

Moreover, it provides valuable information to other designers in the process of producing metro projects in terms of sharing best practices for BIM-based collaboration and design and engineering analysis automation. This study covers the main issues of design collaboration related to design automation, engineering analysis, and information management for metro projects.

The specific aims of the study are:

- Developing a BIM-based design collaboration system.
- Integrating all design disciplines into BIM process.
- Integrating design automation into the process actively.
- Standardizing information management process for the design phase of metro projects.
- Recording all disciplinary change requests of the project within the system.
- Performing analyses/simulations for design alternatives more rapidly.
- Enabling tracking of changes made by other disciplines within each designer's own discipline model.
- Preparing tender documents in a more comprehensive and effective way by saving time in the design process.

1.3. Scope of Research

This study has been carried out for the Turkish AEC industry. It focuses on the preparation of tender documents of BIM-mandated metro projects since all the recently contracted metro projects in Turkey have BIM requirements in their contracts and specifications. In these projects, the project delivery method is Design-Bid-Build. The system proposed in the scope of the study is valid for the design processes from the preliminary stage to the preparation of tender documents. It does not cover the creation of construction drawings and processes related to other construction stages.

Furthermore, the collaboration system has been proposed considering the working systematic of one of the biggest design firms in Turkey. It can be used in design firms working with the same systematic; however, some revisions may be needed in the proposed workflows to use it in different design companies. In addition, while developing the collaboration system, the software solutions and file formats which are most commonly used in the design of metro projects in Turkey and are also currently requested by the employers, have been taken into consideration.

Moreover, the proposed system is very comprehensive and covers the whole design process. In the case study, not all of the principles proposed in the system have were implemented due to various reasons such as technical inadequacies, some design work being out of the scope of the project, and the project not being completely finished owing to the recent recession in the Turkish AEC industry.

In the study, the design of the stations and line structures have been taken into consideration. The design process of the depot areas used for maintenance and operations within the metro system is not included in the scope of the study since their design is very similar to the industrial facilities among the superstructure projects. Therefore, the studies related to depot area buildings have not been included in the system development.

1.4. Method of the Study

The following approach has been adopted for this study. Relevant literature, publications, and studies have been reviewed by examining major academic databases. Subjects used for the literature search were infrastructure, metro system, railway system, design automation, information management, and design collaboration with BIM. Since the railway structures resemble the metro structures at some points, it was investigated within the scope of the research. Also, the process of preparing tender design documents for metro projects in the Turkish AEC industry has been reviewed using some reference documents.

Second, a design collaboration system including design automation, information management, and engineering analysis processes has been developed by considering the special needs of the metro system. The responsibilities of all disciplines have been investigated and they have been updated according to the BIM-based collaboration system requirements.

Then, the proposed system has been tested in a project to ensure the suitability and accuracy of it. The project used in the case study consists of a 15 km long metro line and includes 11 underground stations and 12 tunnel structures. Throughout the study, this project will be referred to as “Project-A”. After that, a comparison between the project that the design documents are prepared with the proposed system and another project developed by the design firm in the past without the use of the collaboration system has been made. The previous project is a BIM-mandated project prepared with standard BIM solutions. It included 3 underground stations with a total of 6 km metro line. Throughout the study, this project will be referred to as “Project-B”. In the previous project, the main disciplines (Architectural-Structural-MEP) specified in the project specifications were actively involved in the BIM process; but disciplines such as route, geotechnical, survey, traffic, and utility were not actively involved. Also, design automation solutions and the impact of engineering analysis procedures integrated within the model generation processes were not preferred in the execution of the project. This sample study has been chosen to compare the effects of the system in which all these design disciplines are actively involved in the BIM processes and to see the benefits of the design automation and standardization and automation of information management processes in the design of a metro project.

Finally, the information obtained from the case study has been analyzed and compared with the previous project in terms of time, cost, numbers of design revisions, number of documents produced in the BIM environment, number of disputes between design disciplines, and number of errors encountered in file sharing process.

The study consists of an introductory section, four main sections, and a conclusion section.

- **Chapter 1** introduces the definition of the problem, the goals, the scope, and the method of the study.
- **Chapter 2** contains the introductory information about the metro system and building information modeling as well as a summary of the relevant literature studies.
- **Chapter 3** presents the BIM-based design collaboration system. It has all the necessary information needed to develop the collaboration system. It includes workflows for each discipline. Disciplinary definitions are also explained in this chapter.

- **Chapter 4** includes the details of the case study. It contains information about the metro project used in the case study. In the last part of Chapter 4, how the developed design collaboration system was integrated into a real-life metro project design is discussed.
- **Chapter 5** discusses the results of the case study. The benefits of implementing the collaboration system, challenges encountered during the development and implementation of the proposed collaboration system, and future study needs are presented in this chapter.
- **Chapter 6** contains conclusions of the study.

CHAPTER 2

LITERATURE REVIEW

2.1. Metro Systems

Due to rapid urbanization and population growth in the last century, urban rail system solutions have been preferred highly for public transformation.

These rail system solutions are categorized according to some technical features and passenger-carrying capacity as a tramway, light rail, metro, monorail, and funicular. Since they are categorized as a combination of different properties, these properties sometimes overlap, and it can be challenging to subdivide rail systems.

Metro systems (Fig. 2.1), which are considered as the transportation systems with the highest passenger capacity among urban public transportation systems, have been operated as the primary public transportation system in many cities around the world. It is a fact that there has been a severe need for urban rail systems in the last century.

Figure 2.1. A Sample Image for a Metro System

2.1.1. Historical Background of Metro Systems

Metro systems were first constructed in major European cities a century ago and have transported billions of people to this day. These systems have offered new opportunities to cities and restructured them until this day (Noyce et al. 2002). In 1863, the first underground urban rail system, The Metropolitan Railway, was opened in London (Fig. 2.2). After that, Budapest Metro was opened in 1896, the second oldest metro system in the world. In addition to London and Budapest, Glasgow and Chicago metro lines were also started to operate in the 19th century (Misachi 2019).

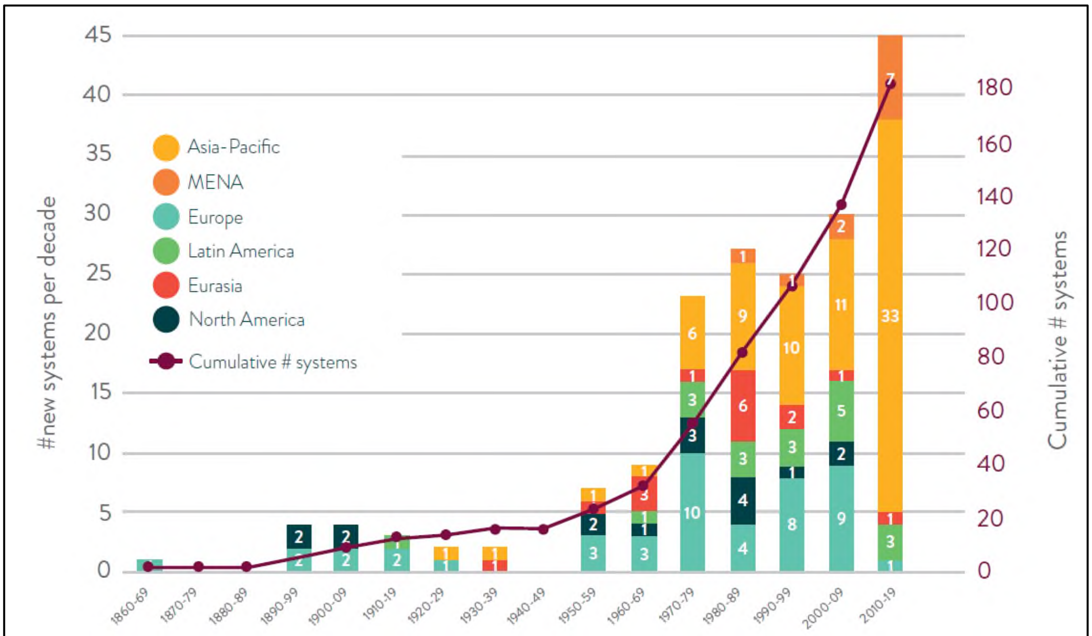

Figure 2.2. Total Number of Metro Systems and the Location of Metro Systems Inaugurated each Decade (International Association of Public Transport 2018)

With the increase in urbanization, metro systems have become more critical for urban transportation all over the world. Therefore, developed and developing countries have increased their investment rates heavily for metro systems. 75 new metro lines were opened from 2000 to 2017, and 178 cities in 56 countries (Fig. 2.3) had metro systems carrying an average of 168 million passengers per day at the end of 2017 (International Association of Public Transport 2018).

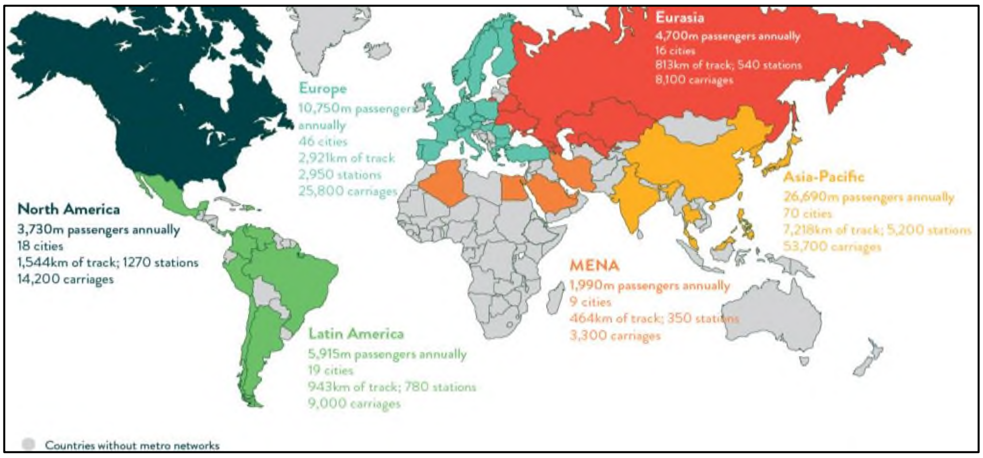

Figure 2.3. Worldwide Metro Networks in 2017 (International Association of Public Transport 2018)

At the start of 2018, the majority of the top 10 cities which have the longest metro lines were from Asia (Fig. 2.4). In the middle of 2018, it is reported that approximately 5400 km of metro system are under construction and testing phase and 1700 km of metro line is in design and tender phase (International Association of Public Transport 2018).

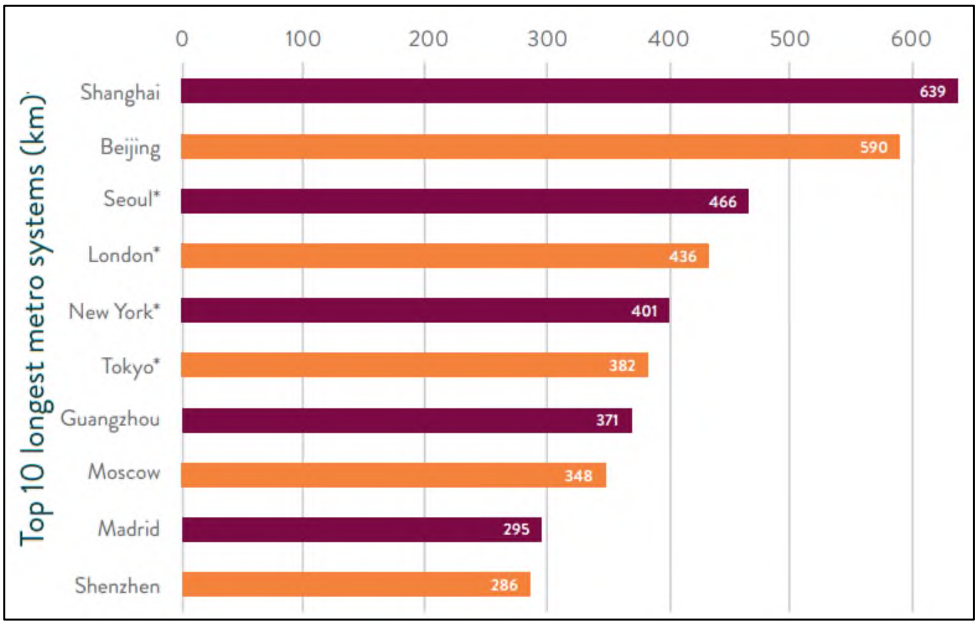

Figure 2.4. Top Ten Longest Metro Systems in 2017 (International Association of Public Transport 2018)

2.1.2. Main Components of Metro Systems

The main components of metro systems are stations, line structures between stations, depot area, railway, and metro vehicles. They, which are fully isolated rail transportation systems, are usually built underground using deep tunnel methods in order to reduce the traffic loads in the city. Depending on the terrain condition, they can also be built at grade or on a viaduct. All of these solutions can be used for both stations and line structures. For underground construction, different methods can be applied such as Cut-Cover, NATM, TBM, etc.

The main function of a metro station should be providing passengers an easy access to metro trains. The main purpose of a line structure is to provide the path between two stations where the vehicle will travel. In addition, both structures include technical systems (Tunnel ventilation fans, water tanks, transformers, catenary, etc.) for the metro system.

Whether the station type will be underground (Fig. 2.5), at-grade or elevated depends on the route, terrain conditions, and existing structures. These conditions also apply to line structures. Figure 2.6 shows that underground metro design is the dominant model in the world and the average distance between stations is calculated as 1.25 km (Fig. 2.7) (International Association of Public Transport 2018).

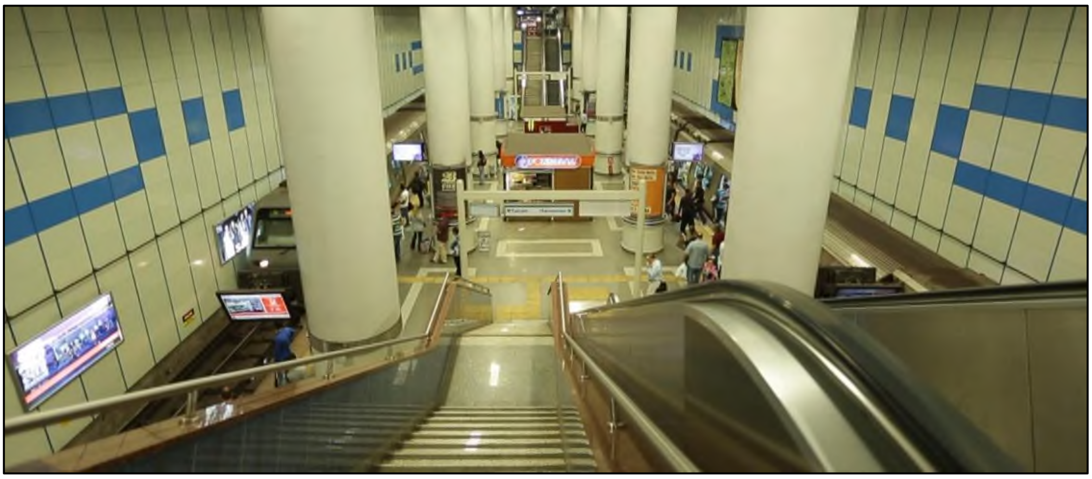

Figure 2.5. A Sample Image for an Underground Station

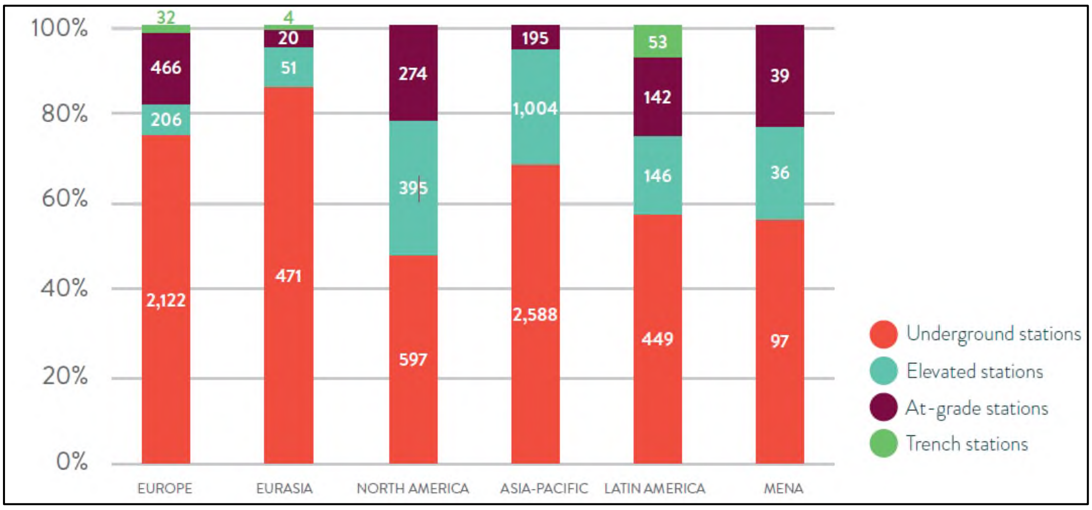

Figure 2.6. Distribution of Metro Stations According to World Region and Type of Station (International Association of Public Transport 2018)

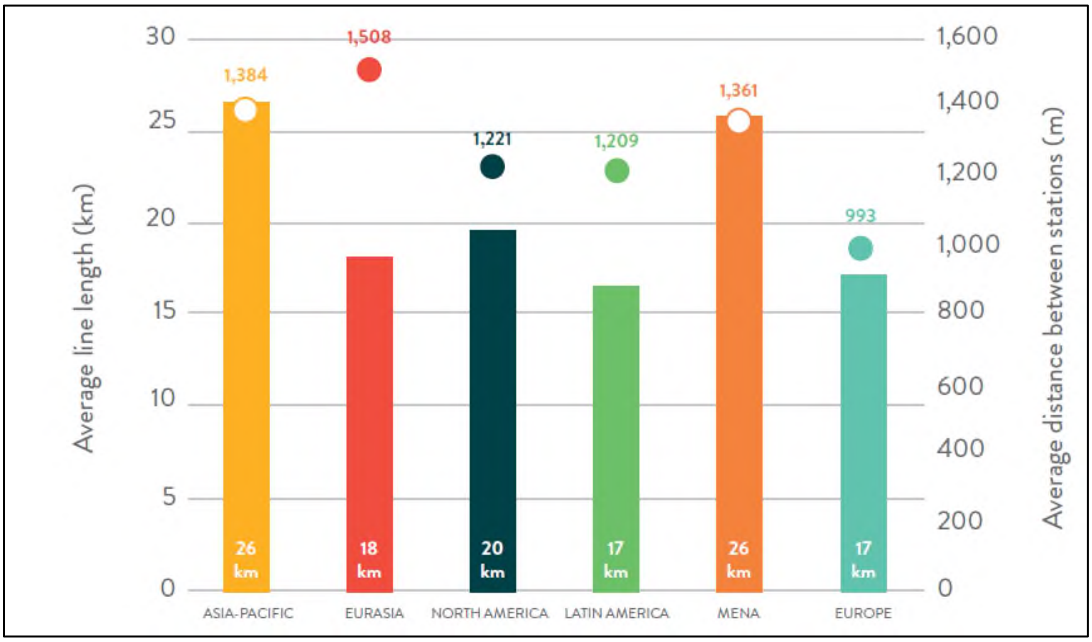

Figure 2.7. Distribution of Average Line Length and Distance between Stations According to World Region (International Association of Public Transport 2018)

Depot area is required for the storage of trains while they are not in operation. In addition, maintenance of vehicles is also performed in this area. According to the function of the metro system, there can be different buildings in the depot area. The available buildings are listed below.

- Maintenance Building (Fig. 2.8)
- Administration Building
- Transformer
- Heat Center
- Car Wash Area
- Parking Lot
- Material Warehouse
- Access Control
- Water Tank

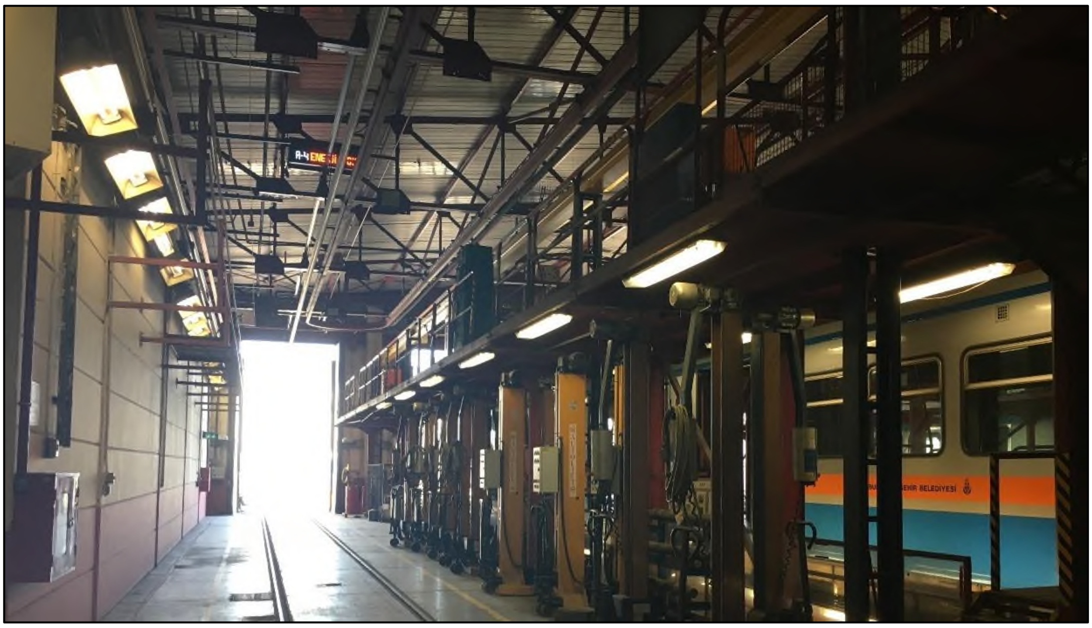

Figure 2.8. A Sample Image for Maintenance Building

2.1.3. Metro Systems in Turkey

The first urban railway system was opened during the Ottoman Empire period in Istanbul. These systems have a history of 150 years in Turkey. Today, 12 cities have at least one of the urban rail systems. These cities are Istanbul, Ankara, Izmir, Adana, Bursa, Kayseri, Eskisehir, Konya, Samsun, Antalya, Gaziantep, and Izmit. However, underground metro system solutions are relatively new.

So far, metro projects have been constructed in 5 cities and these are Istanbul, Ankara, Izmir, Adana, and Bursa. Istanbul metro network with a total length of 100 km and a passenger capacity of nearly 400 million is the most used metro system in terms of passenger capacity. In terms of passenger density, Izmir network has the highest rate (Table 2.1) carrying 100 million passengers despite the length of 20 km (Uysal 2018).

Table 2.1. *Metro Passenger Density per Kilometer (Uysal 2018)*

İzmir	5.0
İstanbul	4.0
Bursa	2.1
Ankara	2.0
Adana	1.4

In Istanbul, everyday railway system operation is provided by approximately 2 million people with the length of 170 km metro systems (Fig. 2.9). With the vision of “Metro Everywhere” rail system investments in Istanbul have gained momentum to have fast, comfortable, and safe transportation. In 2018, a total of 276 km of rail system’s construction has been in progress (Fig. 2.10). When the construction of the ongoing metro projects is completed, the total length of the metro system in Istanbul will be tripled. By the end of 2018, the length of the rail systems in Istanbul was expected to exceed 250 km (Uysal 2018). According to this vision, at the end of 2023 (Fig. 2.11), the total urban rail system target is 1100 km and ninety percent of this will be metro systems (Metro Istanbul 2019). In order to complete these lines in a short time, innovative approaches in the construction industry are started to be used. The most important of these, BIM, has taken its place in technical specifications for all metro projects in Istanbul. Since 2016, all construction and design works that have been tendered carried out by BIM processes. Recently, the first commissioning process of the first metro line constructed with BIM processes has started.

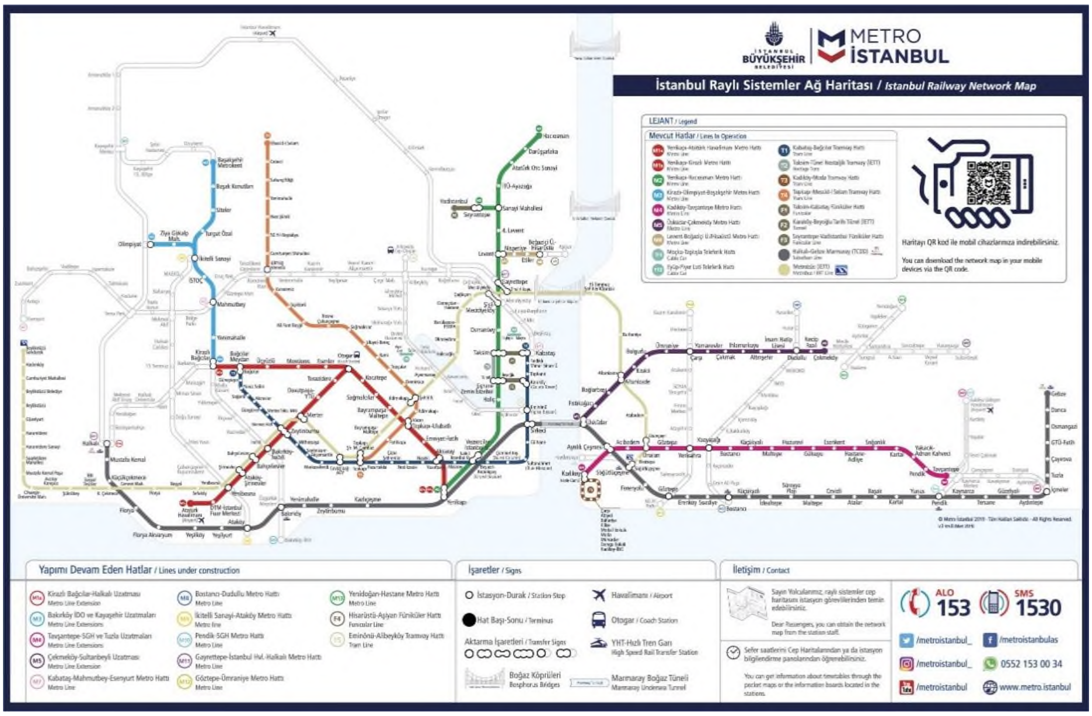

Figure 2.9. Istanbul Railway Network Map – Current Status (Metro Istanbul 2019)

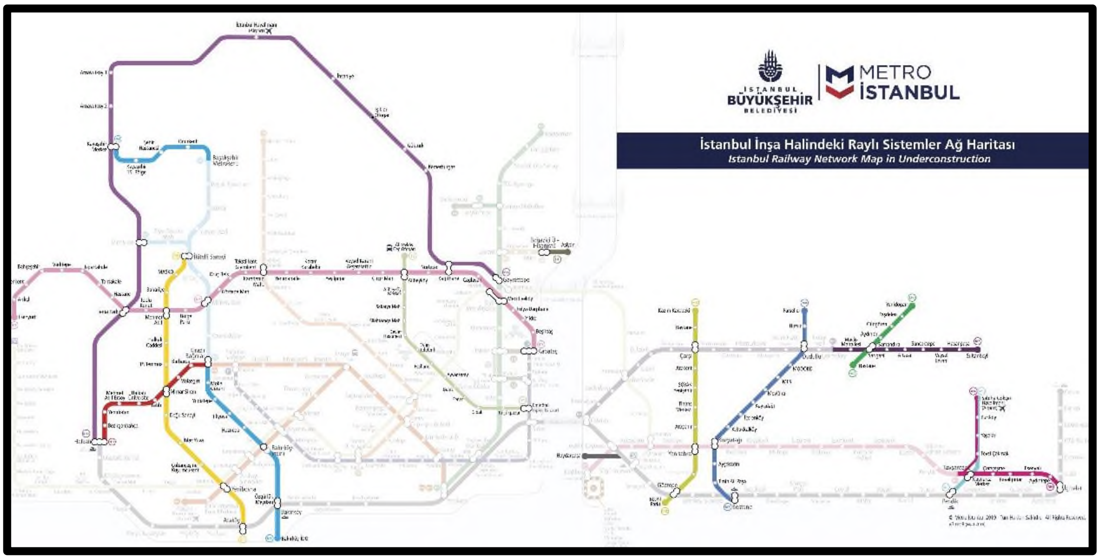

Figure 2.10. Istanbul Railway Network Map – Under Construction (Metro Istanbul 2019)

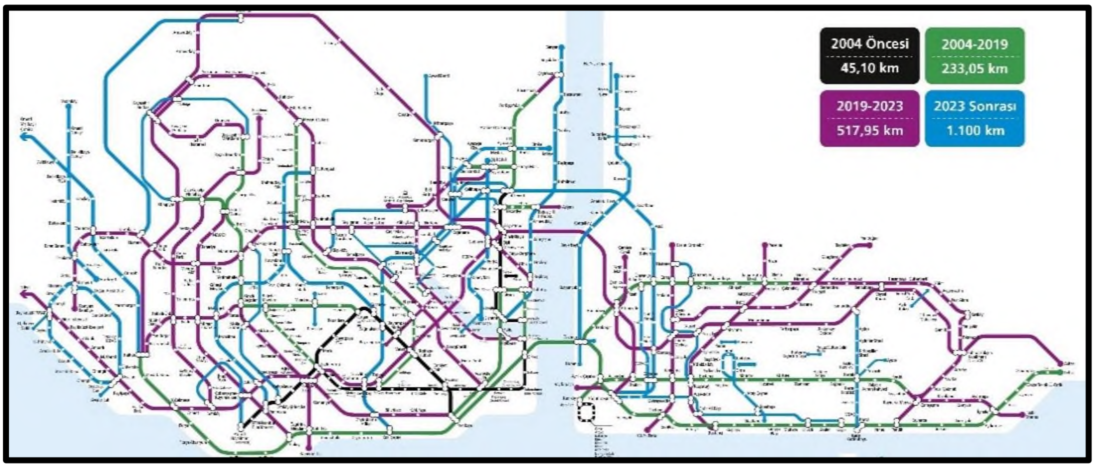

Figure 2.11. Istanbul Railway Network – Future Map (Metro Istanbul 2019)

2.1.4. Project Delivery Method for Metro Projects in Turkish AEC Industry

There are different project delivery methods (PDM) used in the construction sector such as Design-Bid-Build (DBB) Method, Self-Performance Method, Design-Build Method, and Integrated Project Delivery Method. The most common project delivery method having been used in Turkey is DBB.

In Turkey, all public tenders are published in the Electronic Public Procurement Platform (EKAP). The tender documents of the metro projects published on this platform have been examined and it is observed that the project delivery method of all metro projects has been DBB.

DBB is the oldest one among the existing project delivery systems. It is also called a traditional delivery method. In this system, the design, tender, and construction phases are progressing consecutively. In DBB, the employer initially agrees with a designer who will be responsible for the design part of the project. After all the design documents and specifications are prepared by the designer, the tender phase starts. During the tender phase, the contractor responsible for the construction phase is selected (METU 2007). The primary disadvantage of this method is that there is always a huge potential for conflict since the design and construction part become independent from each other (Gould and Joyce 2000).

2.1.5. Tender Documents

In DBB projects, tender documents are always created at the end of the design phase. In line with the decision of the Contracting Entity regarding the tender procedure and method, the tender documents should be prepared for the construction in accordance with the Public Procurement Law in force in a completely impartial manner and without leaving an open party in the tender evaluation. All surveys and quantities should be issued, warranty issues should be determined, specifications and contract text should be prepared. In order to prepare these, all design documents must be qualified for approval.

Tender documents for the metro project should be prepared in accordance with the technical specification and mostly include the following:

- Administrative specification
- Pre-qualification specification
- Draft contract
- General specification for construction works
- Design documents (Models, drawings, reports, etc.)
- All technical specifications
- Administrative specifications and draft contract to be prepared according to the law no. 4734
- Standard forms
- Feasibility study
- Quantities, unit price lists
- Special specifications

Generally, poor-quality tender documents created in the design phase cause conflicts between the employer, contractor, and designer during the construction phase.

2.2. Building Information Modeling

In this section, BIM subjects related with the research described in this thesis study and previous studies on BIM-based design collaboration have been investigated and the literature findings are presented.

2.2.1. Definition

Within the architecture, engineering and construction industry, Building Information Modeling (BIM) is considered as one of the most promising development. By using BIM, digital information model of a structure is created. Besides the exact geometry, the computer-generated model also contains the relevant data needed to support some activities required to realize the building when the model finished (Eastman et al. 2008).

BIM accommodates numerous functions needed to model the lifecycle of a building. BIM changes in the roles and relationships between the project team members and ensures the basis for new construction capabilities. With proper implementation, BIM helps to create a more integrated design and construction process, which results in better quality buildings at a lower cost and reduces project duration (Eastman et al. 2008).

In order to understand why BIM is a revolutionary technology, one must look into the transformation of the way buildings are designed, constructed, analyzed, and managed. According to Interoperability in the Construction Industry Report (Young et al. 2007), the deficiency in communication and collaboration through information has caused construction productivity to dropdown substantially. Current processes and higher interoperability among teams and software packages, better tools, and lesser change orders in the field have been drawing more attention to stakeholders, hence making them consider BIM as a solution (Hardin 2011).

2.2.2. BIM Uses

At the start of the project, the BIM objectives and BIM uses need to be set by the project stakeholders. On the other hand, how this process is carried out may vary depending on the country that the project will take place and sometimes even the employer. In some cases, these goals and BIM uses are directly defined by the employer in the technical specifications of the project.

In order to carry out the BIM processes correctly, it is important that BIM uses is well understood by the team members working in the project. Knowing for what purposes the model would be used until the operational stage will ensure that model content is created in the most accurate way (Computer Integrated Construction Research Program 2011).

There are different reference guidelines which have been prepared by different institutions regarding BIM uses. The guideline developed by a team of individuals within Computer Integrated Construction Research Program at Penn State is the most widely used guideline for this process in Turkey. In this document, 25 major BIM uses such as existing condition modeling (Fig. 2.12), 3D coordination, phase planning (Fig. 2.13), design authoring, record modeling, etc. were identified by considering literature studies and opinions of experts in the field (Fig. 2.14) (Computer Integrated Construction Research Program 2011).

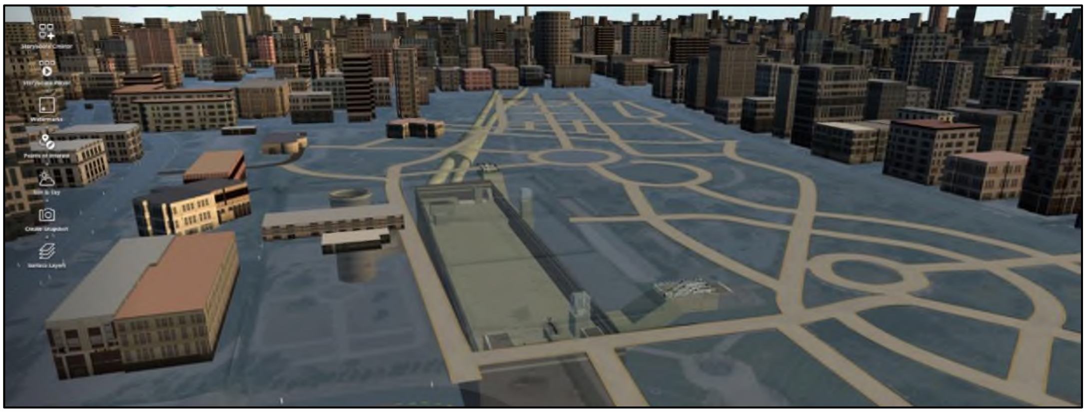

Figure 2.12. A Sample Image for Existing Condition Modeling

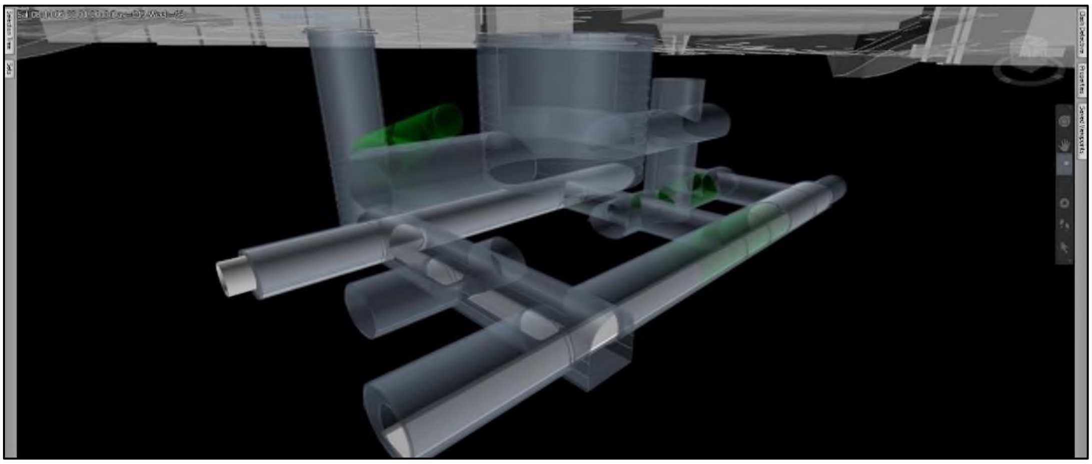

Figure 2.13. A Sample Image for Phase Planning

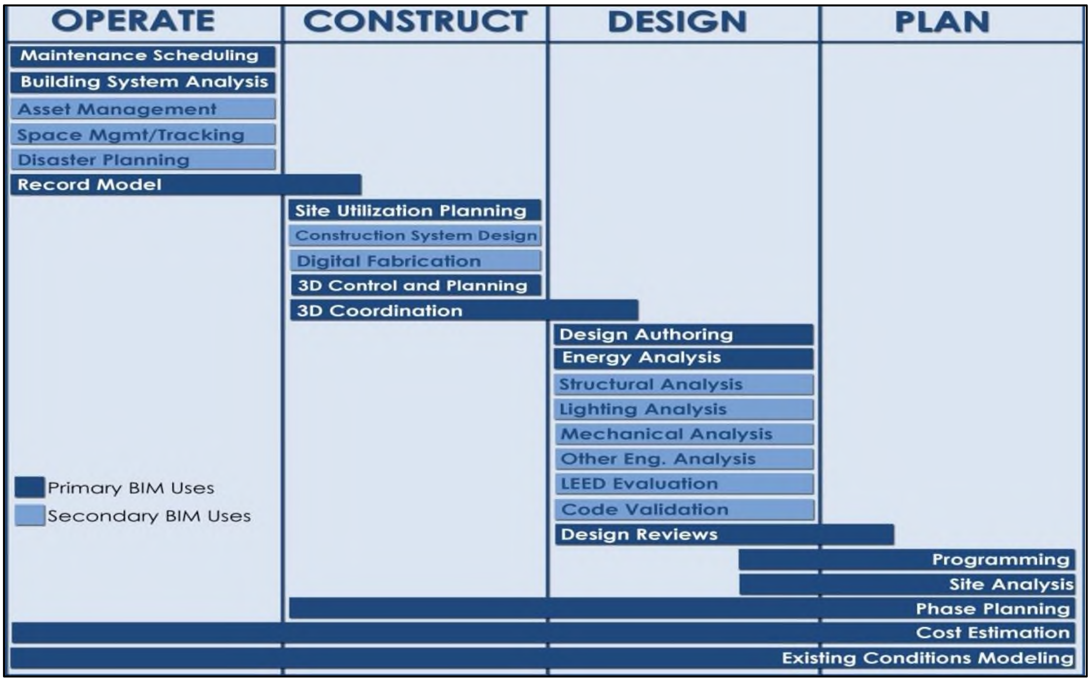

Figure 2.14. BIM Uses throughout a Project Lifecycle (Computer Integrated Construction Research Program 2011)

There is also another guideline prepared by Harvard University Construction Management Council. In this document 20 primary BIM uses were identified as shown in Table 2.2. Although there are some differences between the two documents, they are very similar in terms of significant content.

Table 2.2. *BIM Uses throughout a Project Lifecycle (Harvard University 2012)*

	Design	Preconstruction	Construction	Operations
Existing Conditions	X	X	X	
Program & Space Valida.	X			
Design Authoring	X			
Digital Mock-Up	X	X	X	
Design Options	X			
Design Communication	X			
Design Documents	X			
Design Analysis	X			
Engineering Analysis	X			
Design Coordination	X			
Construction Coordinat.		X	X	
Scheduling		X	X	
Quantity Extraction		X	X	
Logistics Planning		X	X	
Safety		X	X	
Construction Layout			X	
Shop Draw. & Submittals			X	
Field Supplements			X	
Turnover/Record BIM			X	
FM Implementation				X

2.2.3. BIM Standards

In the construction industry, standards exist to provide guidance and best practices on specific issues. There are many standards related to BIM established by different countries. The most used standards are listed below in Table 2.3 by country of publication.

The compliance of the standards with the infrastructure projects is examined. As a result, it is realized that BS standards include procedures and methods for both infrastructure and superstructure projects. It is decided they are suitable to use as a reference guideline for metro projects, as also stated in literature (Bradley et al. 2016).

Table 2.3. *BIM Standards and Guidelines*

International	ISO 19650-1: Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) – Information management using building information modelling - Concepts and principles
	ISO 19650-2: Organization and digitization of information about buildings and civil engineering works, including building information modelling -- Information management using building information modelling: Delivery phase of the assets
United Kingdom	BS EN ISO 19650-1: Same as ISO 19650-1
	BS EN ISO 19650-2: Same as ISO 19650-2
	BS1192:2007+A2 2016 Collaborative production of architectural, engineering and construction information – Code of practice **(Withdrawn, Superseded by BS EN ISO 19650)**
	PAS1192-2: 2013 Specification for information management for the capital delivery phase of construction projects using building information modelling **(Withdrawn, Superseded by BS EN ISO 19650)**
	PAS1192-3:2014 Specification for information management for the operational phase of assets using building information modelling
	BS1192-4: Collaborative production of information Part 4 Fulfilling employer's information exchange requirements using COBie – Code of practice
	PAS1192-5:2015 Specification for security-minded building information modelling, digital built environments and smart asset management
	PAS1192-6:2018 Specification for collaborative sharing and use of structured Health and Safety information using BIM
	BS 8536-1:2015 Briefing for design and construction. Code of practice for facilities management (Buildings infrastructure)
	BS 8536-2:2015 Briefing for design and construction. Code of practice for asset management (Linear and geographical infrastructure)

United States	US National BIM Standard Version 3
	Guide, Instructions and Commentary to the 2013 AIA Digital Practice Documents
	Penn State University BIM Project Execution Planning Guide
	BIM Forum LOD Specification
Canada	AEC (CAN) BIM Protocol 1.0
Finland	Common BIM Requirements
Norway	Statsbygg BIM Manual
Holland	Rgd BIM Standard
Singapore	Singapore's BIM Guide
Australia	NATSPEC National BIM Guide
Hong Kong	CIC BIM Standards

2.2.4. BIM Software and Tools

Today, CAD tools are used by the entire AEC industry. Thanks to constantly evolving technology, these tools are developing day by day. In this way, different solutions are offered to construction professionals. Now, BIM is creating a radical change in the construction sector. It replaces 2D tools and methods (Epstein 2012).

There are many BIM-based software solutions available today. New ones are being added to them continuously, and the capabilities of existing tools are also increasing with each new version. Tekla, Autodesk, Bentley, Graphisoft and Nemetschek are the software companies that develop the most preferred BIM solutions. They are used for many different purposes.

- 3D Modeling
- Design Coordination
- Generative Design
- Algorithmic-Aided Design

- Performance and Analysis
- Collaboration
- Preconstruction
- Cloud Computing
- Fabrication
- Facility Management

Algorithms-Aided Design (AAD) tools have been integrated into many software in recent years. These tools are used to assist in the creation and modification of the model. These tools are based on visual scripting rather than textual scripting and help the designer to overcome the limitations of the design software. Especially in projects where there is a lot of repetitive work like linear infrastructure projects, these tools may have great benefits.

Some of the AAD tools, commonly used by the designers, are listed below.

- Autodesk Dynamo Studio (Fig. 2.15)
- Grasshopper
- Marionette

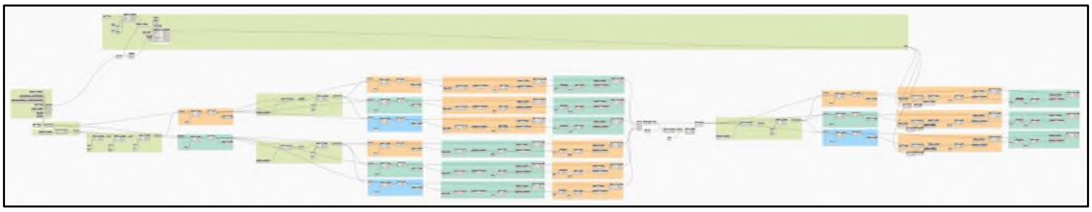

Figure 2.15. A Sample Image from Autodesk Dynamo Studio

Furthermore, many software companies have increased their investments in cloud-based BIM solutions. Improving cloud-based BIM solutions that will enable hundreds of different companies to work on the same platform in a project will significantly increase the efficiency in the construction sector.

2.2.5. Level of Development

Depending on the different BIM uses and phases of the project, the detail level of the elements in the model varies (BIM Forum 2019). In the AEC industry, the most widely used guideline to determine the detail level of an element is BIM Forum LOD Specification. It is published by BIM Forum every year. LOD definitions in this guideline are explained below in detail.

“LOD 100 – LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate.”

“LOD 200 – At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate.”

“LOD 300 – The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.”

“LOD 350 – The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.”

“LOD 400 – The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.”

The required LOD should be determined according to the requirements of the project and the model content should be planned accordingly. In Turkey, LODs are defined in the BIM specification for the metro projects by the employer. Although it is explained in the BIM FORUM LOD Specification that there should be no relationship between a model definition and LOD, minimum LOD definitions are made for the model-basis in the specifications of metro projects in Turkey. Generally, the specifications indicate that a minimum LOD 300 is expected for the model element on each discipline at the end of the design phase. Besides, the relationship between LOD and the design stages is not even mentioned in the specifications.

2.2.6. Information Management

In the construction industry, the most comprehensive standards used for information management are the BS standards. BS1192 standards set out a method to manage information effectively for a construction project. First, it was published as BS 1192-5:1990 in 1990. Then it was replaced in 1998 with the second edition published as BS 1192-5:1998. The third edition, BS 1192:2007, “Collaborative production of architectural, engineering and construction information: Code of practice” was published on 31 December 2007. For BS 1192:2007, sub-versions were published over the years, which were BS1192:2007+A1:2015 and BS1192:2007+A2:2016 (British Standards Institution 2016). Last year, the first set of international standards were published, and BS1192 was the main reference document in the preparation of these standards. BS1192 was withdrawn and superseded by British adoption, BS EN ISO 19650-1:2018 and BS EN ISO 19650-2:2018, of these international standards.

In BS1192:2007+A2:2016, it is mainly described as the process of authoring and sharing information through collaborative environments. In this standard, it is stated that "Projects should follow a common set of generic processes at the highest level, which are fine-tuned on a project-by-project basis. The procedures outlined apply to all approaches to project design production, and coordination of the information model.” According to this standard, the following methods and procedures should be applied in a project for effective collaboration.

- Roles and responsibilities should be clearly defined for various design disciplines.
- Naming convention should be defined to meet project needs.
- A Common Data Environment (CDE) process should be adopted to ensure that information is shared among all project stakeholders
- Stakeholders should agree on an information hierarchy that supports the CDE process.

Nowadays, most of the projects' BIM specifications state that the information management process must proceed in accordance with the CDE. This strategy is also involved in the metro projects that have been tendered in Turkey, in recent years.

There are four phases of the CDE:

I. Work-In-Progress (WIP)
II. Shared
III. Published
IV. Archived

CDE is described with the same fiction in both BS1192:2007+A2:2016 (Fig. 2.16) and BS EN ISO 19650-1:2018 (Fig. 2.17).

According to BS EN ISO 19650-1:2018, the explanation of each of the four states are as follows:

I. Work-In-Progress state is where the work is carried out by project teams. This information should not be visible or accessible to any other task team. The check/review/approve transition should be made by the responsible team.
II. Shared state's common objective is to provide constructive and collaborative development of the information model within a delivery team. These containers should be visible; however, they should not be editable. Moreover, this state can be used for sharing information with the

appointing party for the approval process. This kind of usage for this state is called the client shared state.

III. The published state is used for information that is authorized for use by project stakeholders.

IV. The archive state is used to keep a log of all information that is shared and published during the project lifecycle as well as an audit trail of their development.

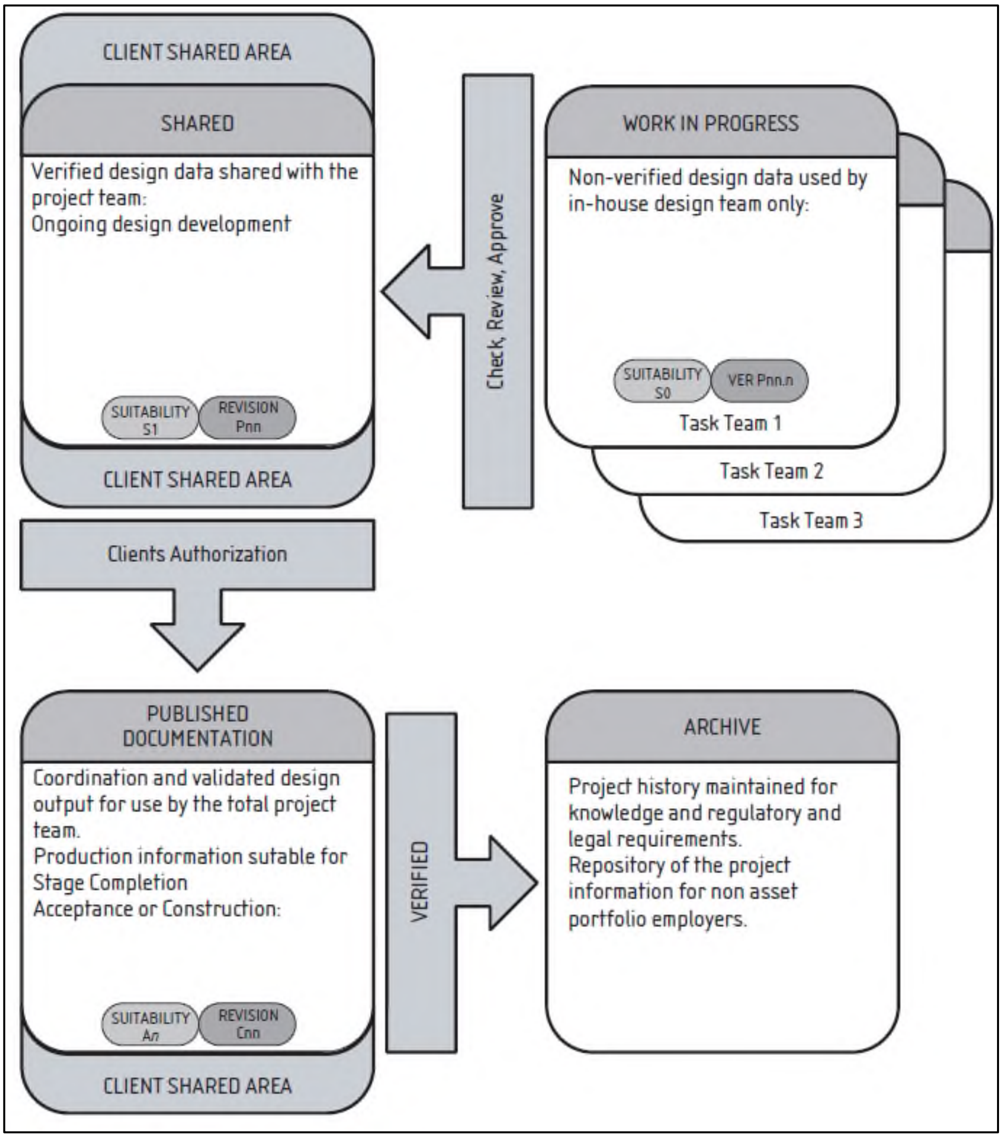

Figure 2.16. Concept of Common Data Environment According to BS1192:2007+A2:2016 (British Standards Institution 2016)

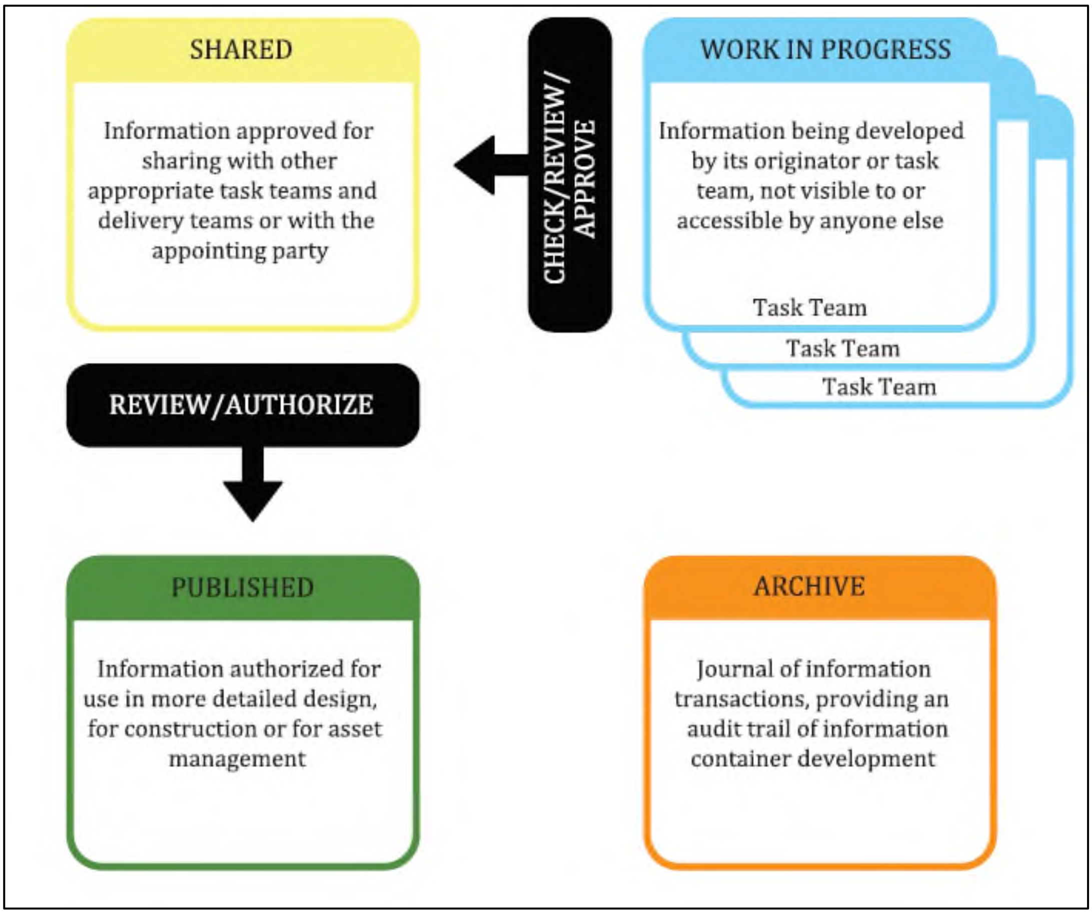

Figure 2.17. Concept of Common Data Environment According to BS EN ISO 19650-1:2018 (British Standards Institution 2018)

The advantages of adopting a CDE solution process, as described in BS EN ISO 19650-1:2018, are listed below.

- "Responsibility for the information within each information container remains with the organization that produced it, and although it is shared and reused, only that organization is allowed to change the contents."
- "Shared information containers reduce the time and cost in producing coordinated information."
- "A full audit trail of information production is available for use during and after each project delivery and asset management activity."

2.3. Relevant Studies

Using different databases, studies relevant with this research were examined from certain aspects. Although relevant studies were investigated in detail through Scopus database, it was considered that not all studies are available in Scopus. Therefore, databases such as Google Scholar and Thesis Center of Council of Higher Education were also examined for searching these studies.

Scopus database was searched by using different keywords and the results were examined. These keywords were searched in the "Article Title, Abstract, Keywords" of the studies. These keywords and the number of publications retrieved as a result of these searches are shared in Table 2.4 below. For the search results with more than 200 publications, the most cited publications and the studies published within the last year were examined in detail. Since it was foreseen that similar publications might be found by using different keywords, the duplicates are investigated and eliminated.

Since "subway system" is preferred to be used instead of "metro system" in some regions, scanning was performed separately for both words. In addition, different search combinations were realized by considering that BIM may be written as building information modeling as well. Since the railway structures resemble the metro structures at some points, it was also investigated within the scope of the study.

Table 2.4. *Search Results (Scopus)*

"Keywords	Number of Publications	Notes
BIM & Metro & Collaboration	0	
"Building Information Modeling" & Metro & Collaboration	0	
BIM & Metro & Design & Collaboration	0	
"Building Information Modeling" & Metro & Design & Collaboration	0	
BIM & Metro & "Design Automation"	0	

"Building Information Modeling" & Metro & "Design Automation"	0	
BIM & Metro & "Design Collaboration"	0	
"Building Information Modeling" & Metro & "Design Collaboration"	0	
BIM & Subway & "Design Collaboration"	0	
"Building Information Modeling" & Subway & "Design Collaboration"	0	
BIM & Metro & "Engineering Analysis"	0	
"Building Information Modeling" & Metro &"Engineering Analysis"	0	
BIM & Subway & "Engineering Analysis"	0	
"Building Information Modeling" & Subway &"Engineering Analysis"	0	
Metro & "Design Collaboration"	0	
Subway & "Design Collaboration"	0	
Metro & Design & "Information Management" & Automated	1	Data collection related
Subway & Design & "Information Management" & Automated	2	Data collection, crack detection
BIM & “Design Automation”	22	
“Building Information Modeling” & “Design Automation”	18	
BIM & “Design Collaboration”	39	
“Building Information Modeling” & “Design Collaboration”	27	
BIM & Metro	51	
“Building Information Modeling” & Metro	21	
BIM & Subway	55	
“Building Information Modeling” & Subway	22	
Metro & Design & Collaboration	35	
Metro & Design & “Information Management”	39	
Metro & Design	3814	

Subway & Design	3444	
BIM & Metro & Design	38	When “building information modeling” keyword is used instead of “BIM”, results are the same or less
BIM & Subway & Design	49	
BIM & Metro & “Information Management”	7	
BIM & Subway & “Information Management”	9	
BIM & Metro & Automated	2	
BIM & Subway & Automated	2	
BIM & “Information Management” & “Design Collaboration”	3	
BIM & “Information Management” & Design & Automated	55	
BIM & Subway & Collaboration	3	Publications for each search result is the same.
“Building Information Modeling” & Subway & Collaboration	2	
BIM & Subway & Design & Collaboration	3	
“Building Information Modeling” & Subway & Design & Collaboration	2	
Railway & “Design Collaboration”	4	
BIM & “Information Management”	942	
“Building Information Modeling” & “Information Management”	640	
BIM & Infrastructure & Design	481	
“Building Information Modeling” & Infrastructure & Design	313	
BIM & Railway	141	
“Building Information Modeling” & Railway	72	
BIM & "Design Phase"	291	
“Building Information Modeling” & "Design Phase"	200	
BIM & Collaboration	805	
“Building Information Modeling” & Collaboration	583	

Only Scopus database search results are given above. In addition to these searches, other databases were searched using similar keywords. Literature findings are presented below in detail.

Since building information modeling covers all the phases throughout the life cycle of the structure, in addition to the studies related with the whole life cycle, there are numerous research in which design, construction and operation phases have been studied separately.

Azhar (2011) stated that BIM is an innovative way to design the projects. It enables all design team members to collaborate more accurately and efficiently than using traditional processes.

The use of BIM at the design phase of the project will also have a positive impact on all project phases. Eastman et al. (2008) stated that using BIM during the design phase leads to more accurate design drawings, faster drawing production and improved quality in design. In their study, they defined the use of BIM during the design phase in 4 different viewpoints. These are conceptual design, design and analysis of building systems, use in developing construction-level information and design-construction integration. They indicated that the use of BIM in the design phase not only contributes to this project phase, but also provides benefits for the next project phases, construction and operation.

Schade et al. (2011) suggested that the early decisions in the design phase would have a positive impact on the life cycle performance of the building. It was stated that a model-based design approach could enable the early decision-making process. Developing and analyzing different design alternatives quickly with the model-based design approach in the design phase, the outcomes of the project can be improved.

Facility management processes can also become more efficient with BIM, even at the very beginning of the design phase. In their study, Wang et al (2013) developed a framework for facility management processes to be considered in early stages of the design phase. It was determined that it would be beneficial to reduce the life cycle cost with space planning and engineering analysis studies to be conducted in the design phase of the project with BIM.

Considering that the collaboration is at the center of the BIM, the studies related to BIM and collaboration were also examined, and it was observed that researchers have addressed this issue from different perspectives.

Bryde et al. (2013) stated that a high level of efficiency in communication and collaboration could be provided by BIM. Sebastian (2011) stated that multi-disciplinary collaboration could only be achieved by using BIM optimally. Leite et al. (2016) indicated that there is still a need for more automated and multi-disciplinary methods to handle interoperability and collaboration problems in the construction industry, along with BIM processes. Porwal and Hewage (2013) also indicated that a common language is needed for the information to be available for everyone, and different software can communicate with each other. While there are some protocols, the most important of which is IFC, for solving this interoperability issue, there are still issues that need to be improved in the current protocol.

Suchocki (2015) approached the collaboration issue related to BIM subject in a different way and discussed the processes in terms of information management. The main aspects described in the study related to collaboration and information management are described below:

- "Data from a mix of these resources will be increased during design development, and users will need to ensure that the data source, version, and proper use are available."
- "All project participants must understand the CDE process."
- "It should be clarified in which formats the data will be stored and which formats it should be in order to avoid risks such as copying, misuse or non-use of the data."

In addition to the studies related to BIM and collaboration covering all project phases, there are studies only covering the design phase of the project.

In their study, Idi and Khaidzir (2018) examined publications related to design collaboration and BIM and aimed to establish the perspective of design collaboration. They reviewed relevant research studies, and their analysis revealed that interdisciplinary design collaboration and teamwork using digital modalities were the main focuses for the majority of articles on the design collaboration with BIM. It was concluded that a definitive framework was incomplete on the constituent parameters of design collaboration. Bråthen (2015) states that design collaboration is still problematic due to the complex nature of a multidimensional interaction between teams. Grilo and Jardim-Goncalves (2010) suggested that instead of focusing solely on the technological level, seeking a solution to the problem of interoperability should include an analysis of a business-level interoperability value proposition. They proposed a model to measure the impact of interoperability at the business level.

Garber (2014) stated that design collaboration in BIM could be classified into three stages, which are architect–client collaboration, collaboration for submission, and collaboration for design check. Leon et al. (2015) proposed a conceptual design stage protocol for pre-BIM phases. The protocol was tested in a conceptual stage study, and the outcomes were presented. It is suggested that the protocol makes a significant improvement for the design studies, and it increases the communication between design teams. In their research, Wang et al. (2014) aimed to improve the design practice of a complex building by assembling BIM technology. A case study was conducted for a complex building in China. With the proposed design collaboration framework, their findings indicated that the duration of the design studies was shortened, and the performance of the design increased. Isikdag and Underwood (2010) proposed a system using the BIM-based approach to facilitate a shared environment. Their system proposal also covered the life cycle of the project, including the design phase.

Design collaboration studies were established through Industry Foundation Classes (IFC) format as well as collaborative studies conducted through the design authoring main file formats. Plume and Mitchell (2007) shared their design studio experiences for a collaborative design approach by using a shared IFC building model. Some of the important issues determined from this study were “the importance of creating a building model that is suitable to support collaborative design” and “the notion of attaching intentions to elements in the project model”. On the other hand, Park and Kim (2016) conducted a study on how to manage design collaboration processes between different software without IFC format. They examined the collaboration processes in terms of civil structures and architectural studies. In particular, they focused on approaches that allow data transfer between relevant software without loss of data.

Web platform-based design collaboration systems were also investigated and examined. Shafiq et al. (2013) mentioned that the document-centered structure of the construction sector is facing a new challenge, together with BIM. In their study, they discussed the process in terms of model collaboration and evaluated different web-based model collaboration systems available in the market and identified the requirements for BIM collaboration. Kim et al. (2016) focused on developing a technology for BIM-based design collaboration related to permission management and file synchronization in the web platform. The proposed collaboration system includes the design authoring software, the solution that enables the conversion to display the models on the web, and the system where the information is stored. Chen and Hou (2011) proposed an internet-based design collaboration platform for inter-disciplinary collaboration. A hybrid network (Client-Server and Peer-to-Peer) used for collaboration between design teams allows them to communicate real-time and transmit model-related information.

There are also studies covering BIM-server based collaboration system. Singh et al. (2011) developed a theoretical framework of technical requirements for using BIM-server as a multi-disciplinary collaboration platform. Focus group interviews were conducted with experts, and a case study was conducted by using an architectural project. It is concluded that more importance should be given to support technical requirements in order to facilitate technology management and interdisciplinary application.

With the introduction of BIM in infrastructure projects in recent years, studies have been carried out on how BIM should be integrated in infrastructure projects and how collaboration processes should be.

According to The Business Value of BIM For Infrastructure Report (2017) conducted by Dodge Data & Analytics, 87% of the survey respondents work on infrastructure projects were claimed that they are receiving positive value from their use of BIM. In this study, respondents were asked to select the top 3 benefits out of a list of 13 benefits that they experience from using BIM in the infrastructure projects. The top 5 results of the survey are listed below;

- Fewer Errors → 34%
- Greater Cost Predictability → 22%
- Better Understanding of Project → 21%
- Improved Schedule → 16%
- Optimized Design → 8%

In addition, it is stated that the use of BIM processes in infrastructure projects reduces repetitive work by 22%, design errors by 29%, and project duration 20%. In addition, when the value of the BIM to the different project phases is examined for each country participating the survey, it is seen that the greatest efficiency can be obtained during the design phase (Fig. 2.18). The Business Value of BIM For Infrastructure Report (2017) demonstrates the positive impact of BIM processes on infrastructure investments.

Bradley et al. (2016) carried out a literature review by using four different databases related to the use of BIM in infrastructure projects. In total, 2997 results were reduced to 84 publications since they can be examined in terms of infrastructure studies. When the relevant documents were examined within the scope of the research according to project phases, research methodology and project type, it was stated that most studies had been carried out on highways and bridges. It was found that the least publication in the use of BIM for infrastructure projects was related to the design phases. The most important reason for this was that most researchers were focusing more on operation phases since it has an essential place in infrastructure investments. Also, since the studies related to the design of a superstructure with BIM have been carried out in excess, the use of BIM in the design phases of infrastructure projects has not been examined in detail by the researchers. Even so, it was indicated that these studies, conducted for the design of superstructures, are needed to be transitioned to be used in infrastructure projects. According to the result of the literature review, the ratio of all studies to the case studies was approximately 10%. Thus, it indicates that there are not many case studies for the design process of metro structures in the recent literature.

	US	UK	France	Germany
Before Design Begins				
Preplanning (US)/Brief (UK, France, Germany)	7%	0%	4%	2%
Predesign (US)/Concept (UK, France, Germany)	15%	22%	10%	19%
During Design				
Design Development (US)/Developed Design (UK, France, Germany)	36%	49%	49%	44%
Construction Documentation (US Only)	11%			
Bidding/Construction/Installation				
Bid Letting (US)	1%			
Production (UK, France, Germany)		13%	20%	22%
Construction (US)/Installation (UK, France, Germany)	28%	7%	3%	13%
Post-Construction				
Project Closeout (US)/As Constructed (UK, France, Germany)	0%	7%	12%	0%
Maintenance (US)/Use (UK, France, Germany)	0%	2%	1%	0%

Figure 2.18. Project Stage at Which BIM Provides the Greatest Value (Dodge Data and Analytics 2017)

When the metro and railway projects, which are among the infrastructure projects, were examined in the literature, it was determined that more work had been realized in particular for railway projects. Therefore, in order to conduct a more comprehensive study, the research studies conducted for two types of projects were also examined.

Taylor (2017) presented the development of BIM platform and digital engineering from the context of railway systems. In this study, the process of digitization from the detailed design stage to the operational phase in London's new Elizabeth line were described. In this project, it is specified that the collaboration processes of different stakeholders were managed according to CDE principles for not only the design phase but also the whole life cycle of the project. CDE provided significant benefits to the stakeholder to manage and control information produced with Geographic Information System (GIS) and BIM processes.

As in the previous study, in general, when the research related to railway or metro systems and BIM are examined, most of the studies are about the integration of BIM and GIS for railway or metro systems. Kurwi et al. (2017) indicates that the integration of BIM and GIS is promising because BIM does not provide geographic data and its scope generally does not go beyond the structure itself. Fosu et al. (2015) states that "combining BIM with GIS would provide a complete picture for the project because of the complementary nature of the information that each technology can provide."

In addition to these studies, there were also research studies focusing only on BIM process for metro and railway projects instead of BIM and GIS integration. When the studies prepared for the design specific were examined among these publications, it was seen that the researchers approached the process from different angles.

Saldanha (2017) presented a preliminary overview of the processes by which BIM can be applied at different project phases for the metro systems. The use of BIM for metro systems were examined separately according to 4 different project phases; planning, design, construction, and operations. In this study, BIM uses proposed to be conducted in the design phase of metro projects were grouped as follows;

- Design documents creation
- Ventilation and air quality analysis
- Fire safety analysis
- Occupant flow modeling

- Designing for improved constructability
- Code validation
- Energy analysis
- Lighting analysis
- LEED assessments
- Clash detection

Most of the infrastructure design phase research was concerned with case studies of practical examples of BIM. Bensalah et al. (2018) aimed to confirm the theoretical results with the integration of Building Information Modeling to railway system projects by executing a real scale experiment. It was described that BIM in rail systems had multiple advantages: cost optimization, time saving, integrated team, improved design visualized throughout the study and conflict detection. They stated that the experimentation was limited, and a more comprehensive study is needed for a whole railway project. Conflict detection, time saving, integrated team, improved design visualized throughout the study and cost optimization.

Nuttens et al. (2018) shared their experience related to implementation of BIM methodology to support the design integration of different disciplines in large rail infrastructure projects. Implementing BIM in their design studies, they aimed to improve their design efficiency, to deliver high-quality integrated study designs and to minimize delays. In their study, they identified the key factors, on company level as well as on project level, to successfully implement BIM technology to large rail infrastructure projects in a large design firm.

Wu et al. (2018) carried out a study on the use of BIM in culvert and bridge design in railway projects. It was realized through a real project application. For a 170 km railway project, each culvert and bridge structure were modeled by BIM processes. At the center of BIM studies, there was only a bridge and culvert design team. Although it was implemented for a real project, in which different disciplines are actively involved in the design studies, an integrated design collaboration system involving other disciplines was indicated as future work.

In their study conducted by Stelzer et al. (2018), the advantages and disadvantages of using BIM methodology for metro projects were discussed. The proposal study was used as a case study in a small area of real metro design. Their findings indicate that the pioneering efforts in implementing BIM oriented approach in tunneling.

Bei and Xianbin (2018) stated that BIM technology can solve problems encountered in the design of metro projects, which are limited site space, complex resource allocation, tight schedule, underground pipeline, etc. Within the scope of their study, a system was performed in a real-life metro project. In their research, an analysis for the entrance area of one station were performed.

Although there were studies covering the design phase, metro projects and collaboration related to BIM separately, a research study related to BIM collaboration system covering all disciplines during the design phase of the metro project were not encountered. In addition, there were very few research studies in which all disciplines are actively involved in the study. Besides, since the case study were carried out for the whole metro corridor, it also increased the importance of the research. This study was carried out to fill these gaps in the literature.

CHAPTER 3

A BIM-BASED COLLABORATION SYSTEM

3.1. Research Methodology

In this research, a system development study was carried out progressively. Firstly, the necessary systems for designing a metro project and the disciplines that are involved in the design of these systems were determined considering the needs of the Turkish AEC industry. From the preliminary stage to the detailed design stage, the responsibilities of these disciplines were specified.

One of the main purposes was to automate the information management process between the disciplines. First, how the file sharing processes should be carried out between these disciplines was determined. For each discipline, files and file formats that are used as a reference in their studies, which are created by other disciplines, were identified. At this stage, interdisciplinary data sharing needs were also identified to automate these processes as well.

Furthermore, how review and coordination activities should be carried out in accordance with CDE was clarified. It was decided that the documents shared for the review should be followed separately from the coordination processes. As a result, the review and coordination processes were decided to be monitored on separate platforms and all review processes to be recorded within another environment. Based on these decisions, the file directory structure was formed.

Secondly, the engineering analysis and simulations performed during the design process was examined in detail. As a result, it was observed that some of these studies were performed only on data belonging to a single discipline, while some of them were made by combining data from different disciplines. When all engineering analysis and simulations were examined one by one, three different scenarios about how the process will proceed have emerged:

ii. Performing the analysis/simulation studies in the software in which the model is created
iii. Performing the analysis/simulation studies in another software using the model data
iv. Performing the analysis/simulation studies with the traditional approach without using the model

The last subject was design automation. In order to improve the design process, the studies where design automation solutions are needed were determined. First, it was determined that which of these design studies can be carried out with the existing solutions currently developed by the software companies. After that, algorithms were created for performing the studies that could not be supported with the existing software solutions. Different techniques (AAD, Application Programming Interface (API), Programming, etc.) were preferred during the development of these automation solutions.

In the end, responsibilities for each discipline were redefined to cover all requirements. Process maps describing the design studies for each discipline were prepared. Besides, the activities in the process maps are described in detail and the integrated collaboration system was finalized.

3.2. Standardizing Information Management

There is a multidisciplinary study process at the center of the design of the metro projects. Thousands of documents will be created by the disciplines from the preliminary design stage to the creation of tender documents. All of the interdisciplinary file exchanges should be standardized and these exchanges should be automated by determining the reference file requirements criteria for each discipline.

In a research study where all major BIM standards were examined in detail, Bradley et al. (2016) deduce that the procedures for a common data environment (CDE), information management, and design collaboration are described in similar ways in BIM standards. CDE principles are at the center of the information management. Therefore, the information management process has been constructed by the principles of the common data environment in the proposed system. It only covers the CDE process from work-in-progress (WIP) to client sharing phases. How this process should be executed is explained in detail below.

First, the document coding procedure should be standardized. This is not only useful for naming documents but also will help in creating support tools that will aid the whole collaboration and automated document sharing process.

Second, design teams and their roles should be defined since a design team may be responsible to create design documents for multiple disciplines. For example, if the same team is preparing the route and traffic projects, a role and folder structure can be created accordingly. WIP folder areas should be identified depending on the design teams and the model division strategy described in the BIM Execution Plan (BEP). According to the operating system, folder permission definitions of the design teams should be determined.

Afterward, a folder area should be created for the project and sub-folders should be defined in it. In this way, all documents produced for the project will be collected in a single folder area. Under the corresponding project folder, sub-folders need to be customized according to categories like tender documents, design handbooks and design documents, BIM execution plan, project management documents, project title block, design documents, etc.

In the sub-folders, first of all; where the project management documents, technical specifications, project schedule, minutes of meeting, document coding systems' guidelines and project title blocks will be kept should be determined. Editing access to these areas should be defined for the senior staff like project manager, BIM manager, or assistant project manager. It is important that other users should have the right of viewing these documents, but not editing. The Figure 3.1 shows an example folder structure for the project's general documents.

Figure 3.1. Folder Structure Example for the Project General Documents

The presence of correspondences in the project management folder or the presence of standards or technical specifications in the same folder will not have a major impact on the project. The important issue here is that these sub-folders should be defined exclusively so each user can access the same information. Discipline, role, or user-based permissions can be given in these areas.

Within the sub-folders, the work-in-progress (WIP) area, which will be used for carrying out design documents creation works, should be established for each discipline as defined in the CDE. The suggested sub-folder structure for different disciplines involved in the design is listed below and the structure may vary depending on the project needs or the definition of the responsibilities of the design teams.

- Architectural
- Structural
- Geotechnical
- Mechanical
- Fire
- Electrical
- Electronic
- Landscaping

- Underground Utilities
- Route
- Traffic
- Survey

At the beginning of the project, sub-discipline folders can be arranged according to the model division strategies defined in the BIM Execution Plan (BEP). Two folders can be defined if architectural aesthetic and functional design works are being carried out by different teams. Similarly, if electrical and electronic systems are modeled together by the same team, these two folders can be combined into a single folder. The critical issue here is that the WIP and SHARED subfolders must be exactly the same.

Under discipline folders, sub-folders should be defined according to the characteristics of the metro structure type (station or line structure), structure information (station-1, station-2, line-1, line-2, etc.) and document type (model, model outcomes, report, simulation, etc.).

After that, a "SHARED" folder area should be created where all design teams can share their works with each other. This folder is where all BIM models, survey files, utility models, route projects, etc. are stored for the use of review and coordination studies. When the file created in the WIP area is at the level of sharing, it should be shared in the relevant "SHARED" folder. In this folder, shared models\drawings folders for coordination or review must be separated from each other by creating separate sub-folders. From the beginning to the end, all the shared documents should be stored in “SHARED” folder area.

Sharing to this folder and accessing to the content shared in the folder should be done automatically from the WIP file. In the case of file sharing, it should be forwarded to the related folder areas automatically. Also, access to all these shared documents should be provided within the model file that current design work is being performed. All versions of the shared documents and the version of the document that is being used in the model file being worked on should be followed easily.

Considering the disciplines involved in metro projects and the file formats in which these disciplines work, sharing should be done not only in the main file format in which the file is produced but also in different file formats that other disciplines using different software tools can utilize. For example, when the file sharing of the architectural discipline model is done, a 3D CAD model (*.dwg file format) should be shared as well as the main file format for disciplines that make 3D CAD design in this file format. Moreover, for disciplines carrying out their studies in 2D, the layout plan of the station should be shared. In addition, for disciplines that use a different design authoring software, the model file should be shared in*.ifc format.

Table 3.1 specifies the suggested file formats to be shared by the disciplines. The list may vary depending on the project needs. It is important that all design teams clarify the decisions regarding the sharing formats to be made at the beginning of the project.

Table 3.1. *Suggested Format Table for Interdisciplinary File Sharing*

Discipline	BIM Model (Main File Format)	3D Model (*.dwg) (3)	2D CAD (*.dwg) (3)	IFC Format	Coordination Model Format
Architectural	x	x	x	x	x
Structural	x	x	x	x	x
Geotechnical	x	x	x	x	x
Mechanical	x	x	x	x	x
Fire	x	x	x	x	x
Electrical	x	x	x	x	x
Electronic	x	x	x	x	x
Landscaping	x	x	x	x	x
Utilities		x	x		
Route		x(1)	x		
Traffic		x	x		
Survey		x(2)	x		x(2)

(1) The 3D model line of the route should be shared.
(2) The existing structures should be shared in 3D, file format may change.
(3) Although *.dwg file format is specified in the table, similar file formats (*.dgn or *.ncz) can also be used instead according to the software used.

When model files are shared for coordination or review, views, sheets, lists and data that will not be used by other disciplines in the model should be removed completely. These definitions can also be defined in the software solution in which the information management process will be managed.

In addition, there will be disciplines working on the whole metro corridor as well as disciplines working on each structure separately in their WIP file. Disciplines producing information models usually carry out the relevant studies separately for each station or line structure. Since the information models have the coordinate information, the related model files can be included in the study of the disciplines working on the whole metro corridor at once, without any problem. The work conducted for the entire metro corridor in a single file should not be included as a whole in the work of the disciplines working separately for each structure. The relevant structure corridors should be identified in the WIP study files (whole metro corridor) and automated sharing for these corridors should be conducted for each structure areas. For example, base map file is created for the whole metro corridor by the survey discipline and it is used directly by the route discipline. On the other hand, it is sufficient to share a base map for a certain corridor from the station area for the architectural discipline.

Automating the sharing process by defining the rights to write in “SHARED” folder only from the design authoring software solutions would be the most appropriate solution to minimize human errors. Only the system administrator should be authorized to intervene in this folder. All other users’ permissions must be defined as read-only. If a design team shares the wrong file, the system administrator must have the authority to delete it. The document removed from the “SHARED” folder area by the system administrator should not be deleted completely. It should be archived in a specific folder area. This folder should be defined with read-only rights for all users and they should be able to see all documents removed from the “SHARED” folder area. When a document of the relevant discipline is removed from the “SHARED” folder area by the system administrator, the design team responsible in creating and sharing this document must be notified automatically. In this way, it can be ensured that the errors that may be made by the system administrator can also be followed.

Furthermore, a solution that checks the model quality in coordination sharing should be used to prevent the sharing of the files that are not suitable for coordination. Since model control definitions can be changed in a project-specific way, a solution that has an ability to define different rules should be preferred. But in general, standard model checklists are used in the design of the metro projects in Turkey. The software can be organized according to these standard checklists.

The system can be applied for every operating system that has the feature of folder structure. For operating systems that do not work with folder structure, however, the system may be designed by using metadata definitions similar to proposed structure.

Since current software systems do not provide sufficient solutions for the proposed information management automation processes, additional tools have been developed within the scope of this research to perform all of the defined processes.

3.3. Engineering Analysis and Simulations

Because of the complex structures of the metro systems and active involvement of many disciplines, different analysis and simulation studies are required in the design studies. The analysis and simulations performed during the design process are listed below:

- Advanced Radio Propagation Analysis
- High-Low Voltage Simulation
- Electrical Selectivity Analysis
- Acoustical Analysis
- CCTV Visualization Simulation
- Advanced Lighting Simulation
- Structural Analysis
- Vibration Analysis

- Pedestrian Dynamic Simulation
- Fire Evacuation Simulation
- Signaling and Catenary System Simulation
- Tunnel Ventilation Simulation
- CFD Analysis
- Traction Power Simulation
- Electro-Acoustical Analysis
- Vehicle (Traffic) Simulation
- Solar Energy Analysis
- Cable Tray Calculation
- Ventilation Flow Calculation
- Heating-Cooling Calculation
- Domestic-Water Calculation
- Waste-Water Calculation
- Sanitary and Drainage Calculation
- Hydraulic Calculation

When all engineering analysis and simulations have been examined one by one, three different scenarios about how the process will proceed have emerged.

i. Performing these studies in the software in which the model is created
ii. Performing these studies in another software using the model data
iii. Performing these studies with the traditional approach without using the model

Although the studies to be carried out with the traditional method will not have an additional contribution to the process, the studies conducted by using the model data and to be carried out within the model will have a significant contribution to the design process. In addition to being able to carry out these studies, it should not be ignored that the outputs of these studies can also be used to prepare calculation reports.

The proposed approaches for analysis and simulations are listed in Table 3.2 below. In preparing this list, the competencies of the software currently used in the design of the metro systems are taken into consideration

Table 3.2. *Proposed Approaches for Engineering Analysis and Simulations*

In BIM Model	**In Another Software Using Model Data**	**Traditional Approach**
• Ventilation Flow Calculation • Heating-Cooling Calculation • Domestic-Water Calculation • Waste-Water Calculation • Sanitary and Drainage Calculation • Hydraulic Calculation • Solar Energy Analysis	• CFD Simulation • Tunnel Ventilation Simulation • Structural Analysis • Vehicle (Traffic) Simulation • CCTV Visualization Simulation • Advanced Lighting Simulation • Advanced Radio Propagation Analysis • Electro-Acoustical Analysis • Cable Tray Calculation • Fire Evacuation Simulation • Pedestrian Dynamic Simulation	• Traction Power Simulation • Acoustical Analysis • High-Low Voltage Simulation • Electrical Selectivity Analysis • Vibration Analysis • Signaling and Catenary System Simulation

3.4. Design Automation

The integration of automation into the design process has become an important subject in the AEC industry. It has the potential to change design processes from top to bottom. It is beneficial for producing different design alternatives quickly and reflecting the changes to the project (Abrishami et al. 2014).

It is important to automate the processes for design activities with a certain systematic. Especially if different design alternatives need to be studied or a revision need arises, the need to create different design alternatives from scratch or the need to manually revised the design will be avoided with the design automation solutions.

Alternative design studies provide a great benefit for evaluating the project in terms of cost, function, and ergonomics. While it has become difficult to keep up with the current design demands within the periods allowed for the design of metro systems, studying different design alternatives becomes unmanageable. Even in a project with a longer duration, design teams may not find the opportunity to work on design alternatives because they have to involve in many repetitive and time-consuming work. For these reasons, automation solutions should be used to eliminate these repetitive and time-consuming tasks. Different design alternatives demanded by the employer should be created quickly with the automation processes. In addition, studies should be revised quickly in case of design changes.

Besides, automating design in terms of modeling processes can enable minimizing human-induced errors. Completing repetitive tasks manually is not only time-consuming and monotonous for designers; it may also result in some mindless mistakes.

By automating repetitive tasks in the design phase, designers can ensure accuracy and also save their creative powers and time for the important issues in the project. Due to these reasons, the design automation solutions are at the center of the proposed collaboration system. The proposed automation solutions are listed below. The list has been prepared considering the existing design processes in Turkey.

- Modeling underground structural tunnels based on the coordinate data taken from the route study file and the maximum tunnel lengths
- Generating the tunnel and station mass models for different route alternatives in the preliminary design stage
- Updating station coordinates on all models depending on the change in the route file
- Creating 3D existing condition models for the whole metro corridor

- Creating Room Data Sheets (RDS)
- Placing architectural finish elements for different alternatives
- Creating structural and architectural reservations
- Controlling and modifying room dimensions in compliance with metro design criteria and national/international standards
- Viewing changes made between different versions of the shared models
- Converting information model to suitable content for some analysis and simulation studies performed in other software solutions

The implementation of automation solutions offered by BIM has great importance in the design of longitudinal structures. Especially in the design of line structures, automation of the process will provide a great advantage to users. Line structure types may vary as viaduct, at-grade, or underground tunnel depending on the terrain conditions. Mostly underground tunnels are preferred for the metro systems in Turkey. In the traditional approach, these underground tunnel structures are presented only as plans and typical cross-section drawings.

In the BIM-mandated metro projects, the creation of information models for line structures (Fig. 3.2) is requested in the technical BIM specifications. Employer's demand causes a significant workload for the design teams. It is time-consuming work to model underground tunnel structures manually with 3, 6, and 12-meter elements for lines running for kilometers.

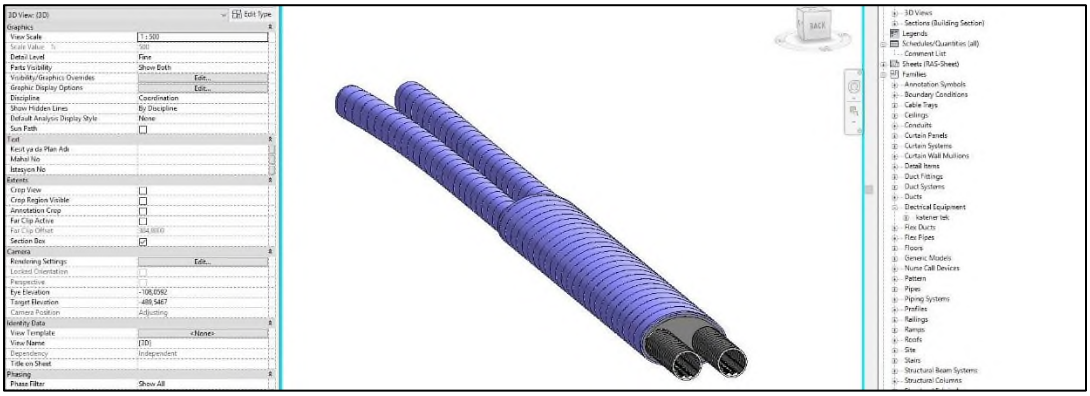

Figure 3.2. BIM Model for Underground Tunnel Structure

In case of revision of the route, the need to update these models also creates a serious waste of time. Changes to the route project and the line structure should be corrected manually wherever there is a revision. Instead, having a system that can automatically create and update the design based on the route data will minimize the design duration spent for modeling these structures. For this study, 3D model line shared in “SHARED” folder by the route team should be used. These modeling studies should be performed using AAD solutions.

In addition, it will be easier to perform route selection and station placement studies for different alternatives by ensuring that these structures are automatically generated during the preliminary design stage. With the existing structures being modeled in 3D, it will be possible to quickly examine the interaction of these structures with the metro line (Fig. 3.3).

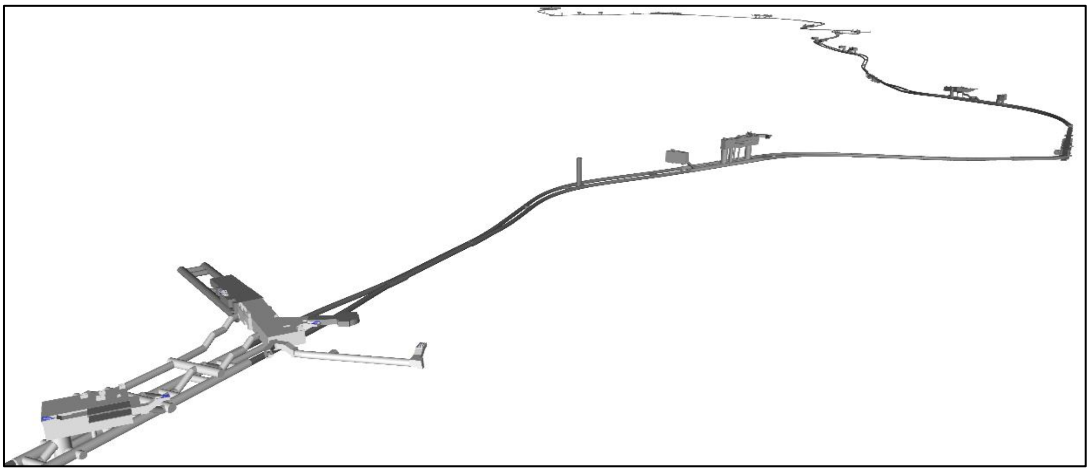

Figure 3.3. Mass Model for Entire Metro System

Another data to be taken from the route file should be the coordinate information of the stations. In the design process, the change of the station layout in small intervals is experienced mostly. When the point where the station coordinate data is entered in the models and the point where the relevant data is read from the route file is standardized, the coordinate information of all discipline models can be automatically corrected when the route file is changed. It is sufficient to take intersection of the platform head with the right-line at x-y plane and intersection of this point with the rail level (+0,00 for station) at z plane for stations (Fig. 3.4).

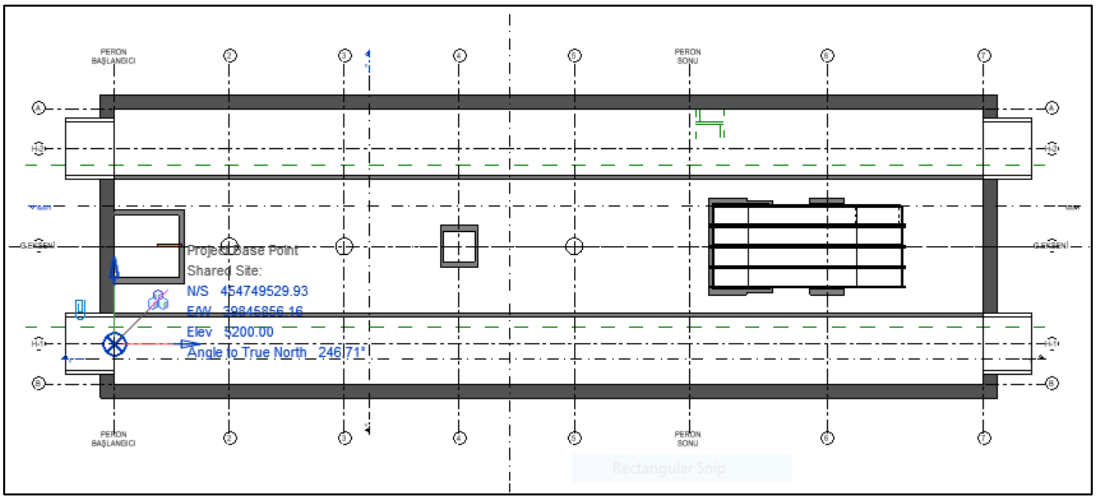

Figure 3.4. Suggested Reference Point in the X-Y Plane for a Station Structure

It is important to examine the interaction of the structures of the metro system with the existing structures (Fig. 3.5). Especially, the interactions of existing structures with the stations (underground, at-grade, or viaduct) should be examined in detail. In the past, this process is being done with 2D route line on orthographic pictures.

Today, it is indicated in technical BIM specifications of the metro systems that this study should be carried out in 3D with 3D modeling technology. Although it is easy to do this for structures designed in a specific area like buildings, bridges, etc., creation of existing condition models for structures lying horizontally along a large corridor, such as metro systems, also increases the workload. It should be determined whether automation solutions will be included in this process depending on the surveying method. If 3D existing condition models are not created using reality capture technology in the project, 3D models should be created automatically using 2D base map plans and updated according to new data received.

Figure 3.5. Existing Condition Model vs. Real-life Image for a Station Area

The process of manually producing the Room Data Sheets (RDS) demanded in the BIM specification for each station should also be automated. Considering that most stations has more than 40 rooms, it would be time-consuming to create these sheets for a metro line with 10 stations. RDS contents should be determined considering the technical specifications of the project. After that, plans, sections, views, equipment tags, and lists should be produced automatically for each room.

Architectural finishes for the stations generally vary for the passenger areas, however; finishes for technical areas are alike. With this in mind, an automation solution that allows the automatic placement of architectural finishing elements will speed up the design process (Fig. 3.6). Only special finishing elements for passenger areas should be modeled manually. To perform this, a data file or interface where finishing information can be entered is needed and the finishing elements must be placed automatically depending on the room geometry definitions by using this input data. It should be noted that sometimes there may be more than one finishing for the wall or floor elements in one room. In case of this, the solution should provide the opportunity to go to the relevant area and choose which finishing will come to each side of the room area. Another important issue will be the rapid creation of different alternatives for aesthetic design presentations to be made to the employer at the preliminary stage.

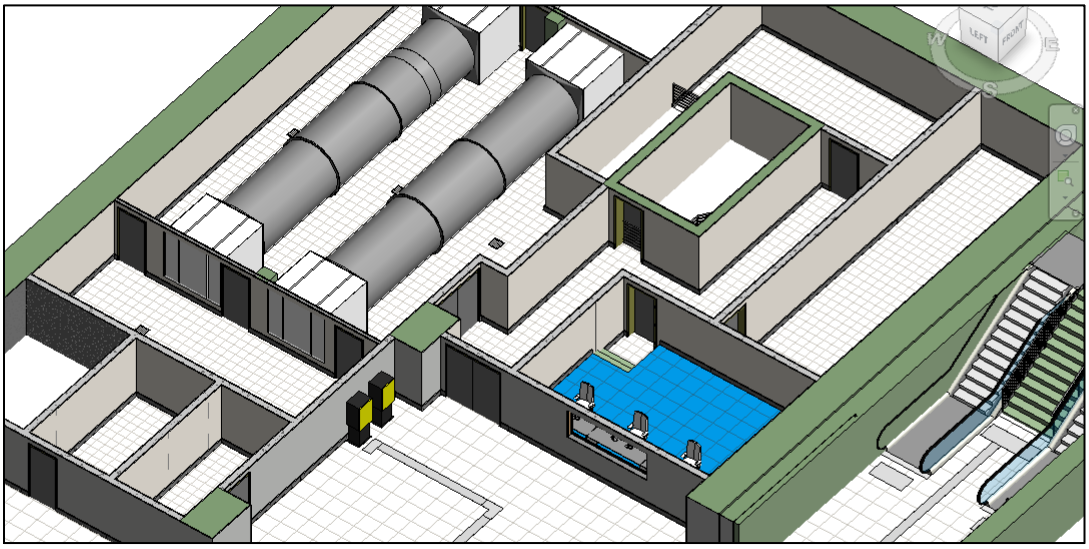

Figure 3.6. Example of an Architectural Model for a Station

In addition to providing passengers with access to metro vehicles, the metro stations are the structure where all the electromechanical systems take part for the entire metro system. There are many areas where MEP systems pass through architectural and structural systems. These necessary reservations must be left automatically (Fig. 3.7).

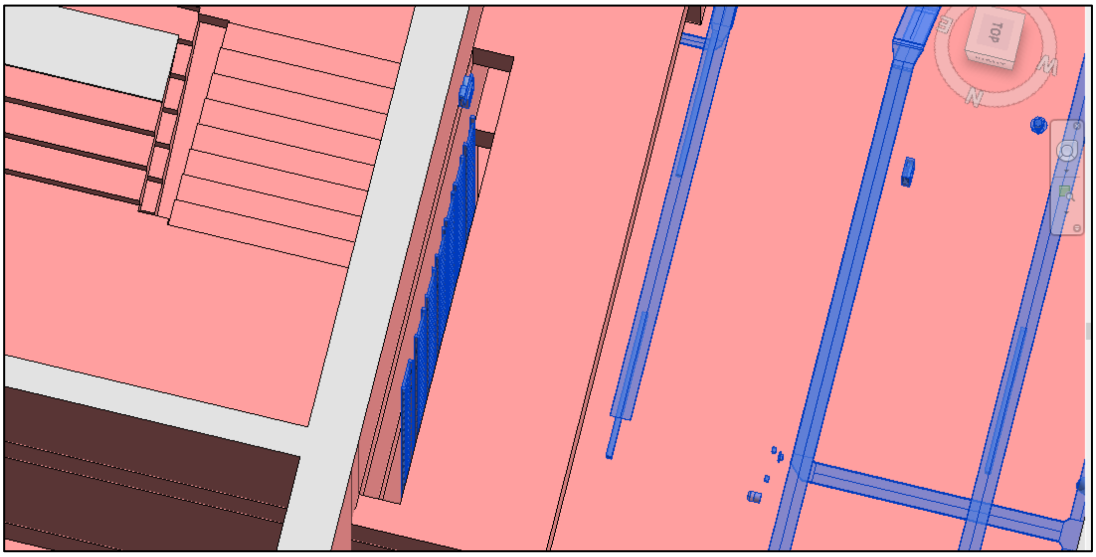

Figure 3.7. Example of a Reservation Area in a Station Structural Model

There are certain design criteria for the rooms of the stations. A system that can be checked in accordance with the shared metro design criteria and standards should be used in the control process. They should not be manually controlled in each new design.

One of the biggest advantages that can be provided to the design teams is viewing differences (deleted, edited, added model elements, or model properties) between shared model files with automated solutions. Important point here is providing an opportunity for the design teams to examine the design differences in their WIP model file.

Not all software in which engineering analysis is performed may be able to directly read data in file formats in which BIM models are produced or converted. Particularly in this process, the translation of the model in the appropriate format should be carried out by using the information contained in the relevant model.

3.5. Design Coordination

Design coordination is one of the biggest advantages for designers that BIM system provides. There are two different design coordination processes. The first is the disciplinary coordination process and the second one is the interdisciplinary coordination process. The first one should be carried out by the discipline BIM specialists, and the second one should be carried out by the BIM Manager or BIM Coordinator working on the project.

BEP should include a clash matrix in which details of the interdisciplinary and disciplinary clash tests are defined for the project. It is necessary to create clash test templates defined in the BIM Execution Plan and share them with all disciplines. It should be noted which tests are interdisciplinary clash tests and the discipline models should be shared for coordination after the clashes found as a result of these tests have been resolved in accordance with the definition of clash-free discipline models. Remaining interdisciplinary clash tests should be optimally resolved by the design teams at BIM coordination meetings. Since disciplinary clashes must be solved by the designers before sharing the model files, only the interdisciplinary process is addressed in the proposed system.

Because files shared by disciplines will be used for the design coordination studies, automated solutions can also be integrated into this process. Firstly, the coordination model file must be created in the WIP area. It should be ensured that the shared BIM models are automatically combined in the coordination model file. Depending on the software solution used for clash detection (Fig. 3.8), the BIM models can be directly included in the coordination model or format conversions can be required. If a format conversion is required, this translation process should be done automatically during the BIM model sharing process and the related file format should also be moved in "SHARED" area. 3D CAD model files can be directly included in the coordination work through the formats in which they are shared.

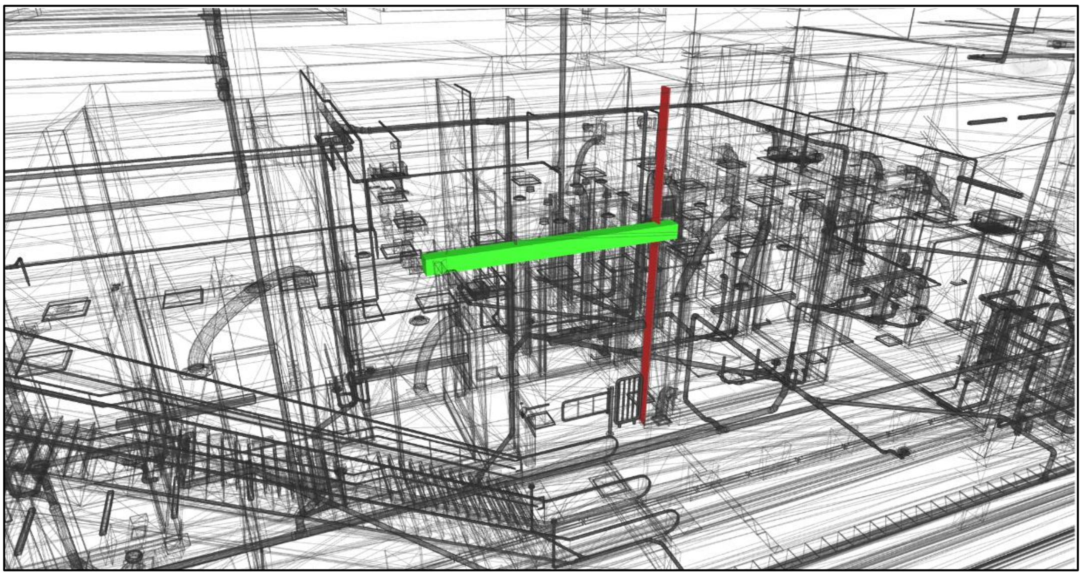

Figure 3.8. A Sample Image for Clash Detection Process

As in standard BIM system, after the clash reports are prepared it should be shared with the design teams. These coordination problems should be discussed in the BIM coordination meetings. In case of a new model shared by one of the disciplines, the coordination file should be automatically updated, and the clash results should be updated according to the new shared file. What is important here is that all coordination models shared with the design teams should be recorded in the "SHARED" area.

Since the main purpose of the preliminary design studies conducted for metro systems in Turkey is to determine line route, station sizes, room sizes and layouts of the stations, the clash analysis can be optionally applied in this process. However, after all the disciplines start modeling studies in the detailed design stage, coordination should be carried out carefully at this stage. In the proposed system, the coordination process is discussed in detail only for detailed design stage. In case of an employer request, it can be applied to the preliminary design stage with the same systematic.

3.6. Process Maps for Disciplines Involved in the Design

The process maps of the disciplines that will be collaboratively involved in the design of a metro project by using the BIM processes are explained in this section. For some disciplines, the process is divided into two stages as preliminary design and detail design. For some disciplines, without any distinction, two design stages are shown in a single process map. In these process maps, the tasks that need to be carried out by each discipline are defined. Terms used in the process maps are explained below.

There are three different areas in the process maps, which are reference information, process, and information exchange. The reference information area is used for inputs prepared or provided from teams/organizations other than the design disciplines involved in the design of the metro system. The process area contains the activities to be performed. The information exchange area is where the inputs and outputs produced by the design disciplines are specified. In addition, the file formats that should be shared with other disciplines is also stated in the information exchange area.

The process maps for each discipline have been described in detail below. Since the automated processes have been described in previous sections in detail, they are not explained in each process map definition but only indicated in process maps instead.

The survey studies to be carried out in the preliminary and detailed design stages are summarized in Figure 3.10.

i. Base map, orthophoto, terrain model, cadastral and zoning plans should be prepared for the initial route corridor by the survey team at the beginning of the project. Related studies will be performed with 2D CAD software.
ii. The created survey files for the whole corridor should be shared to be used in route, underground utility, and existing structure modeling studies.
iii. Afterward, map files should be divided and shared for each structure region so that the other discipline can use these files in modeling activities. During the division process, zoning areas for each structure will be defined in the WIP survey file prepared for the whole corridor (Fig. 3.9), and these areas will be automatically divided and shared with the others for coordination studies.

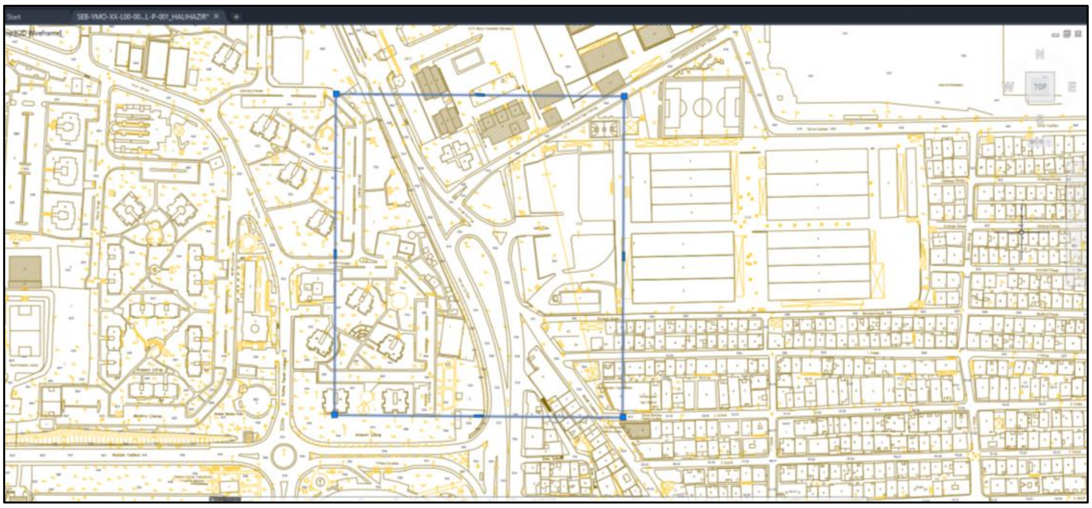

Figure 3.9. A Sample Image for File Division Study for Survey Discipline

iv. Once the layouts of the station are finalized, surveying studies will be carried out topping up the current map data for the relevant station areas. Different techniques, traditional surveying or reality capture, can be preferred for surveying studies. As a result, all documents should be updated, and sharing processes with disciplines should be performed again.

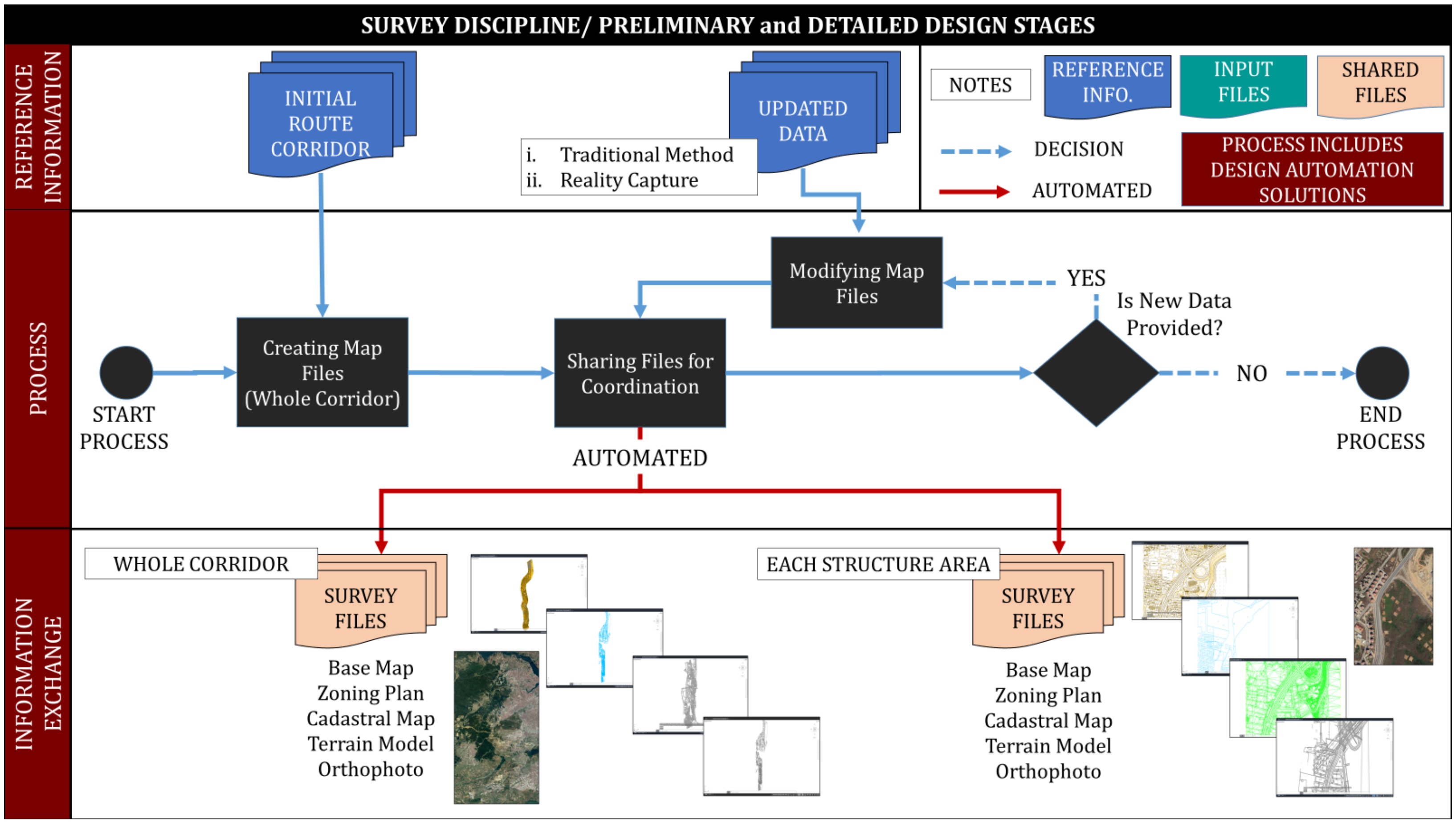

Figure 3.10. Process Map for Survey Discipline – Preliminary and Detailed Design Stages

The route studies to be carried out in the preliminary and detailed design stages are summarized in Figure 3.12.

i. Route studies will be started by using shared map files, estimated station layouts and, if prepared, existing underground utilities (EUU) studies as a reference from other discipline studies. Here, instead of the architectural model itself, automatically shared files in the appropriate file format will be included. Also, the initial route corridor and existing/planned rail system data that has an interaction with the metro system will be used as reference information.

ii. The studies should be shared for the review of the related disciplines. If the revision is needed, the route file should be modified according to the review results.

iii. The current version of the route file should be shared for coordination. When sharing the file, both the 2D CAD file and the 3D model line file must be shared with the disciplines at the same time. 3D model line file will be used in design automation studies such as tunnel modeling, and automatic coordinate placement (Fig. 3.11).

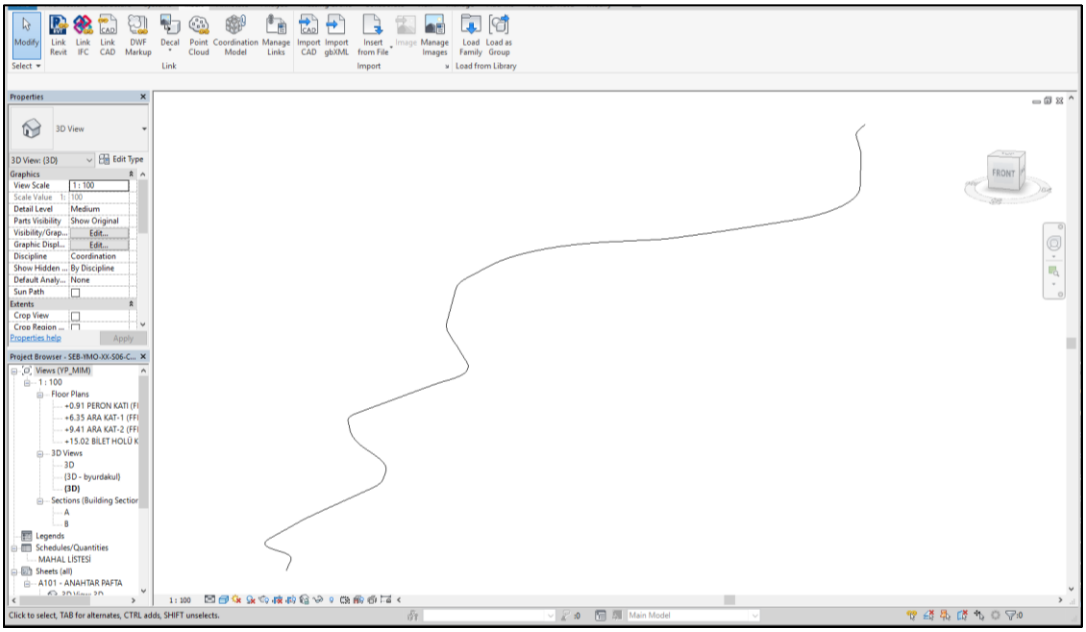

Figure 3.11. A Sample Image for 3D Model Line from the Route Study Used by Other Disciplines

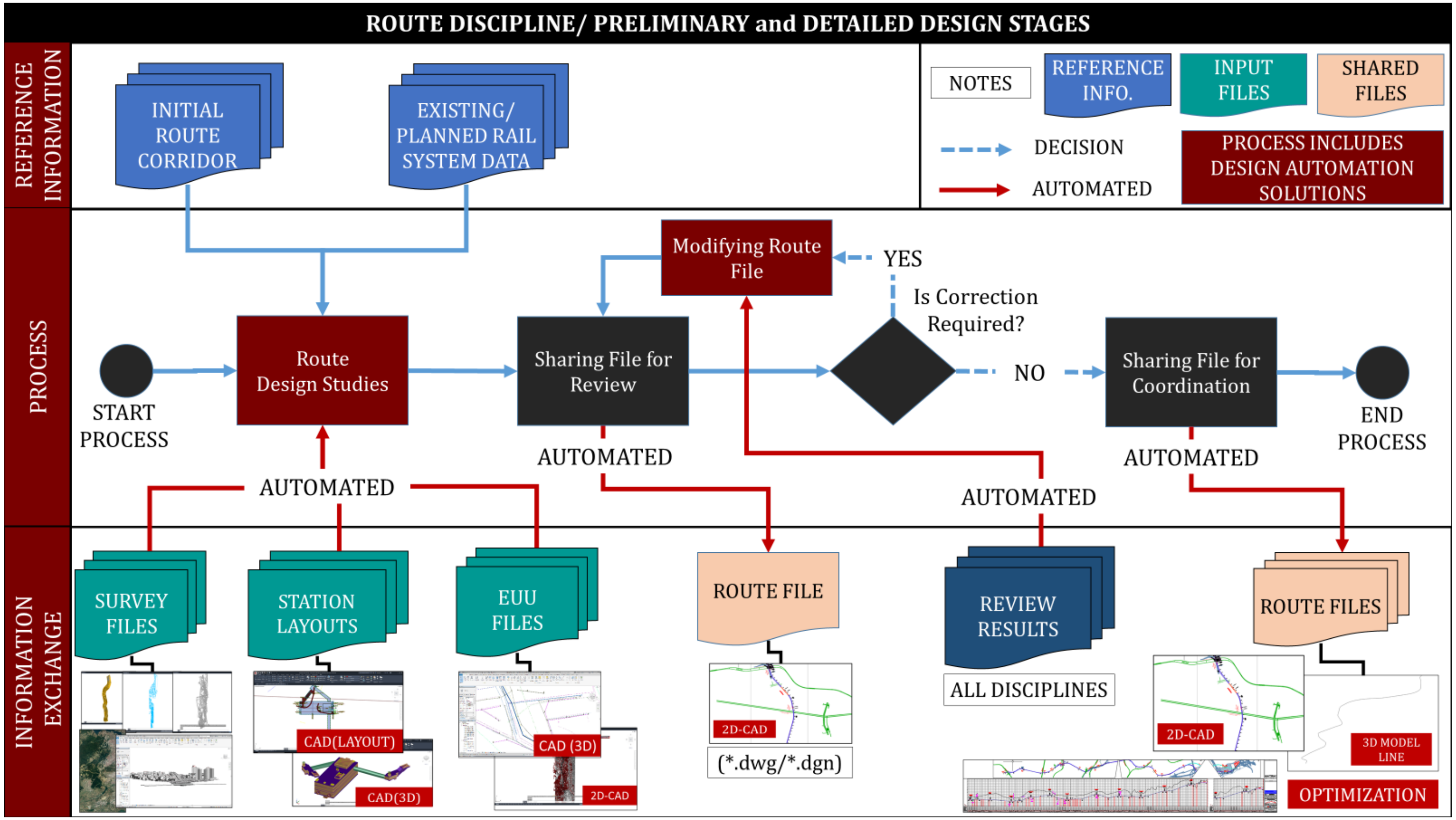

Figure 3.12. Process Map for Route Discipline – Preliminary and Detailed Design Stages

The underground utility studies for the existing condition to be carried out in the preliminary and detailed design stages are summarized in Figure 3.13.

i. Related data requested from the institutions according to the proposed route area will be used as reference information. Route file, station layouts, and survey files will be used as reference information exchanged from other disciplines to create plans for existing underground utilities. Since the data should be controlled at the site, the 3D models should not be created at this stage.
ii. The working file will be shared with the other disciplines for the whole corridor.
iii. After new data provided from the site, 3D models for existing underground utilities will be created.
iv. 3D model files will be shared for each structure region so that the architectural and MEP disciplines can use them in their modeling activities.

The relocation of existing underground utilities studies to be carried out in the detailed design stage are summarized in Figure 3.14.

i. After 3D models for existing underground utilities are created for each station area, using the studies of the disciplines that carry out the station design, the regions that need to be rearranged will be determined. At this stage, geotechnical discipline studies should be used to determine the need for rearrangement of existing utility lines, while MEP studies will be used to evaluate the need for a new utility line from existing lines to the station. In this study, 3D CAD model files shared automatically from BIM models will be used.
ii. The studies should be shared for the review. If the revision is needed, the design should be modified according to the review results.
iii. 3D model files will be shared for each structure region so that the other disciplines can use them in their design activities.

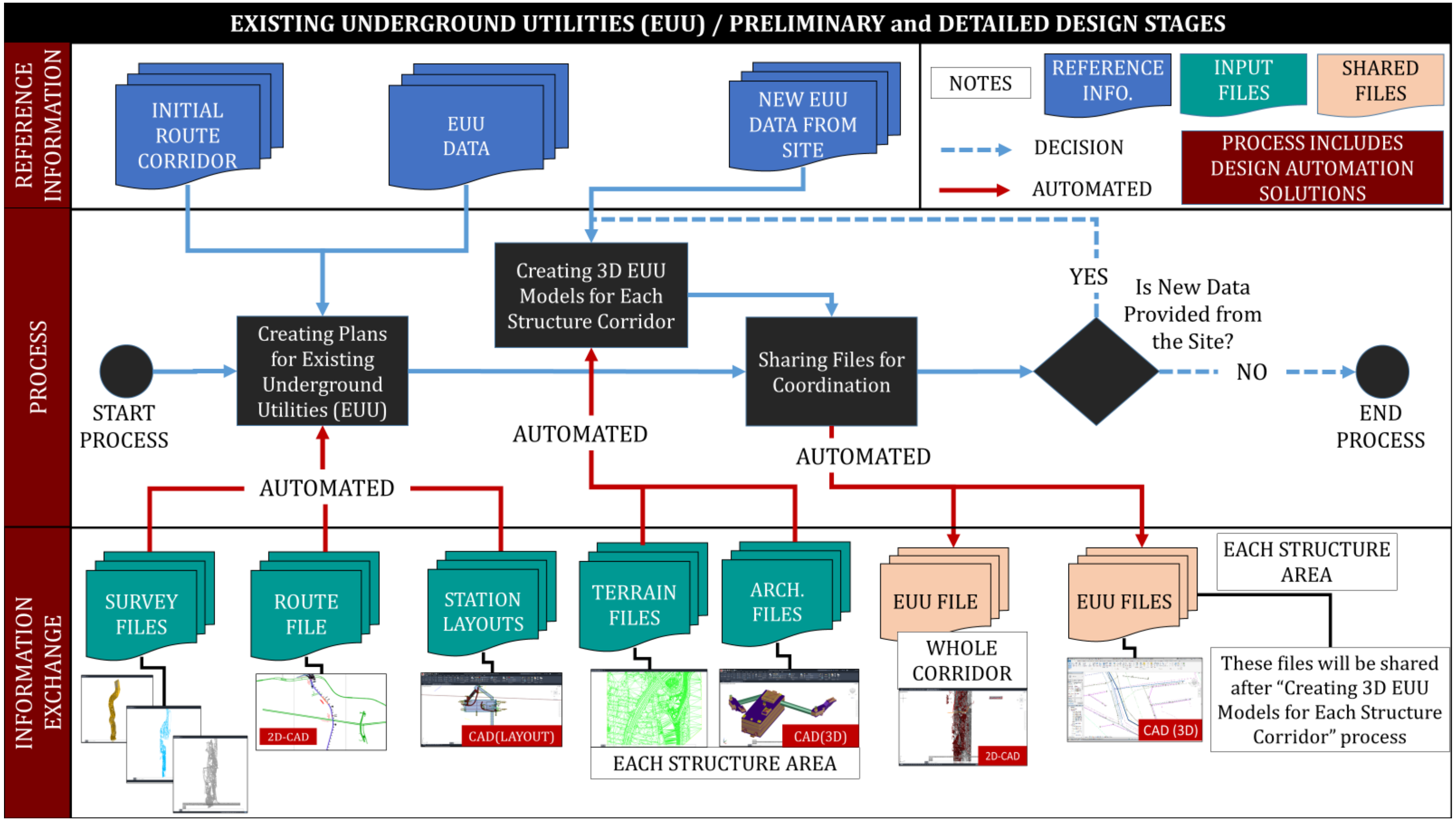

Figure 3.13. Process Map for Existing Underground Utilities – Preliminary and Detailed Design Stages

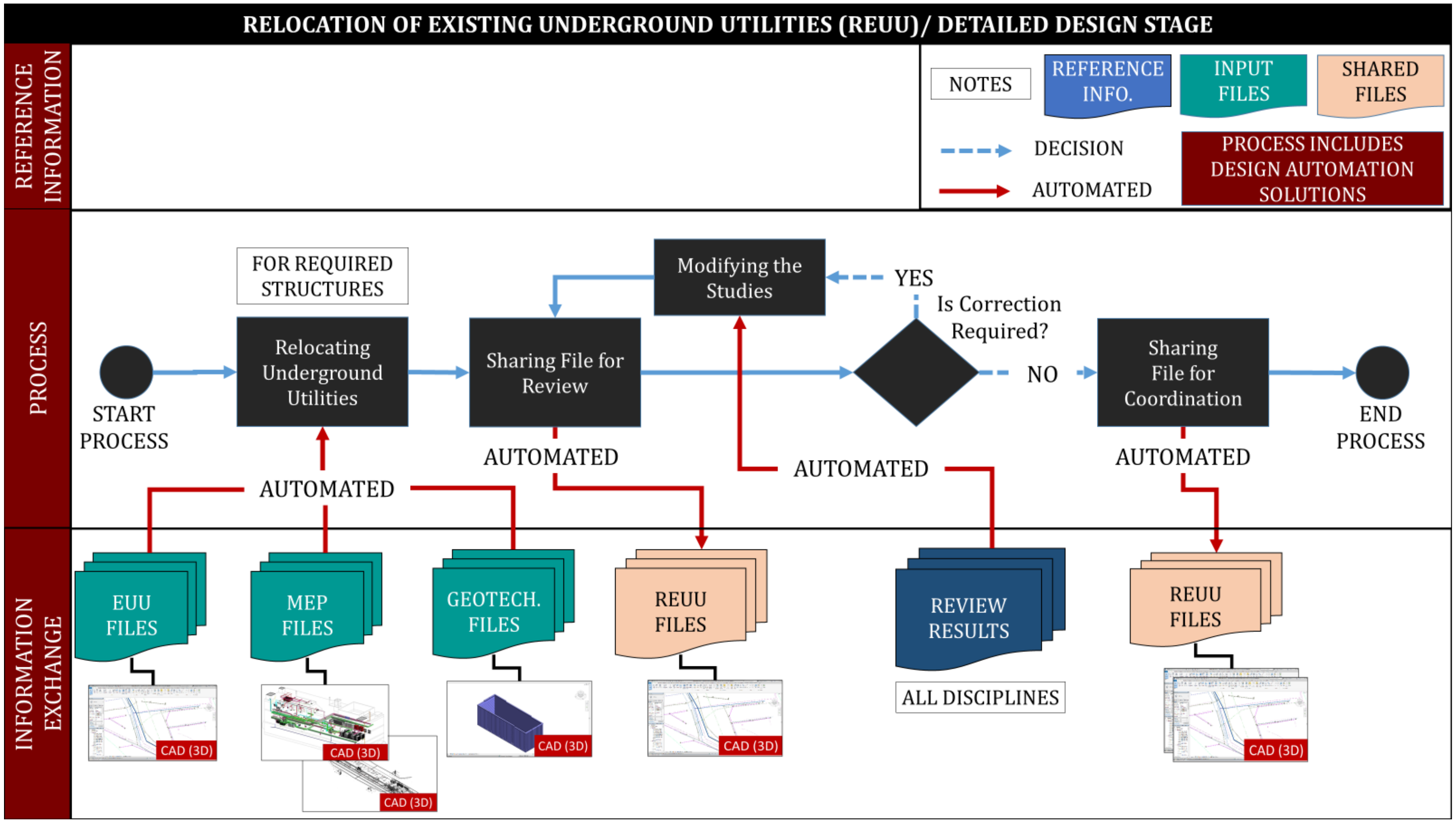

Figure 3.14. Process Map for Relocation of Existing Underground Utilities – Detailed Design Stage

The existing structure modeling studies to be carried out in the preliminary and detailed design stages are summarized in Figure 3.15.

i. Firstly, modeling activities of existing structures will be carried out by using survey files and 3D mass models created for existing/planned critical structure on the metro line. These models should include roads, land, buildings, engineering structures and rail system structures. Since these data are usually provided in 2D at the beginning of the project, models for buildings, terrain, roads and should be created automatically using the information contained in the plans as specified in the design automation.
ii. Afterward, this study prepared for the whole corridor will be divided for each structure area and shared for coordination with the other disciplines. These models can be divided into sub-models for each structure area according to project needs.
iii. If new data are provided throughout the project, this model should be updated and shared again for the revised area. If new data is collected with reality capture technology, 3D models can be created by processing these data. Nevertheless, the underground rail system structures that interact with the line and the 3D models of the critical structures planned to be built in the future should also be included in these models.

3D mass modeling studies for existing and planned critical structures to be carried out in the preliminary and detailed design stages are summarized in Figure 3.16.

i. Modeling studies (3D Mass Models) for critical structures, that will have an interaction with the metro system, will be carried out by using reference information provided from different institutions. If the structure has 3D model, it should be obtained directly from the related institutions. If not, it should be modeled by the design team. Here, in order to keep the workload at an optimum level, modeling should be carried out at the appropriate level of detail according to the project needs.

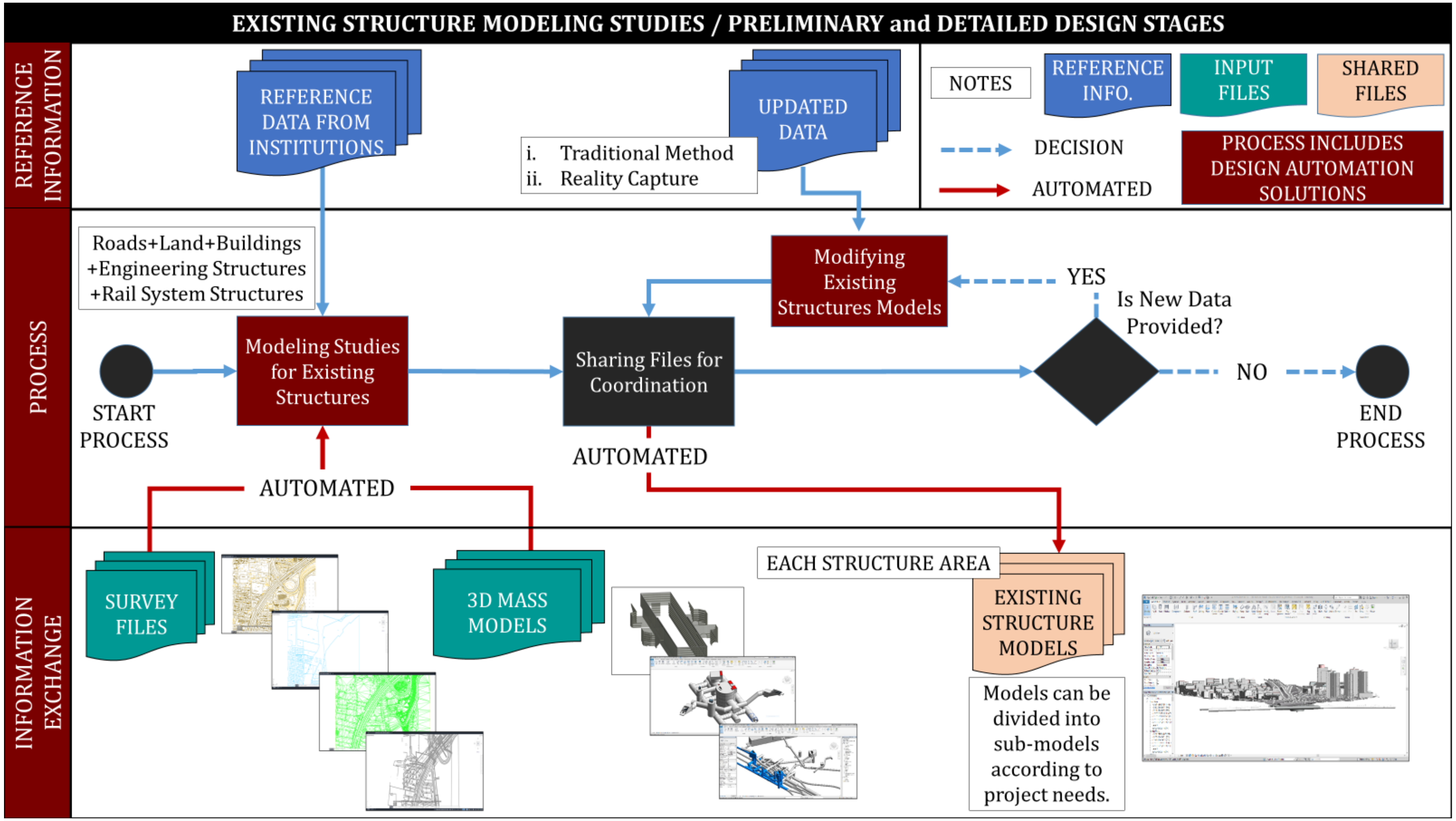

Figure 3.15. Process Map for Existing Structure Models – Preliminary and Detailed Design Stages

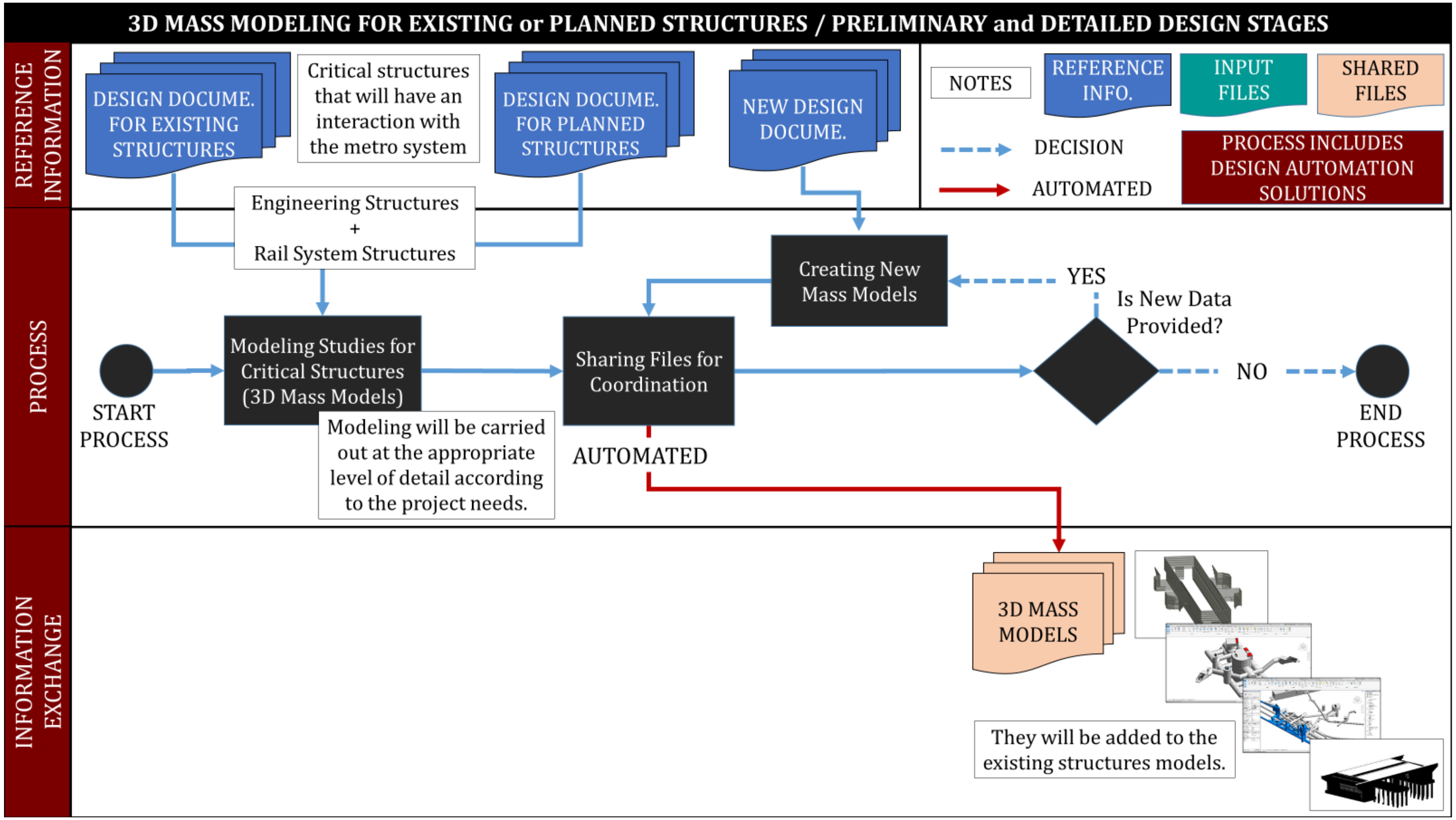

Figure 3.16. Process Map for 3D Mass Modeling for Existing or Planned Structures – Preliminary and Detailed Design Stages

The architectural studies to be carried out in the preliminary design stage are summarized in Figure 3.17.

i. Architectural modeling works will be carried out using survey files, existing underground utilities, route files, and existing structure models.
ii. The model should be shared for the review of the related disciplines. If the revision is needed, the architectural model should be modified according to the review results. In case there is no request from the other disciplines, the architectural models can be shared for coordination. In these processes, the model file must be converted and shared automatically to 3D CAD model, 2D station layout plan, coordination model format, and *.ifc format as well as the main file format in which it is produced.
iii. After the architectural model has been modified according to the comments, it should be shared again with other disciplines for review. In case there are no revision requests from the other disciplines, the architectural models can be shared for coordination.

The aesthetic design studies to be carried out in the preliminary design stage are summarized in Figure 3.18.

i. After the first review of the architectural model (minimum requirements), using an architectural model as a reference model, suspended ceilings, walls, floor finishes, etc. for passenger areas should start to be modeled without changing the architectural model content. If design alternatives are needed, they should be studied in a single file. Design automation solutions should be used for modeling finishes for different alternatives. If the landscaping studies are carried out, shared existing condition models should be used.
ii. The model should be shared for the review of the related disciplines. If the revision is needed, the model should be modified.
iii. Visualization studies (renders, animations, virtual reality models, etc.) will be conducted by using BIM models.

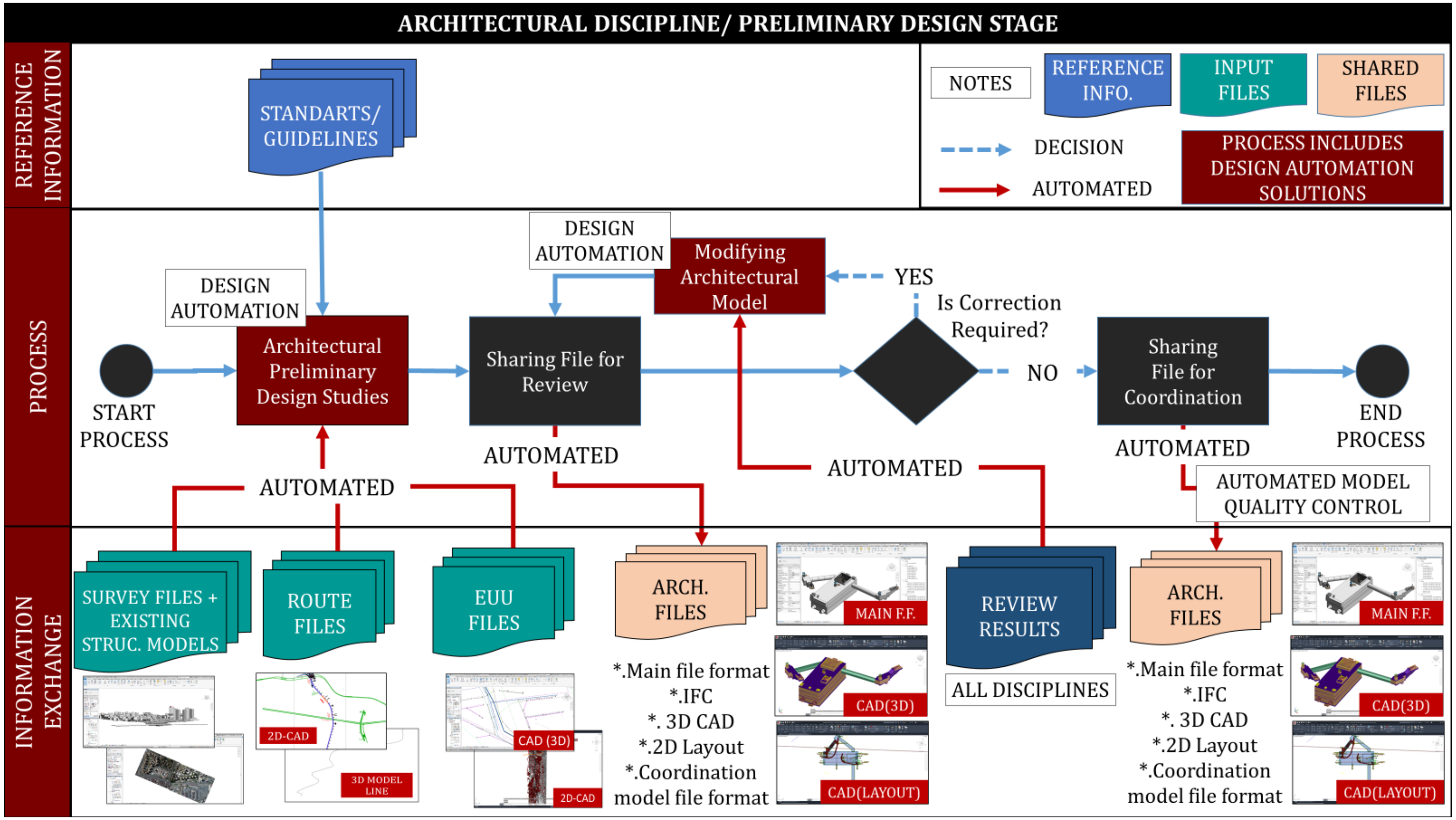

Figure 3.17. Process Map for Architectural Discipline – Preliminary Design Stage

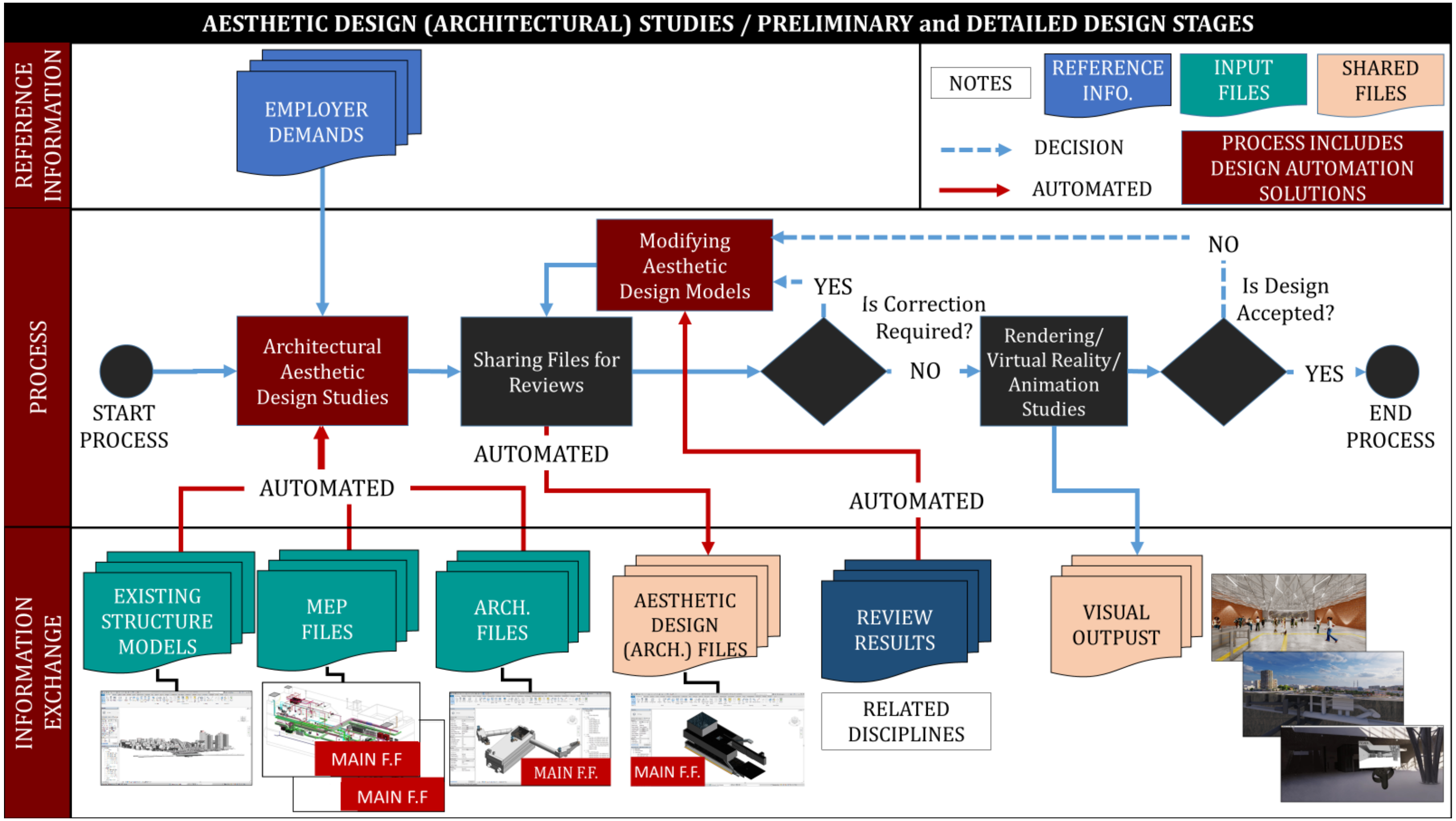

Figure 3.18. Process Map for Aesthetic Design (Architectural) Studies – Preliminary and Detailed Design Stages

The traffic discipline studies to be carried out in the detailed design stage are summarized in Figure 3.19.

i. Related studies can be carried out only for certain structures depending on the existing road structures. For these structures, temporary traffic plans may be required depending on the construction process as well as permanent traffic plans. First, the stations for which the study will be carried out should be specified.
ii. Then, 3D CAD models will be created using survey files, existing underground utilities, related architectural files, and existing structure models.
iii. Model files will be shared for each structure area so that other disciplines can use them in their modeling activities.
iv. If there are revisions in the design, these models should be modified accordingly.

The initial process to start modeling studies for a station in the detailed design stage are summarized in Figure 3.20.

i. If there are revision requests for the architectural models from the employer, the architectural model should be modified accordingly. In case there are no revision requests from the employer, the architectural models can be shared for the model division process.
ii. The revised model should be shared with the other disciplines for review. If the revision is needed, the architectural model should be modified according to the new review results.
iii. In case there are no revision requests from the other disciplines, the architectural models can be shared for the model division process.
iv. Related disciplines that have model elements in the architectural model will take the responsibility of modifying these model elements.

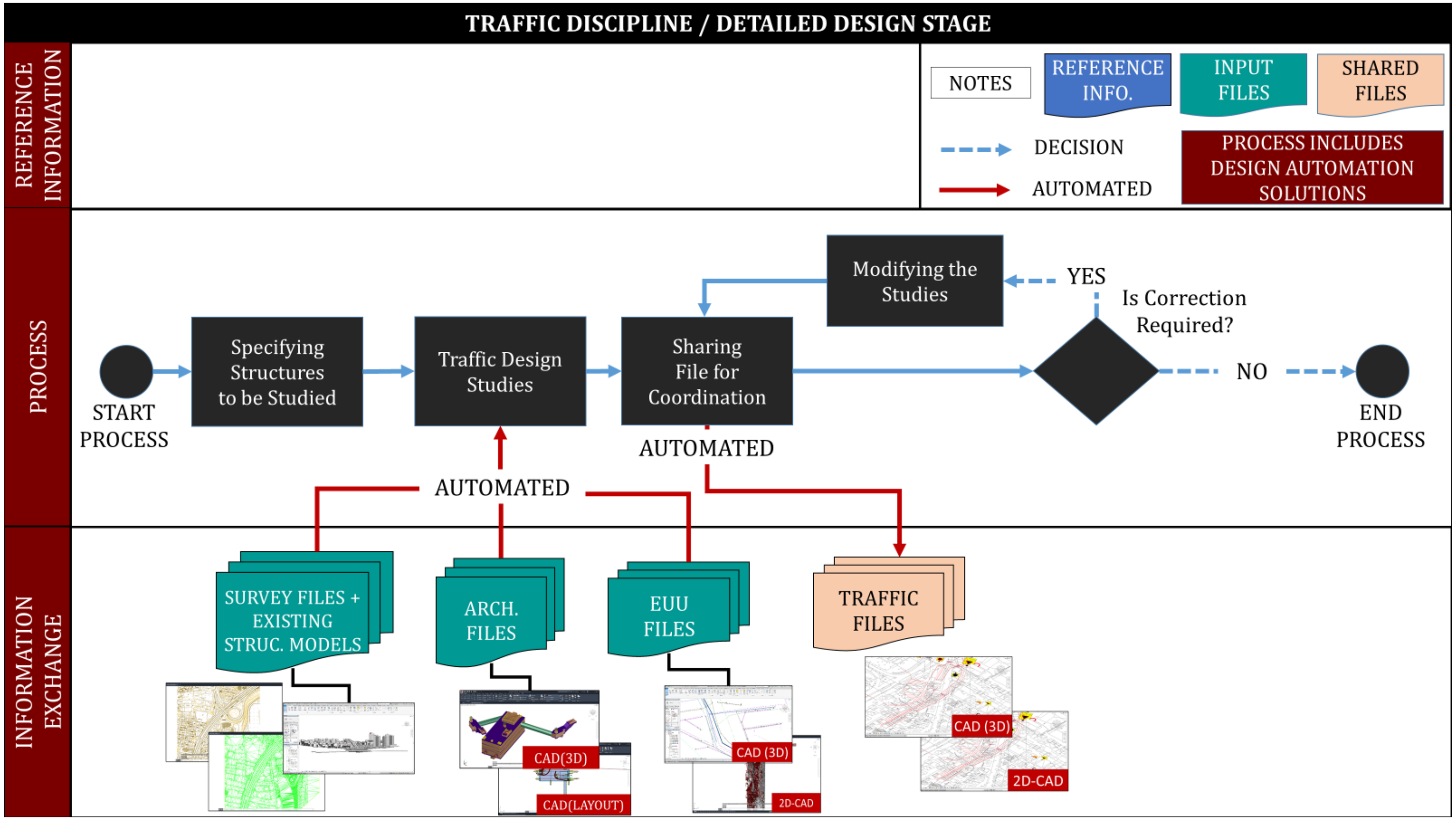

Figure 3.19. Process Map for Traffic Discipline – Detailed Design Stage

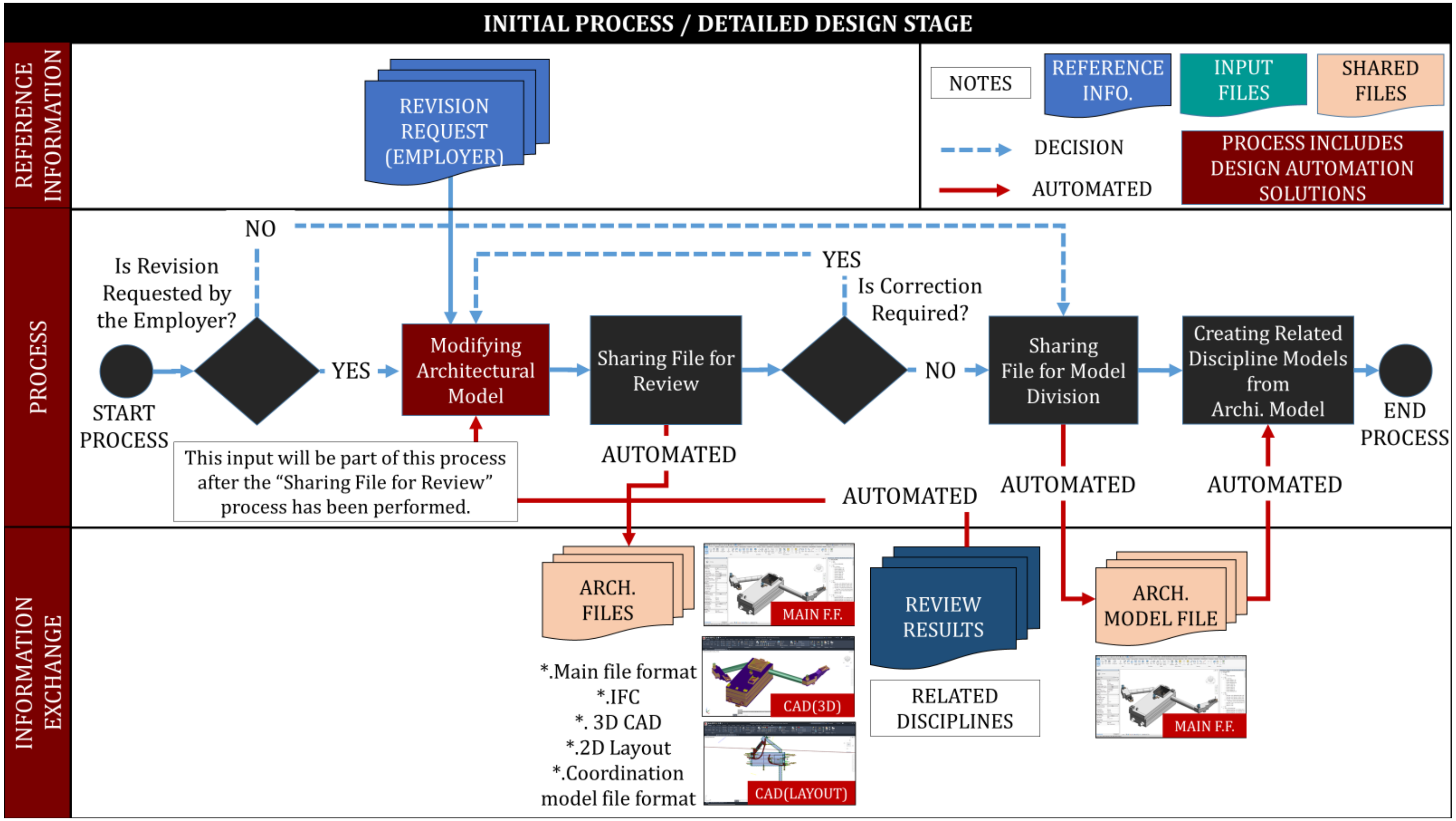

Figure 3.20. Process Map for Initial Process – Detailed Design Stage

BIM modeling studies for architectural, structural, geotechnical and MEP disciplines to be carried out in the detailed design stage are summarized in Figure 3.21.

i. BIM models will be created based on the model division strategy. Survey files, existing underground utilities, route files, traffic files and existing structure models, and other BIM models will be used as a reference information in this process. The most important issue is that all these shared documents should be accessible from BIM WIP model file.
ii. The model should be shared for the review of the related disciplines. If the revision is needed, the architectural model should be modified according to the review results. In case there is no request from the other disciplines, the architectural models can be shared for coordination.
iii. After that, the model file will only be shared for coordination purposes. It must be converted to and shared automatically as 3D CAD model, 2D station layout plan, coordination model format, and *.ifc format as well as the main file format in which it is produced. In this process, a solution that checks the model quality in coordination sharing should be used to prevent the sharing of the files that are not suitable for coordination. By sending warnings to designers about unsuitable model contents, the related errors should be corrected before coordination sharing.
iv. Depending on the design coordination studies, relevant models should be updated when necessary.

Architectural, structural, geotechnical, and MEP disciplines are responsible for different sub-systems of the metro structures. Although different studies are being carried out by each discipline, a single process map has been created since it is aimed that the overall collaboration process will be the same for each discipline responsible of creating BIM models. Automation solutions defined in the previous section should be actively used during the work of the related discipline. In addition, engineering analysis studies should be carried out with 3 different methods as suggested for each discipline.

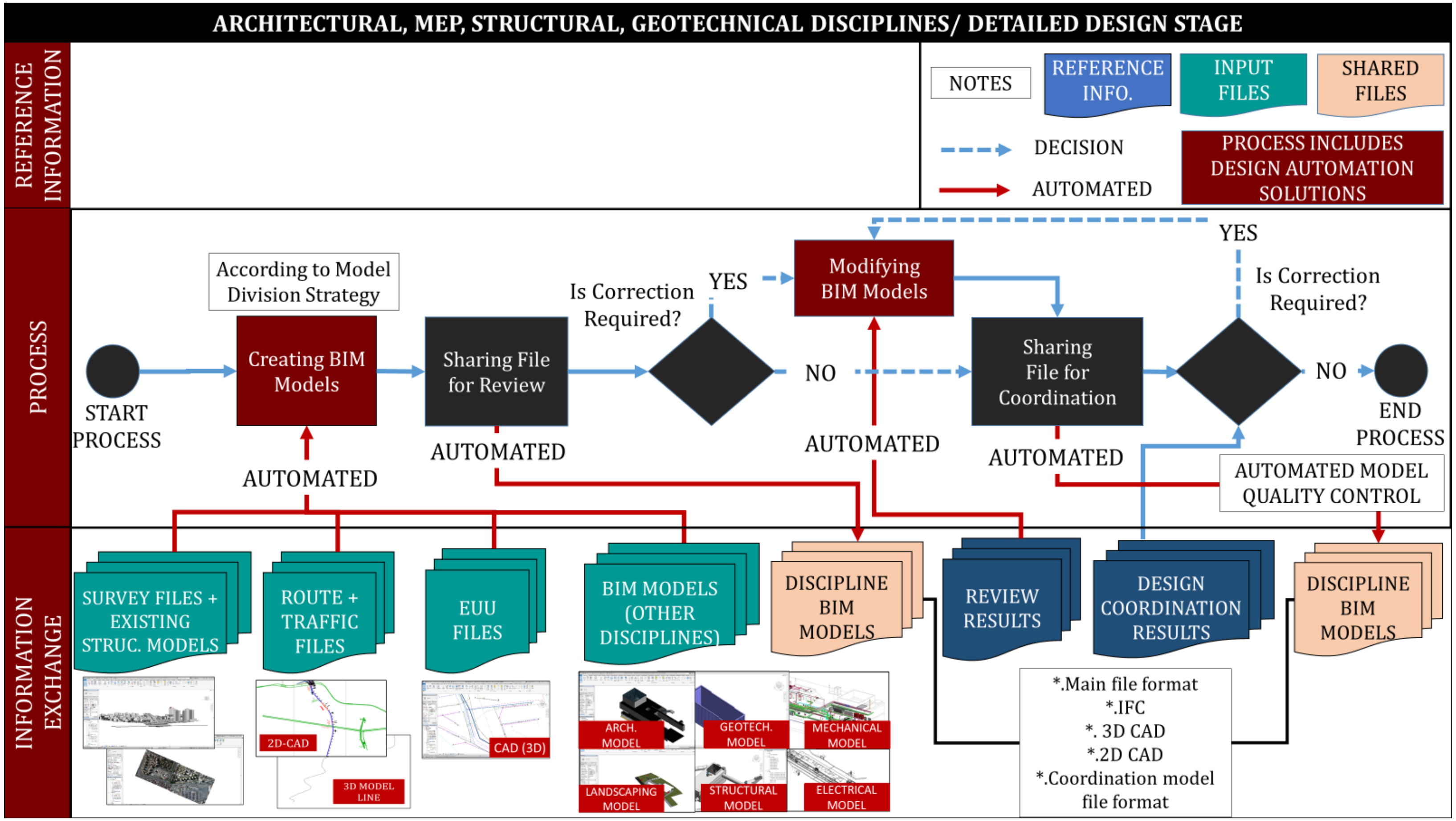

Figure 3.21. Process Map for Architectural, Structural, Geotechnical and MEP Disciplines – Detailed Design Stage

The design coordination studies to be carried out in the detailed design stage are summarized in Figure 3.22.

i. Design coordination studies will be carried out by using 3D BIM and CAD models shared by related disciplines. The 3D models that will be used in the coordination studies are listed below.
    - Architectural
    - Structural
    - Geotechnical
    - Mechanical
    - Fire
    - Electrical
    - Electronic
    - Landscaping
    - Underground Utilities
    - Traffic
    - Existing Structures

Depending on the software solution used for clash detection, the BIM models can be directly included in the coordination model or format conversions can be required. If a format conversion is required, this translation process should be done in the BIM model sharing process automatically and the related file format should also be moved to “SHARED” area. 3D CAD model files can be directly included in the coordination work via the formats in which they are shared.

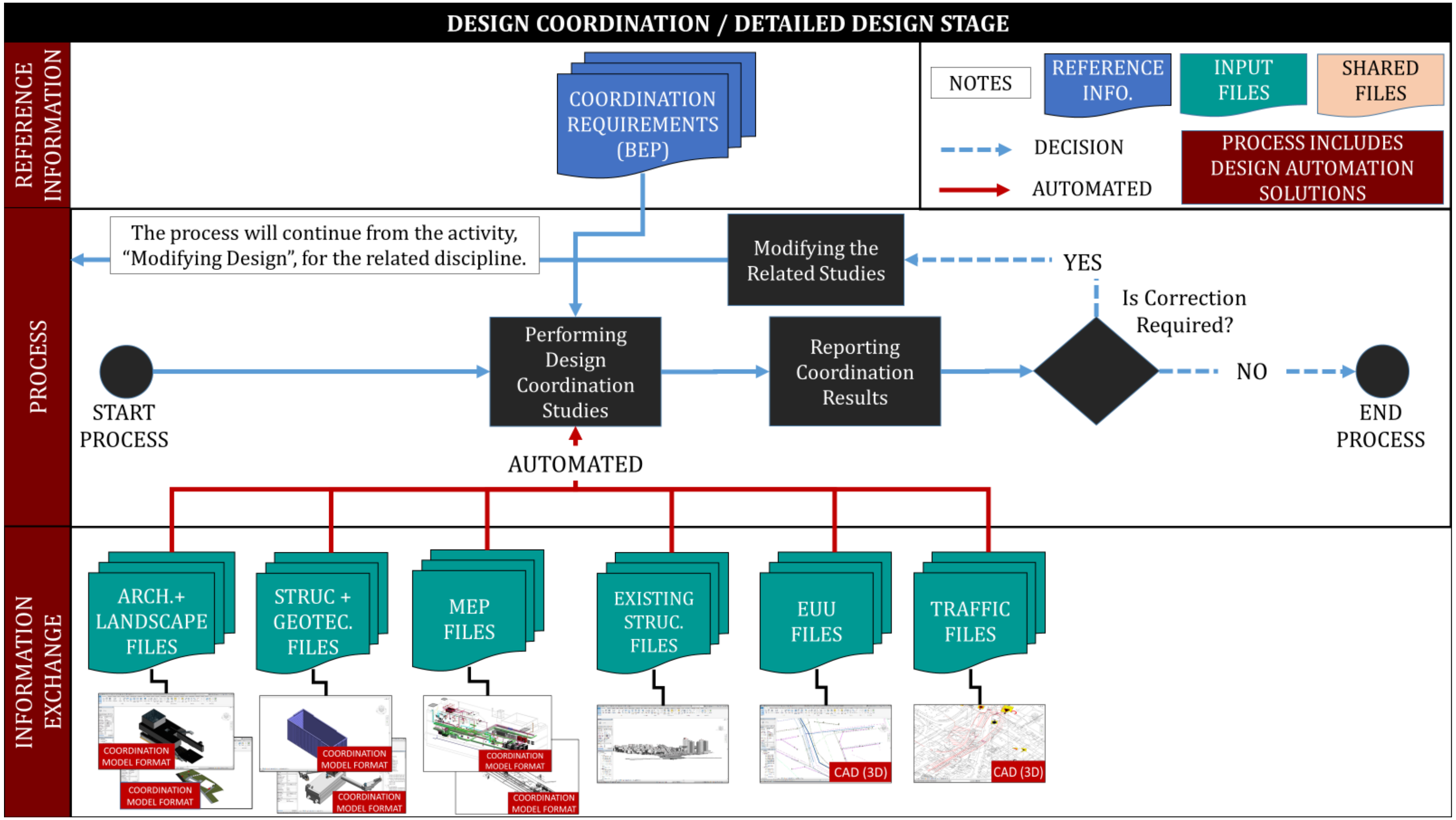

Figure 3.22. Process Map for Design Coordination – Detailed Design

CHAPTER 4

CASE STUDY – IMPLEMANTATION OF THE SYSTEM IN A REAL METRO PROJECT DESIGN

4.1. Introduction

The proposed system has been used as a case study in the process of preparing tender documents for a real-life metro project design. Design documents have been produced with the proposed system. Modeling activities of the disciplines involved in the project, information management process, interdisciplinary collaboration process, engineering analysis studies, and design automation process have been followed in detail during the 13 months period. As a result, the benefits and limitations of the proposed system have been determined.

The duration of the project was estimated as 18 months and there are still 5 months until the completion of the design. The study has been examined by taking into consideration the 13 months process outputs.

4.2. Project Information (Project-A)

The total length of the metro line used in the study is 15 km, and the line intersects at 5 points with other planned or existing rail system lines. It consists of 11 underground stations and 12 underground tunnel structures. Depending on the construction method, there are two types of underground stations in the project, which are cut-cover and deep tunnel types. The central platform has been used in all stations. In the project, the distance between the two stations varies between 1.5 km and 2 km, and the depth of the stations varies between 20 meters and 50 meters. Moreover, all the line structures consist of underground tunnels, which includes TBM and NATM types. Modeling of MEP elements for line structures was not in the scope of the project, and only structural components have to be modeled according to the BIM specification.

The Project delivery method is DBB, and the duration was estimated as 18 months. At the time of this evaluation, 13 months have passed since the start of the project.

4.3. Project Documents

The project contained the most comprehensive BIM specification for the metro systems in Turkey. The reference international standards and guidelines specified in the project BIM specification are listed below.

- BS1192:2007 + A2 2016 Collaborative Production AEC Information – Code of Practice
- PAS-1192-2:2013 Specification for Information Management for The Capital Delivery Phase of Construction Projects Using BIM
- BIM Forum Level of Development Specification Guide 2018
- Penn State University BIM Project Execution Planning Guide

BIM Uses indicated in the specification are listed below.

- Design Authoring
- Design Documents
- 3D Coordination
- Cost Estimation
- Existing Condition Modeling

In addition to the specification, engineering analysis was one of the BIM uses implemented in this metro project.

4.4. LOD Requirements

For the projects, the BIM specifications generally indicate that a minimum LOD 300 is expected for the model elements in each discipline model at the end of the design phase. In the specification, the relationship between LOD and the design stages is not mentioned. At the beginning of the project, a detailed LOD table for the model elements was created considering the specification requirements by the design team.

Station Structures:

- It was stated that LOD300 requirement, specified for architectural model elements in the BIM specification, should be followed at the detailed design stage for architectural model elements.
- In the preliminary design stage, the LOD definition for the structural elements, created in the architecture model, was determined as LOD200. For the detailed design, it was determined as LOD300.
- In the preliminary design stage, LOD definitions for electromechanical equipment, created in the architecture model, was determined as LOD200. For the detailed design stage, the demand for modeling MEP systems in accordance with the BIM specification was stated.
- For geotechnical model elements, it was stated that the main structural components should be modeled for the coordination purpose, and it was stated that there is no need for modeling of sub-components.

Line Structures:

- For underground tunnel structures, shotcrete and inner lining components of NATM tunnels were requested to be modeled as LOD200. TBM tunnels were decided to be modeled as LOD200.
- There was no modeling request for the other elements in the line structures.

Although the LOD definitions described above were requested by the employer, there were cases where the design teams carried out modeling studies beyond these LOD requirements to perform some studies and to create some design documents from BIM models.

4.5. Software Used in the Case Study

Autodesk Revit software was used for modeling of architectural, structural, and MEP systems of the stations. Autodesk Civil 3D software was preferred to use for modeling underground utilities and surveying studies. Autodesk Navisworks Manage software was used for clash detection and quantification processes. The software solutions used in Project-A are listed in Table 4.1.

Table 4.1. *Software List Used in Project-A*

Purpose	**Software Name**	
Existing Condition Modeling	a) Autodesk Revit b) Autodesk ReCap	c) Autodesk Civil 3D d) Autodesk Infraworks
Design Authoring	a) Autodesk Revit b) Autodesk AutoCAD	c) Autodesk Civil 3D d) Autodesk InfraWorks
Design Coordination	a) Autodesk Revit	b) Navisworks Manage
Design Documents	a) Autodesk Revit b) Navisworks Manage c) Autodesk AutoCAD d) Autodesk Civil 3D e) Bentley Microstation	f) Lumion g) Autodesk Infraworks h) Autodesk 3Ds Max ı) Autodesk Advance Steel j) Bentley Openroads
Cost Estimation	a) Autodesk Revit b) Microsoft Excel	c) Navisworks Manage
Engineering Analyses	a) Sap2000 b) Autodesk Revit c) Microsoft Excel d) Mass Motion e) Carrier HAP f) Autodesk CFD g) SES (Subway Enve. Simul.) h) EASE Address i) IP Video System Design Tool j) Relux k) DIALux	l) E-Design m) Ecodial Advance Calculation n) iBwave o) ETAP p) Autodesk Robot Structure r) Plaxis s) Elumtools t) Midas GTS NX Full u) Settle 3d v) Slope/W y) Autodesk Insight
Additional Software Solutions	a) Enscape b) Twinmotion c) Unity d) Ms Project e) Autodesk Dynamo Studio	f) Ms Office g) Sketchup h) Autodesk BIM360 i) AMP Yaklaşık Maliyet j) Adobe Creative Cloud k) Revit Live

4.6. Disciplinary Processes

In this section, the processes carried out according to the proposed system for each discipline have been examined individually and findings are presented.

4.6.1. Initial Studies

With the decision made between the stakeholders at the beginning of the project, it was decided that the design firm can work in its local server until client-sharing. First, the document coding system was determined depending on the employer's needs.

Folder structure was created following the definitions specified in the information management process. Based on the model division strategy agreed by all stakeholders in the project, WIP and shared sub-folders were created (Fig. 4.1). In the model division strategy, it was decided to create 7 BIM models for one station. These models were architectural finishes for passenger areas, other architectural elements, structural, landscaping, geotechnical, electrical-electronic, and mechanical. The model contents have been described in detail under the following sections of the related disciplines.

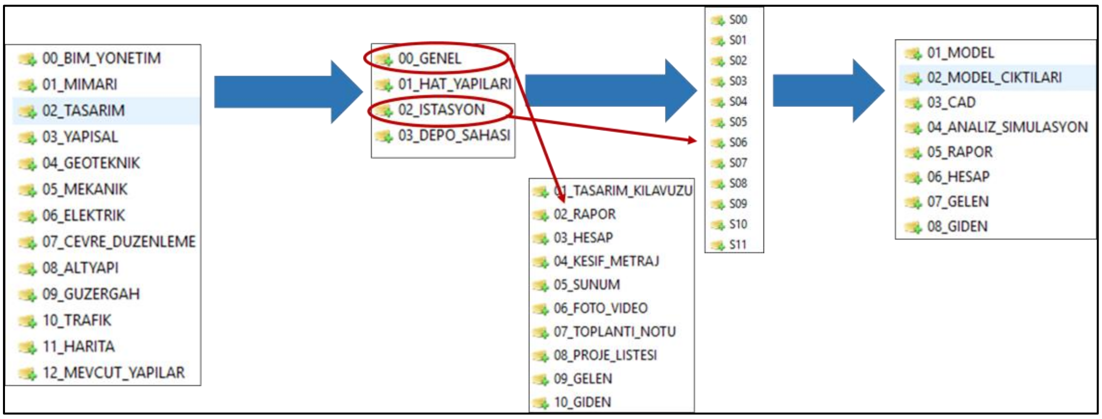

Figure 4.1. WIP and SHARED Sub-Folder Structure Created for the Project

At the beginning of the project, the development of all automation solutions was not completed. It was stated that the studies would continue systematically. For the ongoing studies, it was decided that manual approaches would be used until automation solutions are finished. These studies are listed below:

- Creating Room Data Sheets (RDS)
- Viewing changes made between different versions of shared models
- Converting model files to suitable format and contents for some analysis and simulation studies performed in other software solutions

4.6.2. Architectural

In this case study, two different teams were involved in architectural studies. The architectural design team, which will be called Architectural Team-1 in the case study, was responsible for the studies such as station layout, room arrangement, and modeling activities for technical areas of the station. The aesthetic design team, which will be called Architectural Team-2 in the case study, was responsible for designing finishes, ceilings, special design elements for the passenger area of the station.

Firstly, station layouts were studied together with the route team. In this process, the existing underground utility data, survey files, and existing structure models prepared by the responsible disciplines were used as a reference.

After the station layouts were determined, the room arrangements of the stations were started to be studied by Architectural Team-1. Since some stations are similar to each other, three information models were created for each similar station type in the preliminary design stage. Nevertheless, similar stations were copied from these information models for layout studies and their coordinate values were changed to examine the interaction with existing structures. The coordinate information is automatically taken from the route file as suggested.

Autodesk Revit was used to create the BIM models by Architectural Team-1 (Fig. 4.2). All architectural models were shared twice with the other disciplines for review in the preliminary design stage. Disciplines issued their review results through the developed applications. In this way, the whole review process was recorded as suggested. Then, architectural models were shared for coordination with the other disciplines.

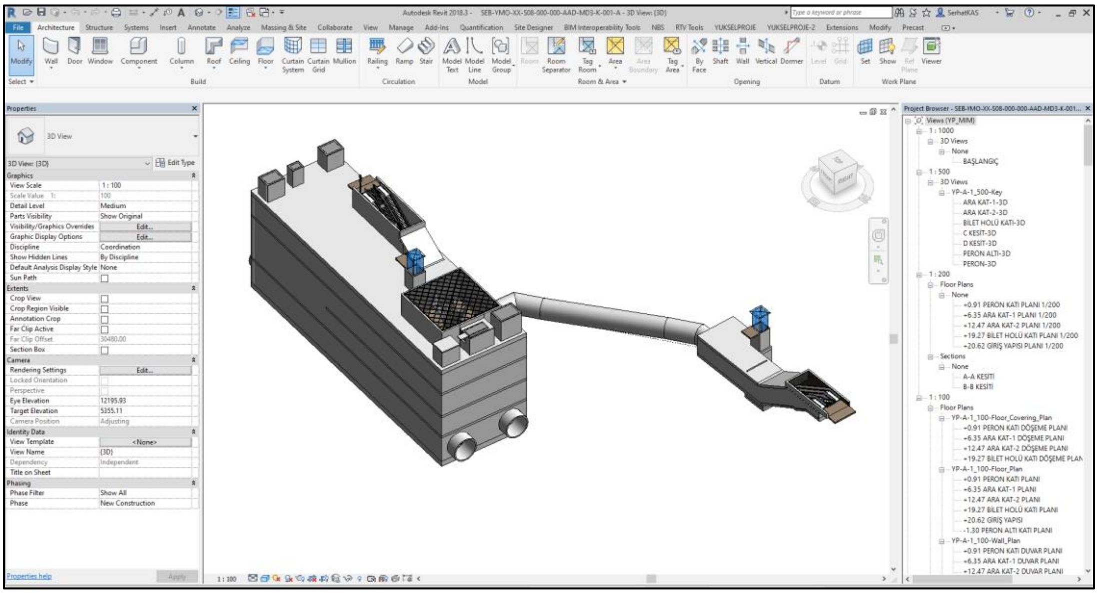

Figure 4.2. A Sample Image for an Architectural Model from the Case Study

At this stage, Architectural Team-2 started aesthetic design works for the passenger areas. Although the aesthetic design studies in the previous projects were carried out in the detailed design stage, the aesthetic design studies were started after the first architectural model was published for coordination purpose by following the proposed system. Using the architectural model as a reference model, suspended ceilings, walls and floor finishes for passenger areas started to be modeled in a different information model. For electromechanical elements that must be shown in the renders, the elements were added to the model by working with the related MEP disciplines. In this way, the location of some electromechanical elements started to emerge at the preliminary design stage of the project.

Employer presentation was prepared for different aesthetic design alternatives in a short period of 1.5 months for three types of stations. At this stage, the design automation solution that places architectural finishes into the model was of great importance in accelerating the process.

In order to study different design alternatives within the same model to follow the proposed system, “Design Options” tool in Revit was used (Fig. 4.3). In addition to the materials information defined in all architectural elements, textures of these materials were also defined in the model elements. In this way, a great advantage was gained in the rendering process in terms of time (Fig. 4.4).

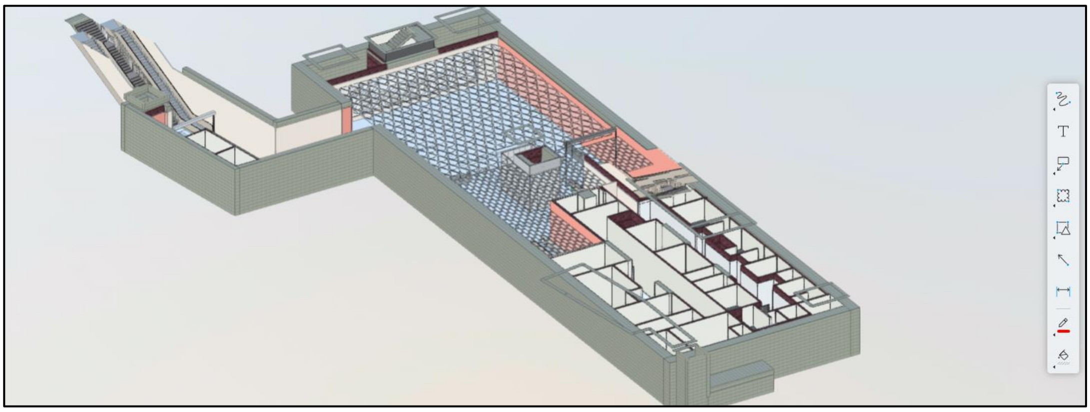

Figure 4.3. A Sample Image for the Concourse Level of the Architectural Model from the Case Study

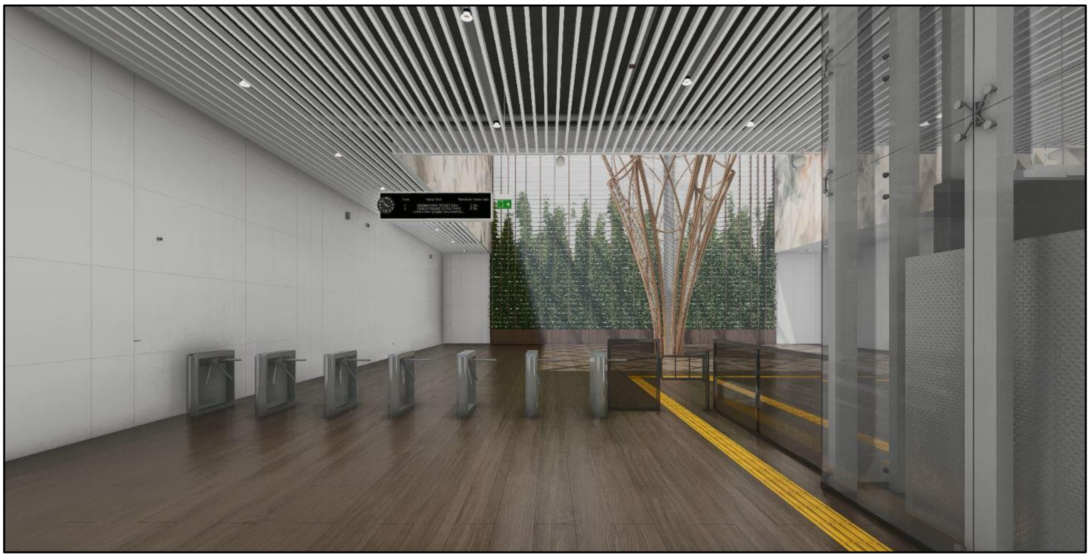

Figure 4.4. A Sample Render for a Concourse Level from the Case Study

All material properties, textures, and other related information were defined into model elements and all renderings were prepared through the information model. It was verbally shared with the designer that this work was one of the fastest accepted aesthetic designs by the employer.

Furthermore, virtual reality (VR) technology was actively used in the design process. VR solutions were used to design and examine the aesthetic architecture elements of the stations to meet the visual requirements (Fig. 4.5). VR solution, in which the station design appears most realistic and offers the option to change model elements through the interface, was chosen for use in the design process.

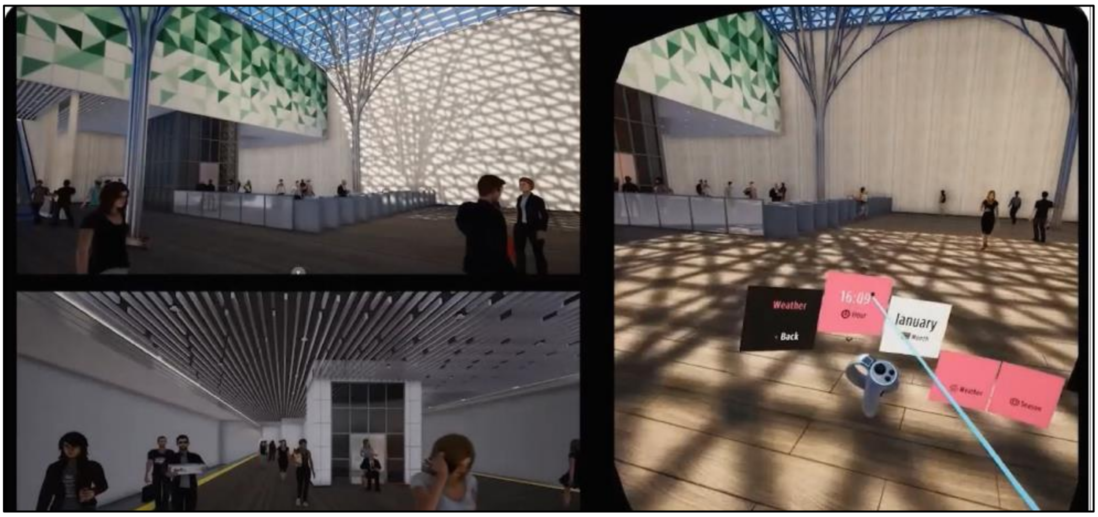

Figure 4.5. A Sample Image for the VR Model from the Case Study

The client presentation for aesthetic design alternatives was also made through virtual reality technology. In addition to client presentations, these solutions were actively used in design coordination and design review studies.

Although two different architectural teams worked together in the project, in fact two groups represented the architectural discipline. It can be stated that all the works were carried out, as suggested. Although two different architectural models were created, these models were combined as one model according to the employer's request to create design documents.

4.6.3. Structural

Structural discipline only involved in review studies of the architectural design at the preliminary design stage. By using the structural elements defined in the architectural model, a rapid transition to analysis software was achieved at this stage. The analytical models were converted to the appropriate format automatically as suggested.

In the detailed design stage, the structural discipline started the modeling activities. Structural models were created (Fig. 4.6) from the revised version of the architectural models arranged at the start of the detailed design stage according to the employer's review results.

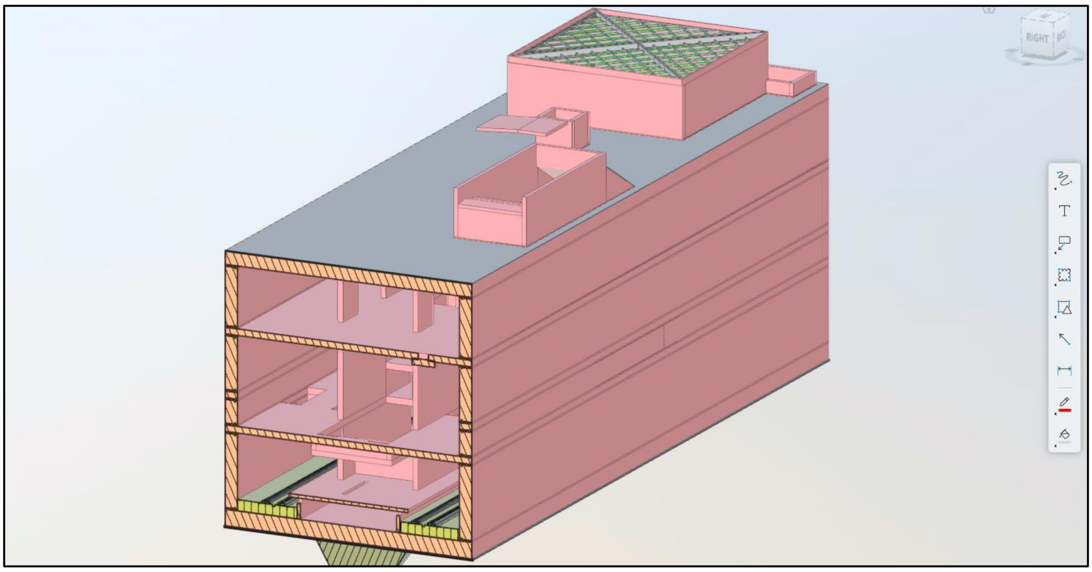

Figure 4.6. A Sample Image for a Structural Model from the Case Study

Since the requested LOD for reinforced concrete elements was LOD300, reinforcement elements were not modeled in 3D. Two different methods might be followed for the reinforcement drawings. They would either be created as 2D (Drafting Views) in Autodesk Revit or drawn as 2D CAD. They were created in

Autodesk AutoCAD at the request of the employer. They were drawn on the formwork plans produced from the information models. Eliminating the inconsistency between the drawings made it difficult to follow the revisions. This led to a decrease in the efficiency of the process of creating structural drawings.

For the steel elements used for the skylight, main structural elements were created within the Revit model, on the other hand, the connection details were studied in Autodesk Advance Steel.

Structural tunnel models (Fig. 4.7) were created by using automated solutions as suggested. The preparation of the tunnel structure models for the whole line was completed within 2 days. They were modeled using 3D model lines shared by the route discipline. In the case of revision of the route project, it took only few hours to modify the structural tunnel models.

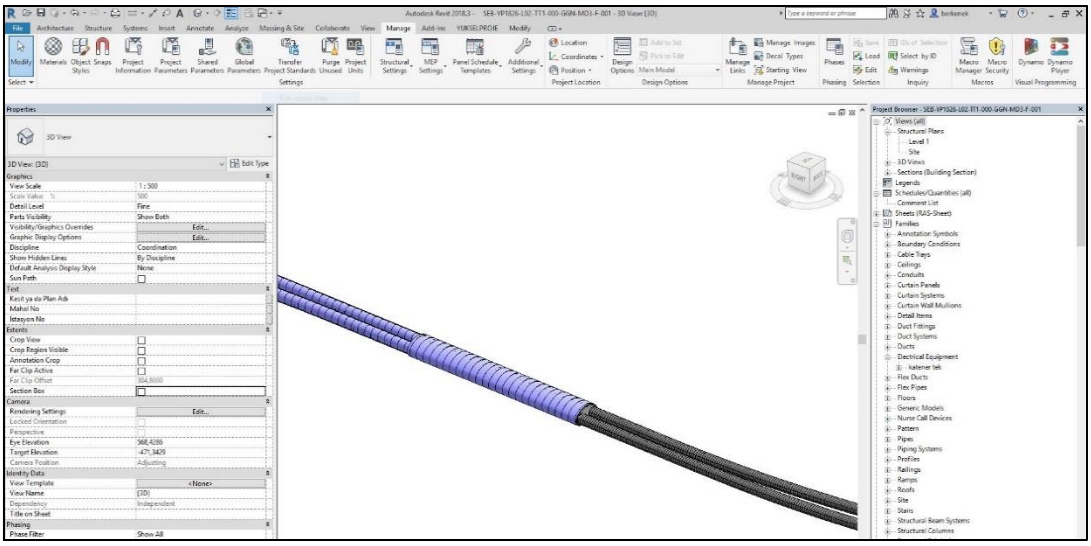

Figure 4.7. A Sample Image for a Structural Tunnel Model from the Case Study

It was observed that the solution developed for the automatic creation of reservations during the detailed design stage was insufficient. Although the relevant solution accelerated the process, the AAD solution did not work correctly for specific areas.

Since this was entirely related to the algorithm behind the AAD solution, its positive impact on the process should not be ignored.

4.6.4. MEP

At the preliminary design stage, mechanical, electrical, and electronic disciplines involved in the review process together with other disciplines. During the preliminary design stage, equipment placement studies were also carried out in the WIP model files of the MEP disciplines to be shared with the architectural model.

Another study conducted during the preliminary design stage was the modeling MEP elements that has an effect on the aesthetic design of the passenger area in order to perform the renderings studies. The works requested by Architectural Team-2 were realized and shared with them.

In Project-A, ventilation, plumbing, and firefighting systems were modeled together in the mechanical model for each station (Fig. 4.8).

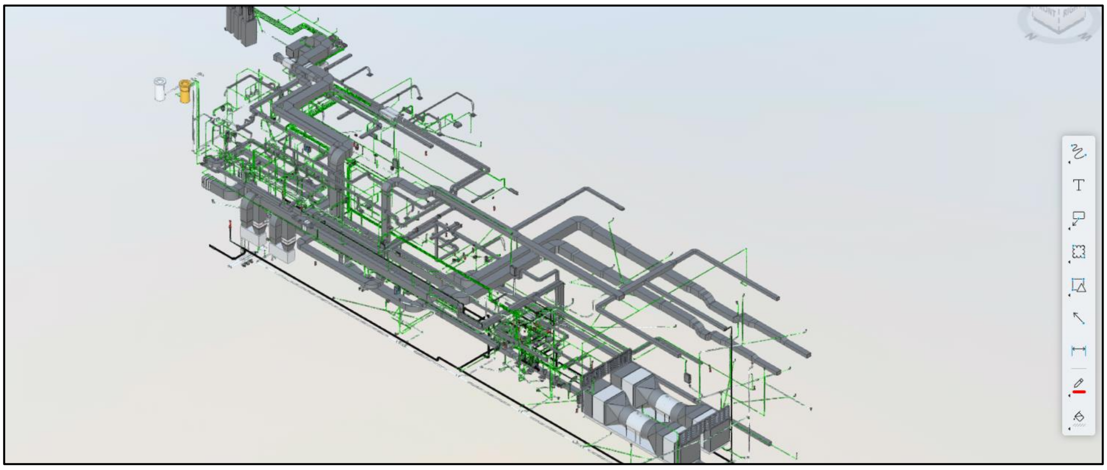

Figure 4.8. A Sample Image for a Mechanical Model from the Case Study

The same applied to electrical and electronic disciplines and it was decided to work in a single model for these disciplines at the start of the project (Fig. 4.9). A fire detection system was also included in this information model.

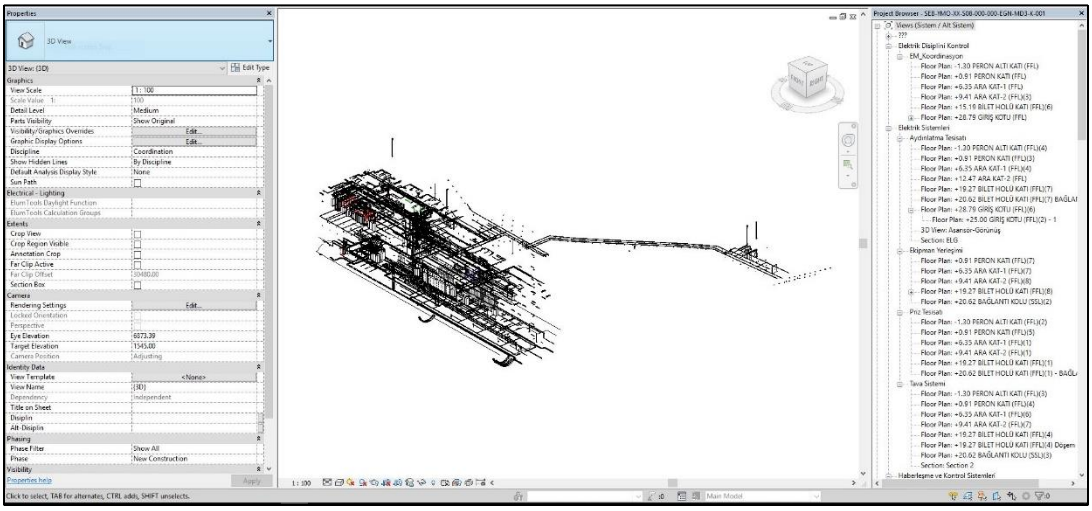

Figure 4.9. A Sample Image for an Electric-Electronic Model from the Case Study

The main advantage of information models was that engineering analysis and simulation processes were performed faster. Many mechanical analysis studies like ventilation flow, heating-cooling, domestic-water, waste-water, etc., were carried out in the model as proposed with the developed AAD and API solutions apart from the more extensive studies like CFD, fire evacuation, pedestrian dynamic, and lighting simulations.

For CFD studies, which have an essential place in the design of metro stations, it was planned to use the architectural model that shared with the other disciplines. However, when the architectural model was used without making any modification, it is observed that the analysis time for CFD increases. Thus, a new approach was needed to perform this study. As a solution, an automation algorithm that can convert the architectural model shared for coordination into a 3D mesh model by including only the necessary information was created and used (Fig. 4.10).

Although it is one of the first attempts of the company to make calculations for electrical and electronic systems through the information model, many analysis processes have been carried out within the system. One of the most important of these was lighting simulation for a station (Fig. 4.11).

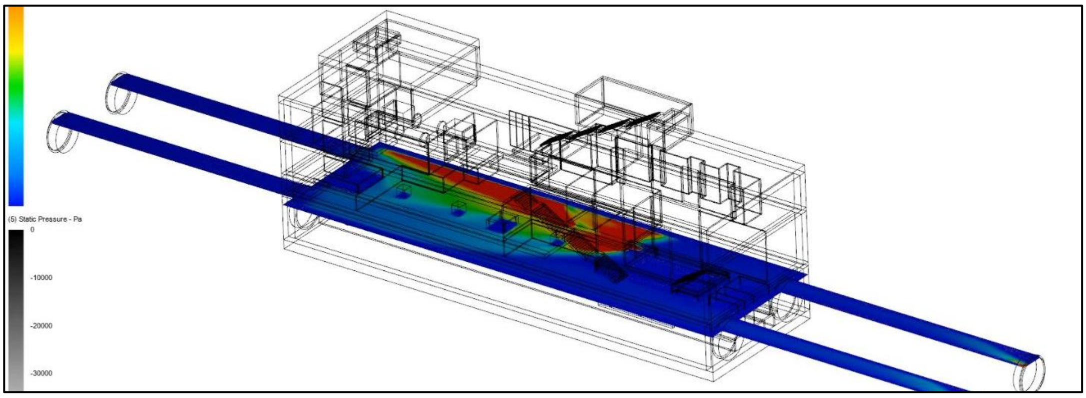

Figure 4.10. A Sample Image for a CFD Model from the Case Study

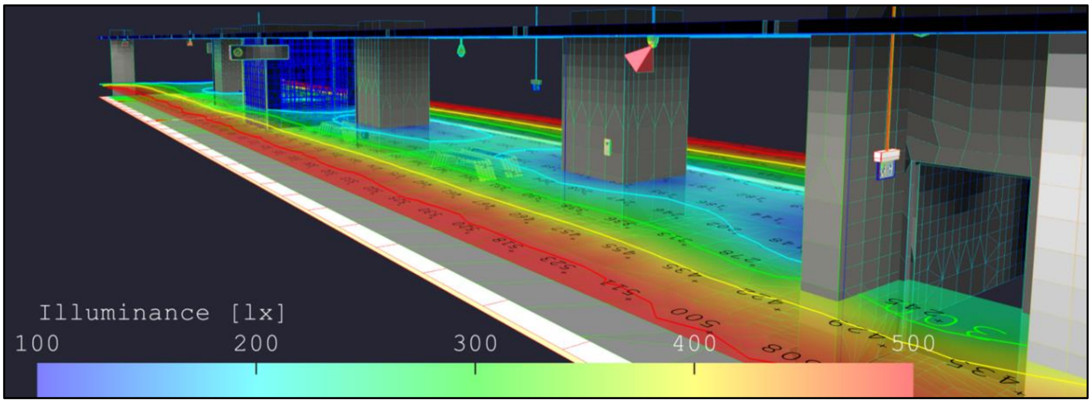

Figure 4.11. A Sample Image for a Lighting Simulation from the Case Study

4.6.5. Geotechnical

In the project, geotechnical elements were modeled in the detailed design stage. Modeling studies were performed according to specification requirements. Although some drawings were created from BIM models, not all drawings were produced from the models.

3D models in *.dwg file format converted from these information models were used as a reference in relocation of underground utilities (Fig. 4.12).

Geotechnical elements for tunnel elements are modeled automatically within the scope of the developed automation solutions. Cross-sections for geotechnical structures of the tunnels were prepared in 2D CAD.

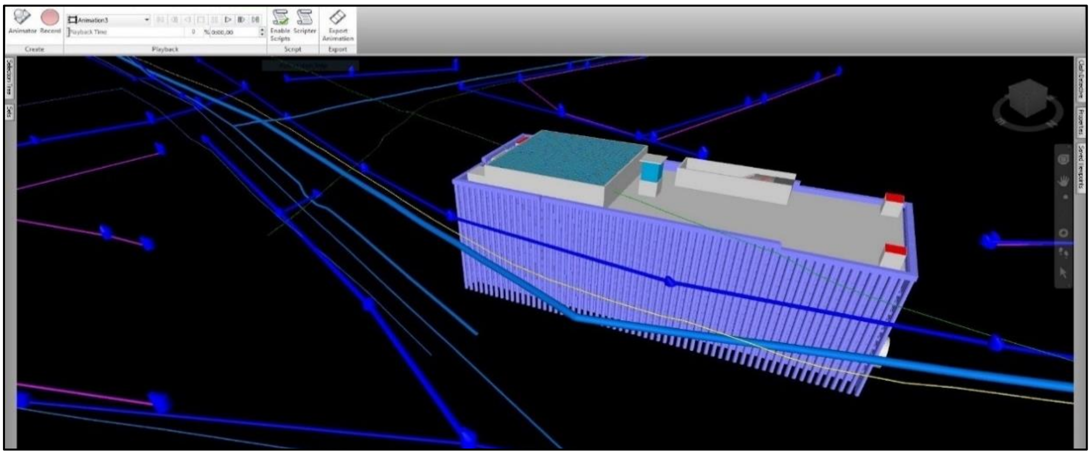

Figure 4.12. A Sample Image for a Geotechnical Model from the Case Study

4.6.6. Underground Utility

In the preliminary design stage, underground utility projects were prepared according to the data provided by the relevant institutions. Since the data should be controlled at the site, 3D CAD models were not created at this stage. Route file, station layouts, and survey files were used as reference information to create plans for existing underground utilities (Fig. 4.13).

Figure 4.13. A Sample Image for a Waste-Water Plan from the Case Study

After actual data from the site is provided, 3D CAD models for existing underground utilities were created (Fig. 4.14). Existing underground utilities within the station corridor were studied in Autodesk Civil3D.

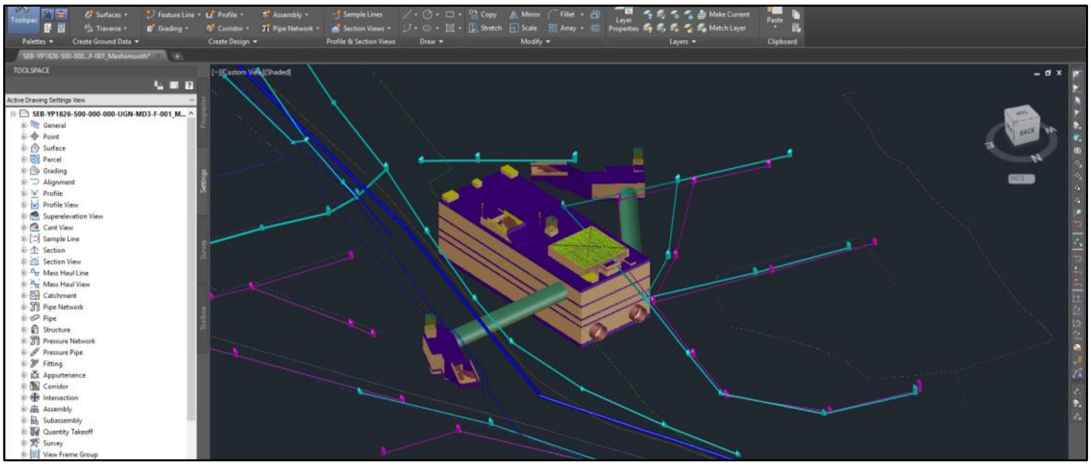

Figure 4.14. A Sample Image for an Underground Utility Model from the Case Study

After 3D models for existing underground utilities were created for each station area, the areas that needed to be rearranged were determined by using the 3D models of the disciplines responsible for station design. At this stage, geotechnical models were used to determine the need for rearrangement of existing utility lines, while MEP models were used to study the need for a connection to the existing lines from the station (Fig. 4.15).

3D CAD model files converted automatically from BIM models were used in these studies. Since they were created in *.dwg format, information models created in Autodesk Revit were converted into related format automatically as suggested in the system to enable this discipline to use these models in its own studies. In other words, while the geotechnical information model was shared, the 3D CAD model in *.dwg format was also shared for the related disciplines. In this way, the relevant discipline was able to access the reference information quickly without any conversion. Besides, they did not have to deal with a software they do not use in their design studies.

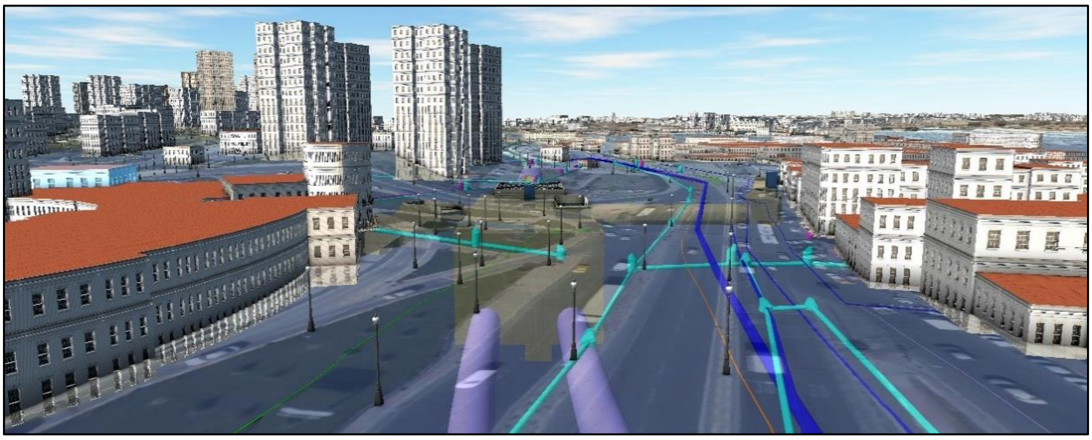

Figure 4.15. A Sample Image for a Relocated Underground Utilities from the Case Study

4.6.7. Route

All activities were carried out by the route discipline during the preliminary design stage, as suggested. At the beginning of the project, station layouts were studied with Architectural Team-1. In this process, the existing underground utilities data prepared by the related discipline was also taken into consideration. Then, route alternatives were presented to the employer for the approval. In the detailed design stage, the project was revised, detailed plan and profile studies were prepared.

The route file was used as reference information for many automation processes throughout the project. When sharing the file, both the 2D CAD file and the 3D model line file created in Autodesk Civil 3D were shared with the disciplines at the same time. 3D model line file was used for tunnel modeling study and automatic coordinate placement of the stations.

Although an employer presentation was not made, the design teams produced tunnel and station mass models for different route alternatives during the preliminary design stage to test the proposed solutions. As a result of a one-day study, the mass models for three different alternatives could be created. Along with the 3D modeling of existing structures, the interaction of the existing structures with the metro line could be examined in 3D instead of 2D (Fig. 4.16).

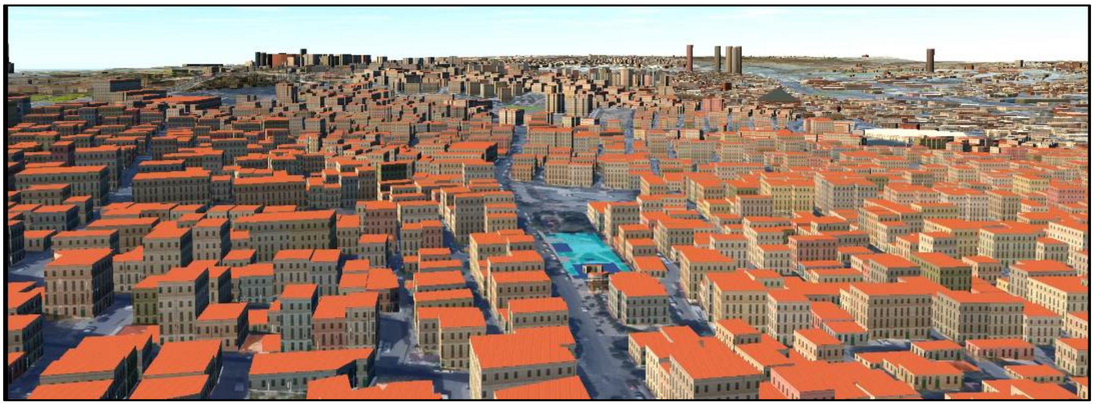

Figure 4.16. Perspective View for a Virtual Project Model from the Case Study

4.6.8. Traffic

Related studies were carried out only for six stations depending on the existing road structures. For these station corridors, temporary and permanent traffic plans were prepared.

3D CAD models were created using survey files, existing underground utilities, related architectural files, and existing structure models, as suggested. Model files were shared for each structure so that other disciplines could use them in their design studies.

4.6.9. Survey

According to the initial route corridor, survey files were prepared for the whole corridor. Related studies were performed with 2D CAD software. The created survey files were base maps, zoning plans, cadastral plans, orthophotos, and terrain models.

Afterward, these files were divided and shared for each structure region as suggested so that other disciplines could use these files in their modeling activities. During the division process, zoning areas for each structure were defined in the WIP file prepared for the whole corridor, and these areas were automatically divided and shared with the others for coordination studies. Since all line structures were underground tunnels, survey files for these structures were not created separately.

With the clarification of the layouts of the stations, the existing structure model was created by the survey discipline for the entire metro corridor using the available data (Fig. 4.17). Autodesk Civil3D and Infraworks software solutions were used at the preliminary design stage. Afterward, the model was divided for each station region, and they were shared with other disciplines.

Figure 4.17. Plan View for an Existing Structure Model (Entire Metro Corridor) from the Case Study

Modeling studies (3D Mass Models) for critical engineering structures that have an interaction with the metro system were carried out by using reference information provided from different institutions. Besides, 3D mass models of the existing/planned rail system structures that have integration with the Project-A were created. These 3D mass models were added to the existing structure model. The revised station corridors were shared with the other disciplines.

With the acquisition of available data for the station regions, all of these contents were updated. The updated model was divided for each station region; all of these models were shared again. Two different techniques, traditional surveying method and reality capture technology, were used.

For critical station areas in the project that have integration with other metro lines, reality capture technology was preferred to be used. Existing condition data of the station corridor was captured by using a laser scanner and UAV depending on the situation. Autodesk ReCap software was used for the data-processing study. Existing structure models were not created for these station areas, and 3D models generated from the captured data were used directly (Fig. 4.18).

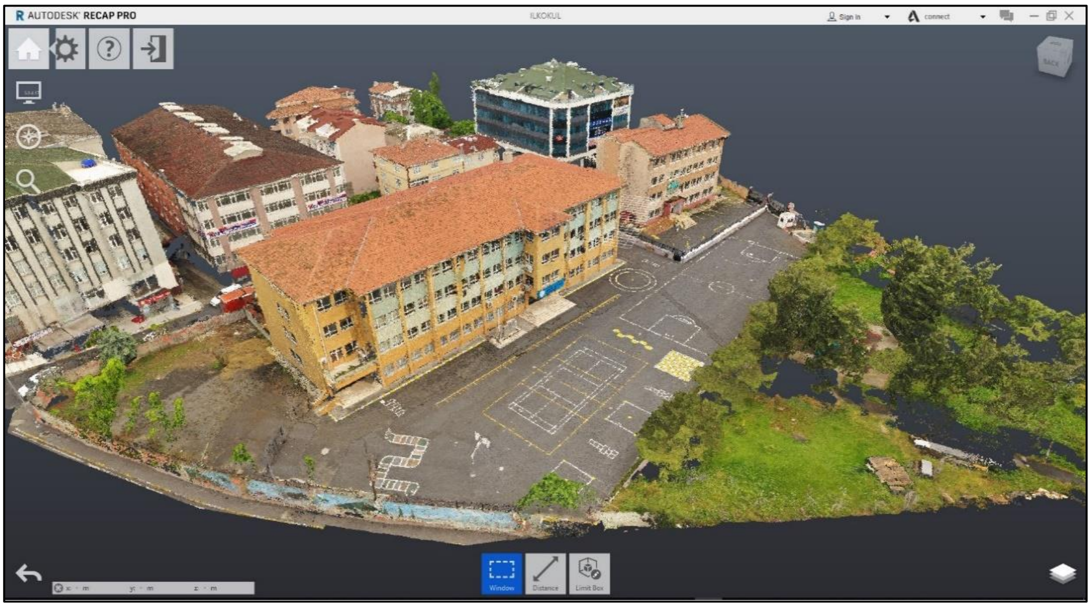

Figure 4.18. A Sample Image for an Existing Structure Model Created in Autodesk ReCap

4.7. Design Coordination

The design coordination studies were carried out only in the detailed design stage. Autodesk Navisworks software was used in these studies. Models were converted into *.nwc file format. It was ensured that the shared BIM models are automatically combined in the coordination model file (Fig. 4.19). Design coordination problems were discussed in the BIM coordination meetings. In the case of a new model shared by one of the disciplines, the coordination model file was automatically updated, and the clash results were created according to the new shared file.

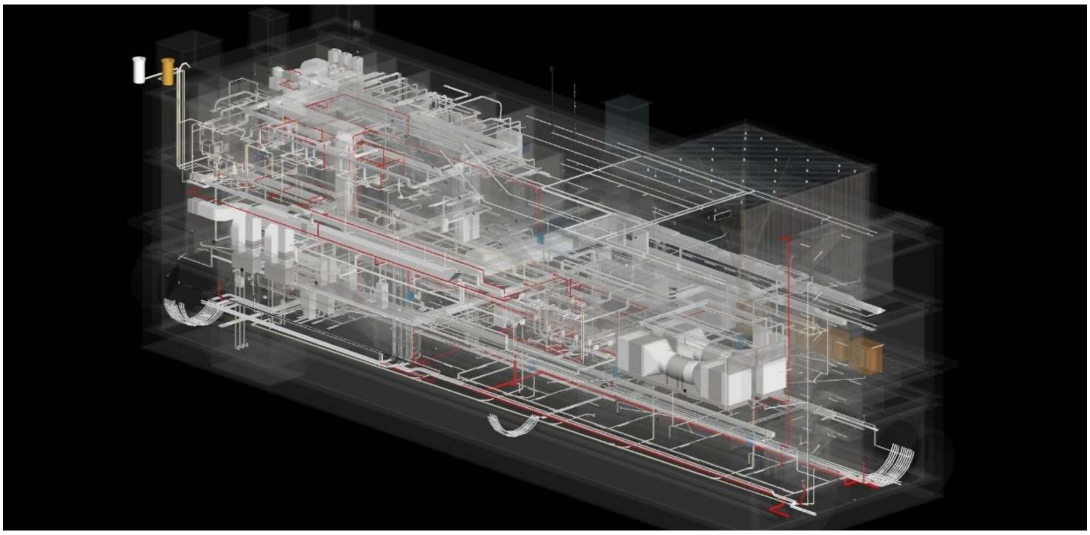

Figure 4.19. A Sample Image for a Coordination Model Including BIM Models from the Case Study

Design coordination studies were carried out not only with 3D BIM but also 3D CAD files shared by related disciplines (Fig. 4.20). The 3D models used in the coordination studies for a station were structural, geotechnical, mechanical, electrical-electronic, landscaping, underground utilities, traffic, existing structures, and two different architectural models.

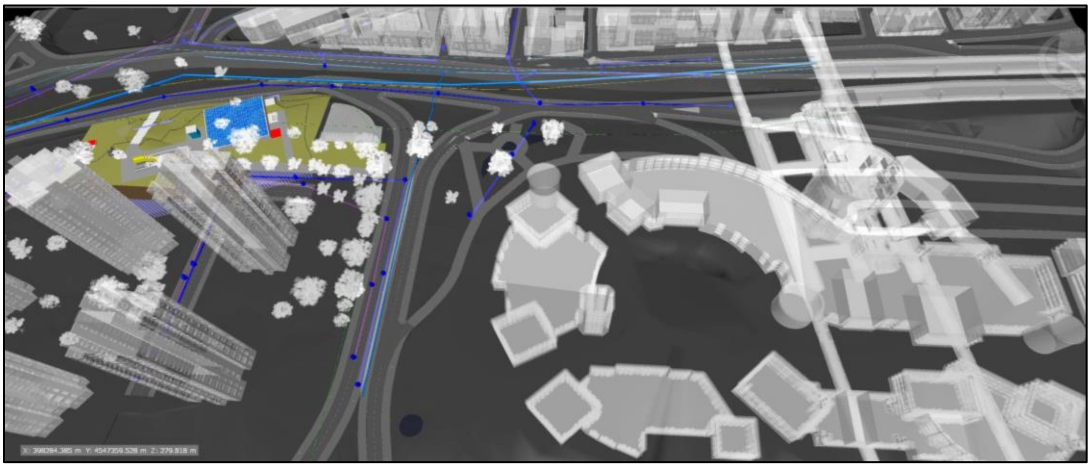

Figure 4.20. A Sample Image for a Coordination Model Including 3D Models from the Case Study

In addition, existing structure models produced with reality capture technology were also used in coordination studies for specific station areas with BIM models and 3D CAD files (Fig. 4.21.).

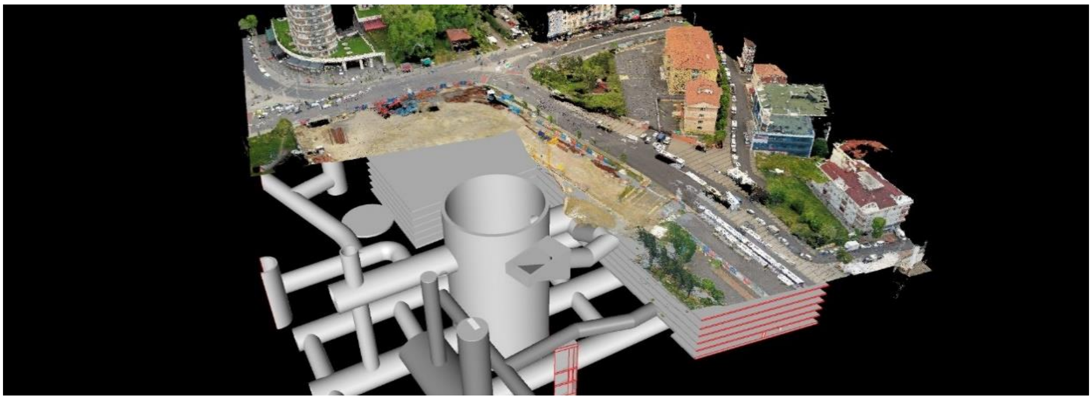

Figure 4.21. A Sample Image for a Combination of a Station Model and Existing Structure Model

CHAPTER 5

RESULTS AND DISCUSSION

In this study, a BIM-based design collaboration system has been developed and it is implemented during the design of a metro project as a case study. In this chapter, the benefits of implementing the collaboration system are discussed by comparing the outputs with a comparable metro design project that was completed in the same design firm before the proposed system has been implemented. Challenges encountered during the development and implementation of the proposed collaboration system are also discussed. Finally, future study needs are presented.

5.1. Comparison

In this section, Project-A is compared with another metro design project (Project-B) in the same city which is completed two years ago by the same design firm for the same employer.

Outputs of the projects have been compared in terms of:

- Number of documents (produced in the BIM environment).
    - Models
    - Drawing documents
    - Design documents
- Numbers of design revisions
- Time
- Cost
- Number of disputes between design disciplines
- Number of errors in file sharing

Some terms used in the comparison study are described below in Table 5.1.

Table 5.1. *Terms Used in Comparison Study*

DESIGN DOCUMENTS →	DRAWINGS + MODELS + REPORTS
DRAWINGS DOCUMENTS →	DRAWINGS
PRODUCED DESIGN DOCUMENTS →	REVISION 0 + REVISION 1 + REVISION 2 + REV…
PRODUCED DRAWING DOCUMENTS →	REVISION 0 + REVISION 1 + REVISION 2 + REV…
DESIGN DOCUMENTS for REVISION 0 →	DRAWINGS + MODELS + REPORTS (REVISION 0)
NOTE 1: Terms covers the documents produced during the detailed design stage. **NOTE 2:** "DESIGN DOCUMENTS for REVISION 0" also represent the total number of documents to be delivered. **NOTE 3:** Each model file, report or drawing is counted as 1 document.	

5.1.1. Reference Project Information (Project-B)

Project-B includes the preparation of tender documents for a metro system consisting of 3 stations and 4 line structures. The total line of the metro system was approximately 5 km. The scope of the tender documents covers architectural, structural, electromechanical systems. The tender documents submitted for Project-B contain the same scope as Project-A used for the case study.

The total design duration of Project-B was 16 months. The preliminary design stage took a total of 5 months to complete. The detailed design process lasted for 10 months. The remaining time for the creation of tender documents was 1 month.

Architectural, structural, mechanical, fire, electrical and electronic discipline studies were carried out from 3D information models. In the process of producing design documents, 2D CAD solutions were also preferred for these disciplines. All the processes, such as underground utilities, geotechnical, route, traffic, design interactions with existing structures, were carried out by traditional methods outside the BIM system.

Although the disciplines within the BIM system managed the processes according to CDE processes, the whole collaboration process was performed manually. Unlike Project-A, automation solutions for information management process and design activities were not used in the Project-B. Besides, design automation solutions were not included, and manual modeling activities were carried out throughout the process. A few parts of the analysis and simulation processes were carried out within the information models. The vast majority of them were studied by traditional methods.

5.1.2. Comparison of Number of Design Documents and Design Revisions

In this section first the design document production details of Project B are presented. In total, over 1500 design documents including sheets, models, and reports were delivered to the employer at the end of the project. Final deliverables do not include different revisions of the same document. The distribution of the design documents submitted by the disciplines at the end of the project is indicated in the Figure 5.1.

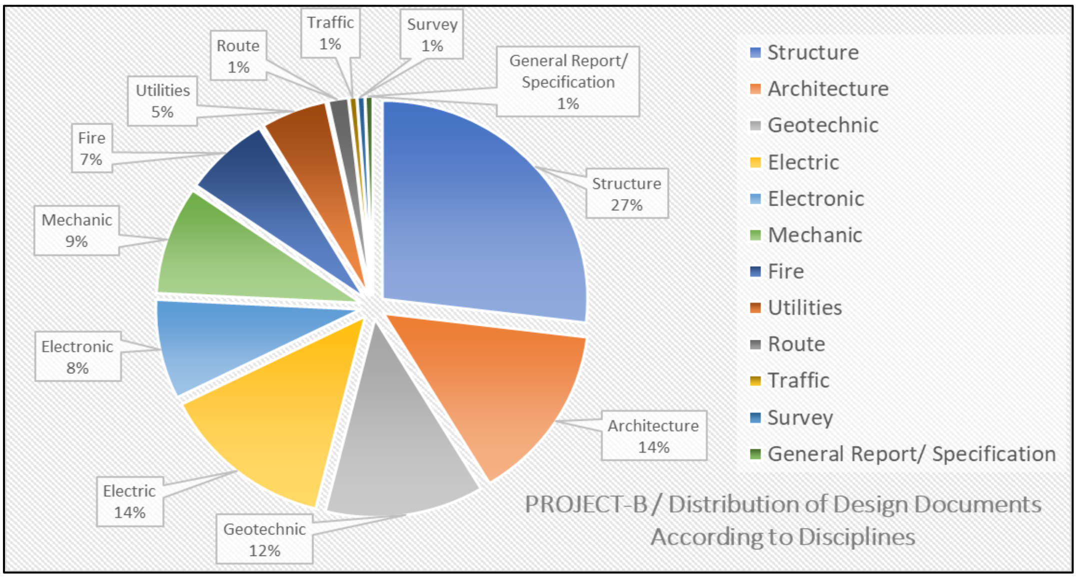

Figure 5.1. Distribution of Design Documents According to Disciplines for Project-B

According to this, 27% of the design documents were produced for structural purposes. The majority of these were related to reinforcement. After the structural discipline, most of the documents were delivered by architectural and electrical disciplines, with 14% of total documents for each discipline. After these disciplines, the distribution continues as follows:

- Geotechnical → 12%
- Mechanical → 9%
- Electronic → 8%
- Fire → 7%
- Utilities → 5%
- Route + Survey + Traffic + General Reports → 4%

When all the documents submitted to the employer are examined throughout the design, it is determined that the total number was approximately 3100 documents. It includes different revisions of the same document. Around 100 of these were produced and delivered at the preliminary design stage, while approximately 3000 documents were delivered to the employer during the detailed design stage (Fig. 5.2). The documents produced and delivered in the preliminary design stage constitute 3% of all documents delivered during the project. When the documents produced in the first 5 months and in the last 11 months are compared, a significant difference is observed. The detailed design stage is more critical for the design disciplines.

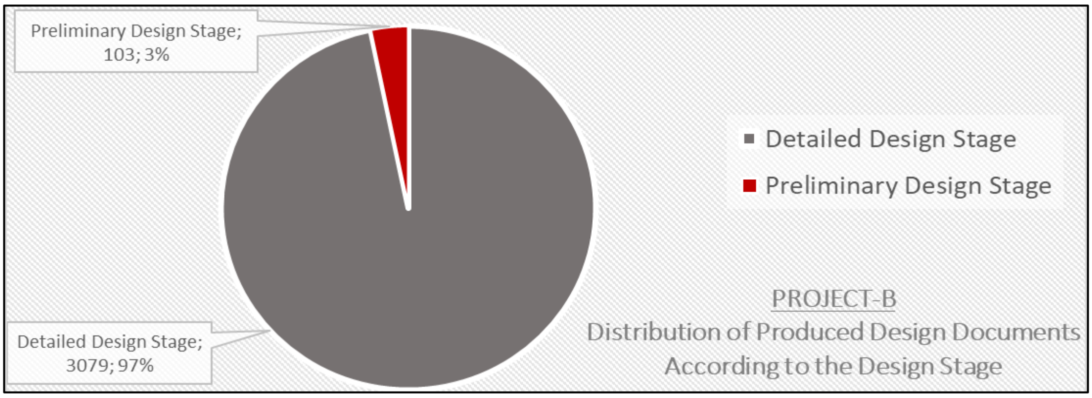

Figure 5.2. Distribution of Produced Design Documents According to the Design Stage for Project-B

If the distribution of revised documents created in detailed design stage is examined, it is seen that some of the documents were revised once and some were revised twice. When the distribution of the total delivered documents according to the revision processes is examined, a total of 1558 documents were revised. 1208 of these were revised as Revision-1 and 350 documents were revised for the second time (Fig. 5.3).

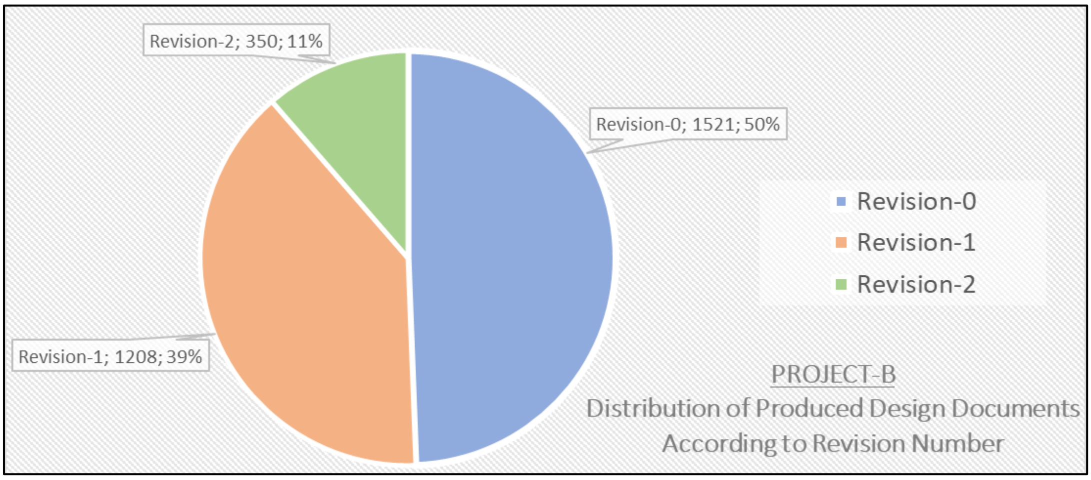

Figure 5.3. Distribution of Produced Design Documents According to Revision Number for Project-B

When the 1,521 submitted documents during the detailed design stage are examined, it is observed that 79% of them were revised once and 23% were revised a second time. Only 320 documents were accepted at the first delivery stage (Fig. 5.4).

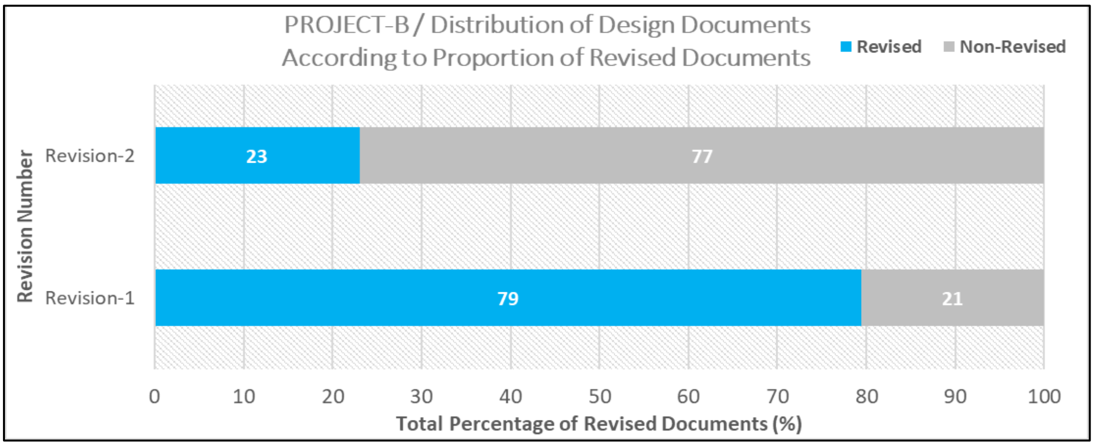

Figure 5.4. Distribution of Design Documents According to Proportion of Revised Documents

A total of 15 information models were created for Project-B during the detailed design stage. Each station structure was divided into 5 discipline models which were mechanical, electrical, architectural, structural, and geotechnical models. Drawing documents produced from these information models in the project constitute 30% of the total drawing documents that were submitted (Fig. 5.5).

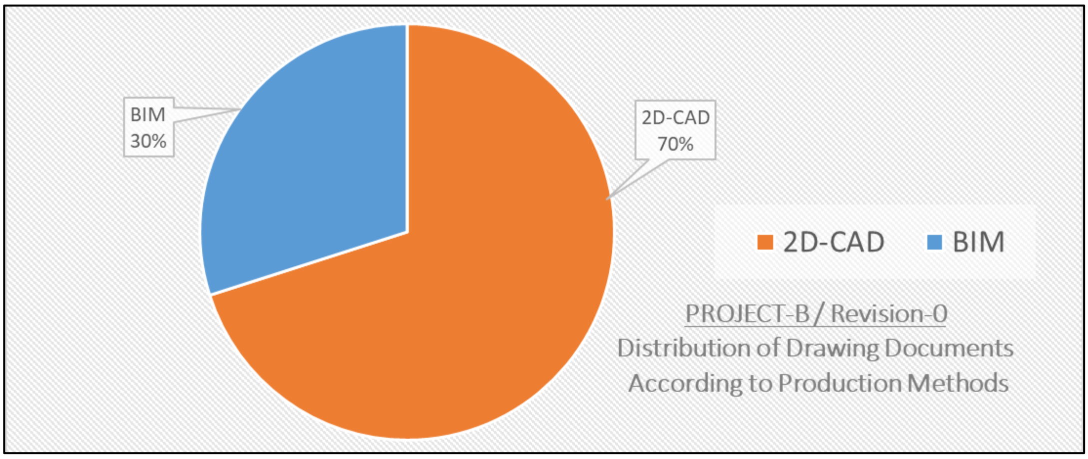

Figure 5.5. Distribution of Drawing Documents According to Production Methods for Revision-0 of Project-B

Detailed bar charts showing the number of drawing documents according to production methods per each revision for Project-B are presented below (Fig. 5.6).

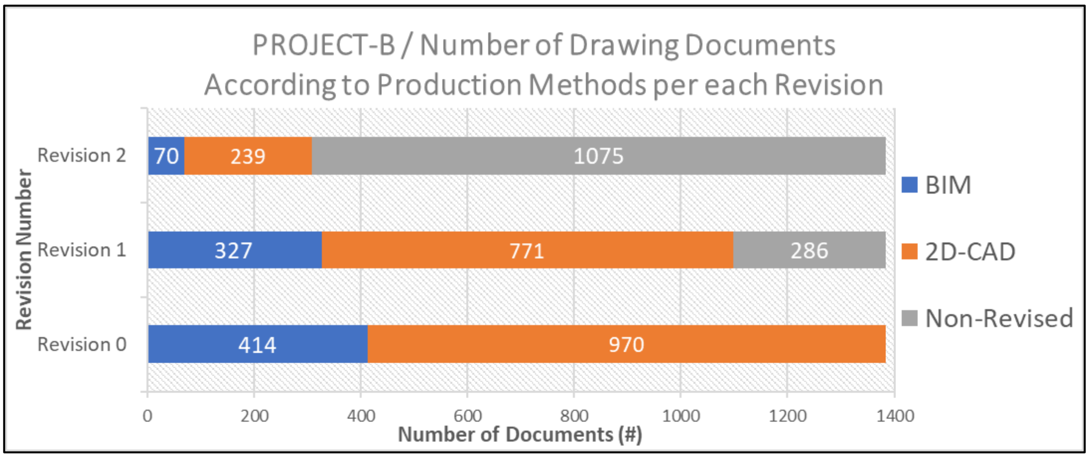

Figure 5.6. Number of Drawing Documents According to Production Methods per each Revision for Project-B

In the rest of this section, the design document details of Project-A are discussed. When all the documents planned to be produced at the end of the Project-A are examined, it is estimated that 17% of the design documents will be produced for structural purposes (Fig. 5.7). The majority of these will be related to reinforcement components as in Project-B. After the structural discipline, most of the documents will be delivered by mechanical discipline with 16% of total documents. After these disciplines, the distribution continues as follows:

- Geotechnical → 13%
- Architectural → 13%
- Electrical → 13%
- Electronic → 11%
- Utilities → 6%
- Fire → 5%
- Survey → 3%
- Route → 2%
- Traffic + General Reports → 1%

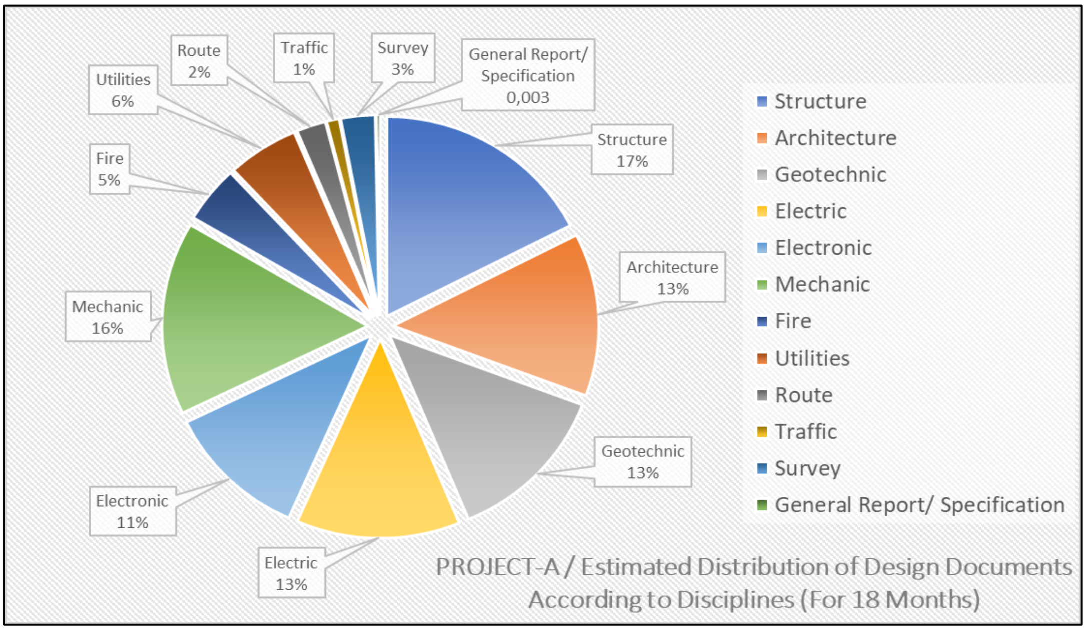

Figure 5.7. Estimated Distribution of Design Documents According to Disciplines for Project-A

When documents produced within first13 months of Project-A are examined, it is seen that most documents have been produced by architectural discipline (Fig. 5.8). This is followed by structural discipline with 18%. Although there are similar proportions between estimated and actual, it could be seen that the actual document delivery rate is lower than the estimated delivery rate for the geotechnical discipline.

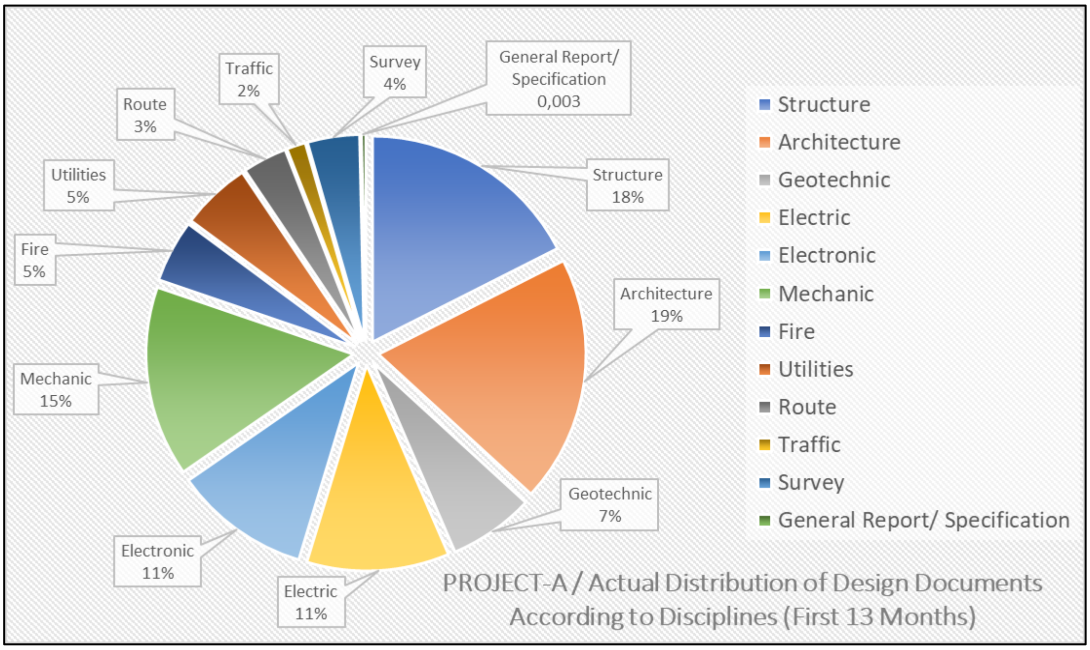

Figure 5.8. Actual Distribution of Design Documents According to Disciplines for Project-A

When all the documents that have been submitted to the employer are examined it is determined that the total number is approximately 2300 documents. It also includes different revisions of the same documents. 141 of these were produced and delivered at the preliminary design stage, while approximately 2127 documents have been delivered to the employer during the detailed design stage. The documents produced and delivered in the preliminary design stage constitute 6% of all documents delivered during the first 13 months period. (Fig. 5.9). When the documents produced in the first 6 months and the documents that have been produced in the last 7 months are compared, a significant difference is observed. The reason of this was deceleration of the project at the beginning due to external reasons.

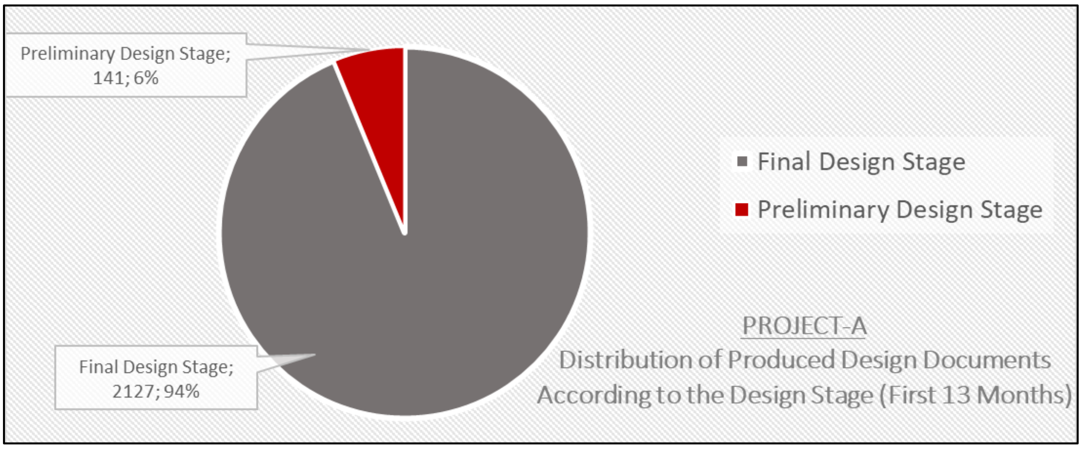

Figure 5.9. Distribution of Produced Design Documents According to Design Stage for Project-A

A total of 105 models have been created for the project in the first 13 months during the detailed design stage. Drawing documents that have been produced from these information models constitute 57% of the total drawing documents (Fig. 5.10).

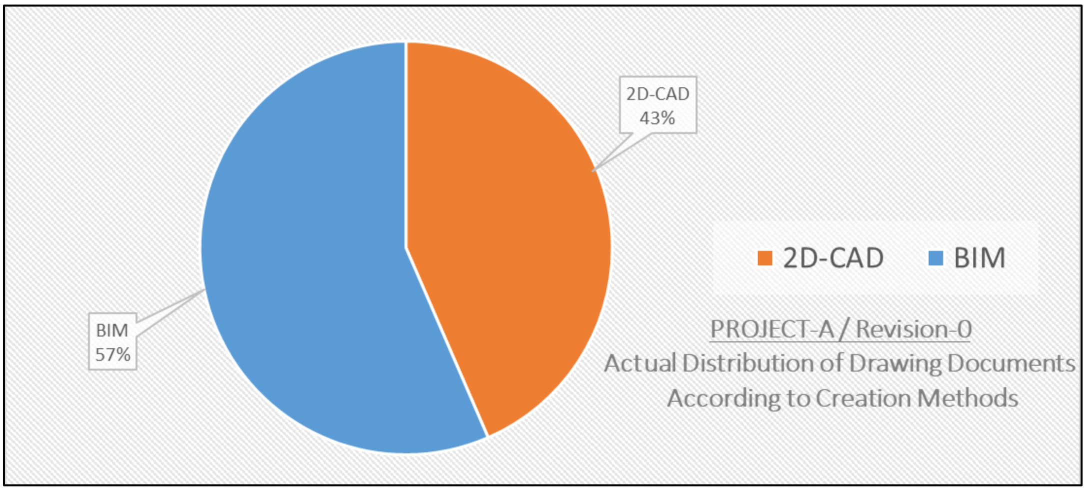

Figure 5.10. Actual Distribution of Drawing Documents According to Creation Methods for Revision-0 of Project-A

At the end of the project, a total of 124 models will be created as part of the detailed design stage. Estimated number of drawing documents produced from these information models constitute 65% of the total drawing documents to be submitted (Fig. 5.11).

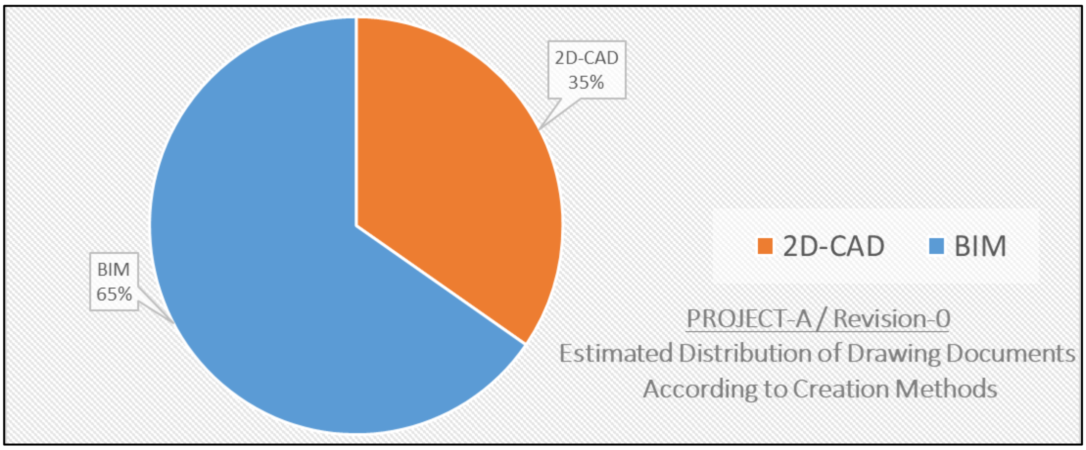

Figure 5.11. Estimated Distribution of Drawing Documents According to Creation Methods for Revision-0 of Project-A

Some documents have been approved and some documents have been already delivered to the employer, but a response has been waited for Project-A. Currently, there were no response for most of the delivered packages. Therefore, detailed statistical data on revision processes could not be extracted as the request for revisions comes from the employer.

The effects of the implementation of the proposed collaboration system is explained in terms of the following items in a comparative manner.

- Produced design documents according to the design stage
- Number of documents (Produced in the BIM environment).
    - Models
    - Drawing documents
    - Design documents
- Numbers of design revisions

When the documents produced in two projects according to the design stages are examined, it is seen that over 90% of the documents are produced in the detailed design stage (Fig. 5.12). All disciplines actively produce design documents at this design stage. These statistical data confirm how important it is to keep interdisciplinary collaboration at the forefront for this design stage, where all disciplines are actively involved in the design.

Comparing the number of models produced for both projects, over 100 models in Project-A have been produced in less time than the total 15 models produced in Project-B (Fig. 5.13). Especially with the design automation solutions, the possibility of performing similar works quickly provided this situation. In these statistics, alternative studies have not been taken into account and only the documents presented to the employer for approval have been considered. At the end of Project-A, a total of 124 models will be created. Although the same model division strategy has been applied in both projects, approximately eight times more models will be produced in Project-A than Project-B within comparable duration (Fig. 5.13).

Furthermore, it is aimed to decrease the number of revisions in Project-A with the proposed system. All revision statistic for Project-B were elaborated such as distribution of produced design documents according to revisions (Fig. 5.14) and drawing documents according to creation methods per each revision (Fig. 5.15). However, this condition could not be examined for Project A since the approvals of design documents has been still expected.

In addition to modeling studies, when the design documents produced from the models are examined, there has been a significant increase in the number of documents produced from 3D information models. The rate has been increased from 30% to 57%. At the end of the project, it is expected to reach 65% of the total drawing documents (Fig. 5.16). Particularly with the advantage of time gained in the design process, detailed drawing files that are not in the scope of Project-A have also been created in the models.

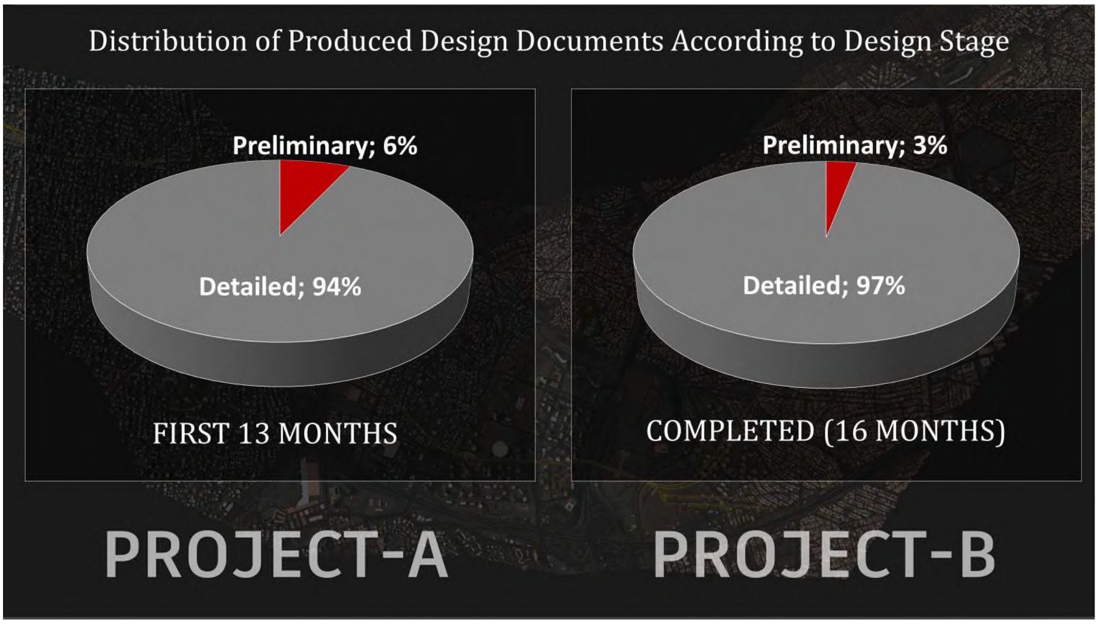

Figure 5.12. Distribution of Produced Design Documents According to Design Stage for Each Project

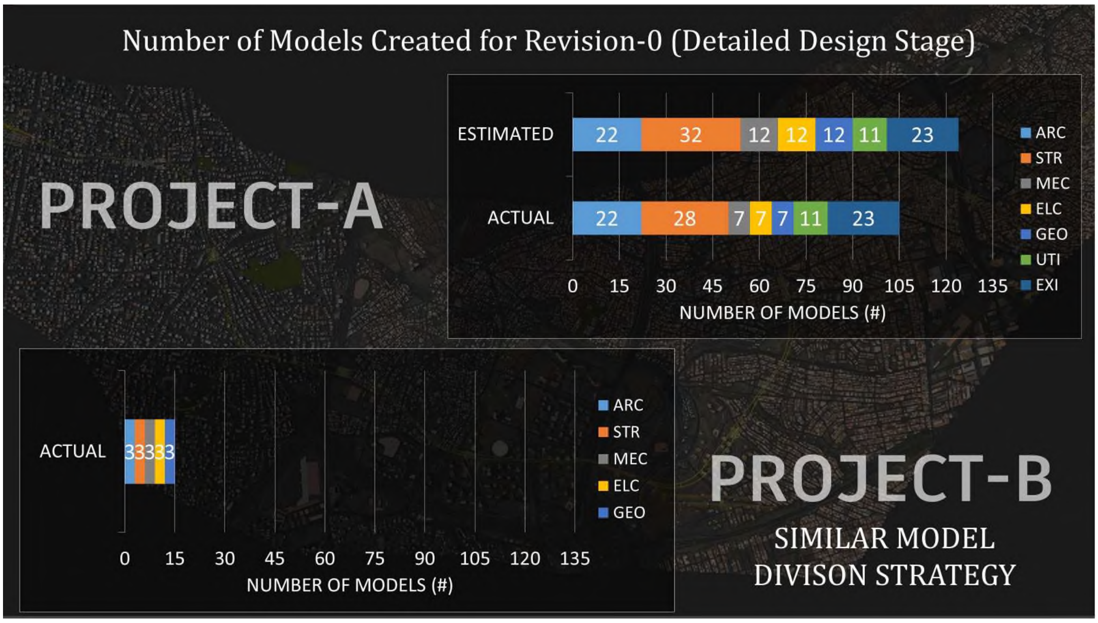

Figure 5.13. Total Number of Models Created for Revision-0 of Each Project and Estimated for Revision-0 of Project-A

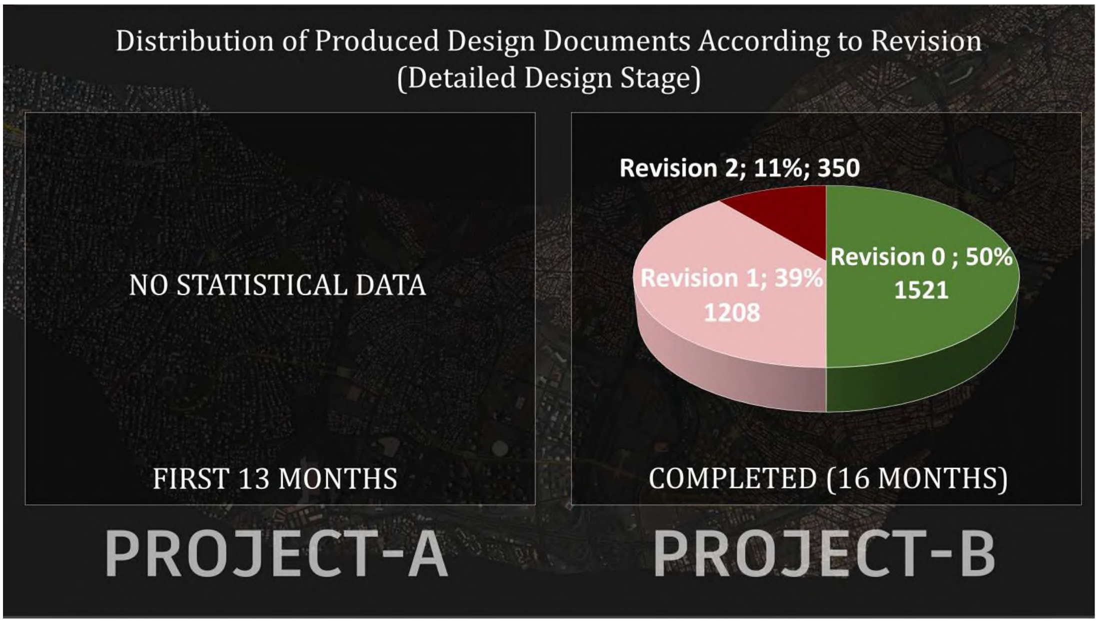

Figure 5.14. Distribution of Produced Design Documents According to Revision for Each Project

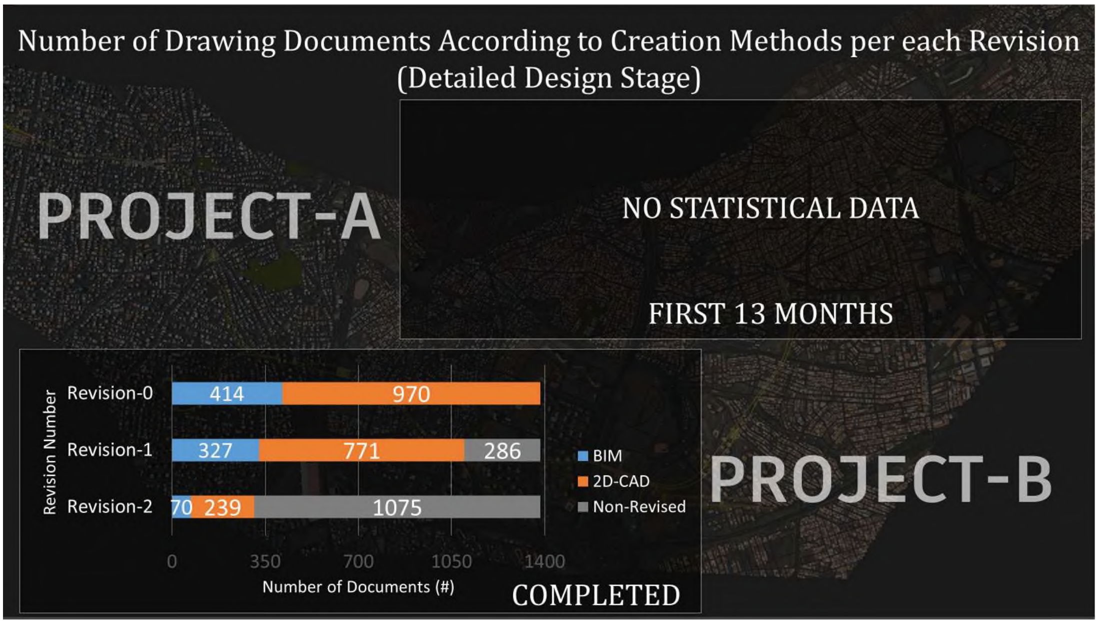

Figure 5.15. Distribution of Drawing Documents According to Creation Methods per each Revision for Each Project

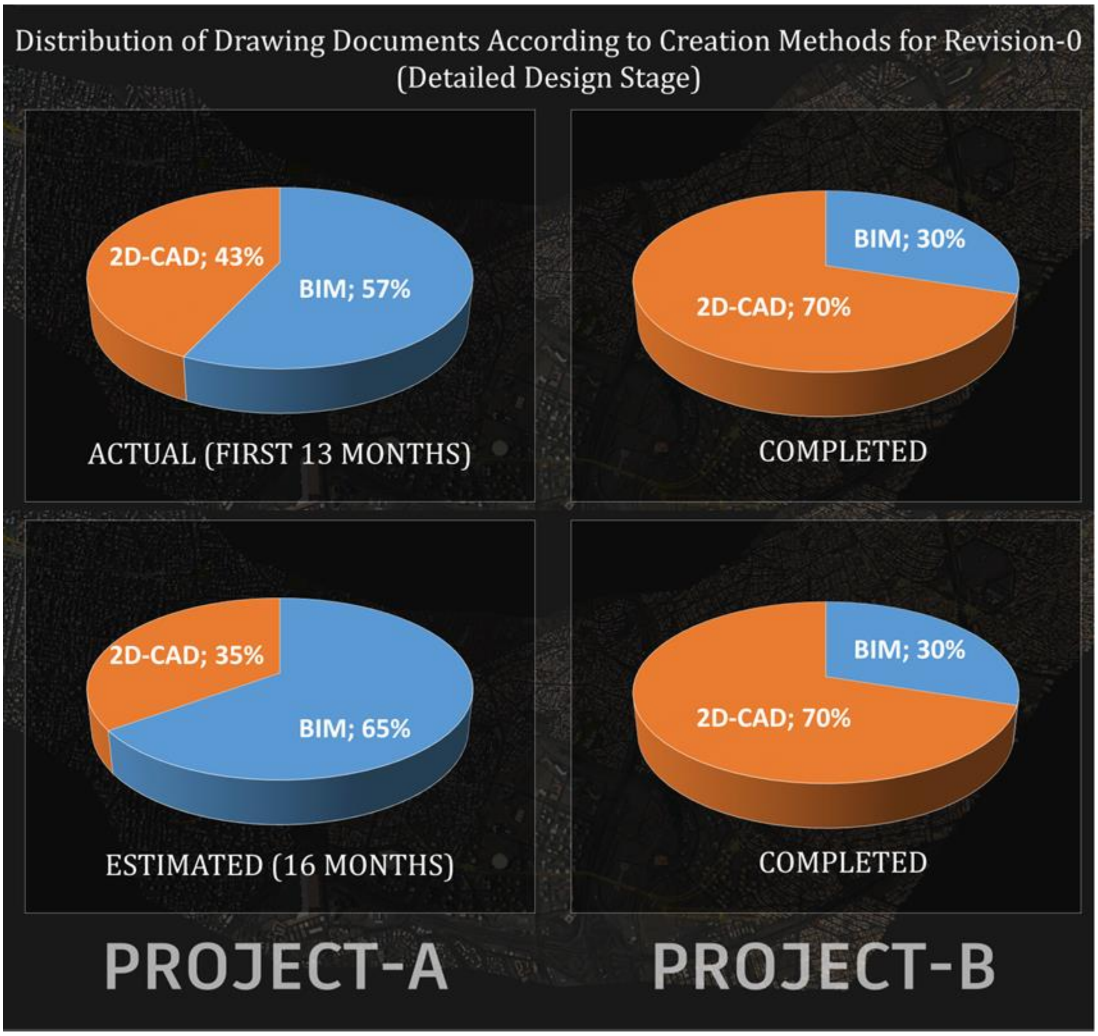

Figure 5.16. Distribution of Drawing Documents According to Creation Methods for Revision-0 of Each Project

5.1.3. Comparison of Time

When comparing the two projects in terms of time, overall project progress should also be examined.

Project-B was planned to be completed within 10 months; however, it took a total of 16 months. 8% of the documents required to be submitted within the planned project schedule were not delivered (Fig. 5.17). Within 16 months, a total of 5 km metro line design was completed with the whole tender package.

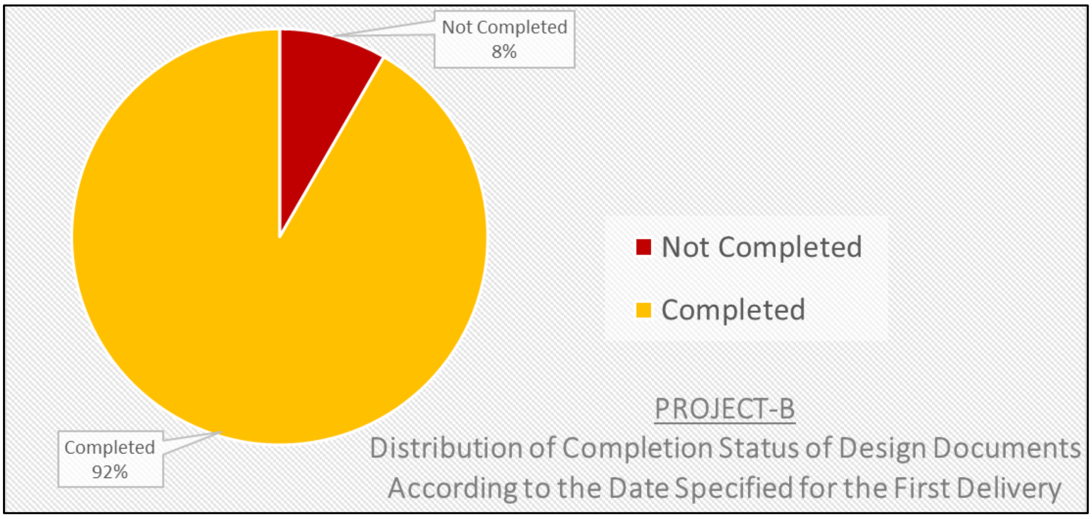

Figure 5.17. Distribution of Completion Status of Design Documents According to the Date Specified for the First Delivery

The period foreseen for Project-A was 18 months and at the time of this evaluation first 13 months has been completed (Fig. 5.18). If Project-A can be completed within 18 months, the design of the metro that is almost three times larger than Project-B will be completed with only two months of extra work.

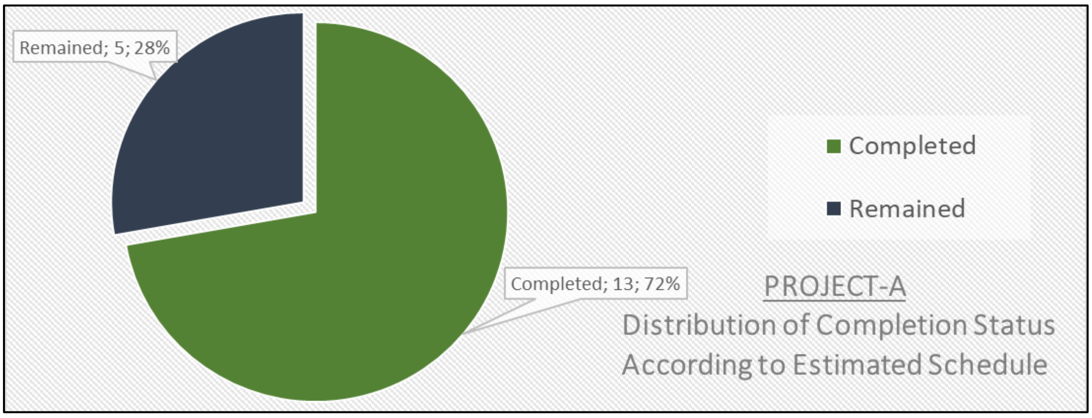

Figure 5.18. Distribution of Completion Status According to Estimated Schedule

According to the documents that are planned to be produced in Project-A, the completion rate of 66% is achieved (Fig. 5.19). In the next 2 months, the completion rate is expected to be 95% with the documents planned to be delivered. If the delivered documents are approved by the employer, the design disciplines will have 3 months to complete the remaining 5% and to prepare the tender documents.

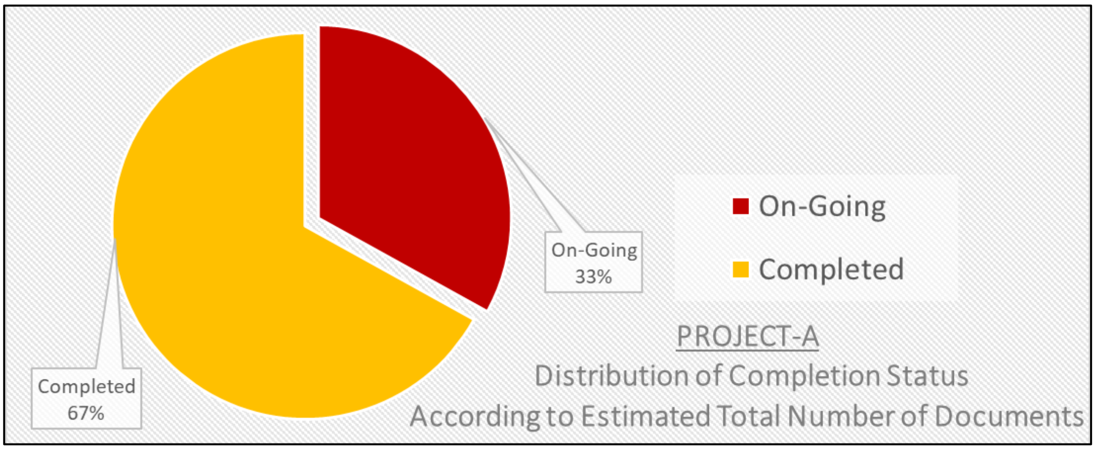

Figure 5.19. Distribution of Completion Status According to Estimated Total Number of Documents

When the proposed system is examined in terms of design documents produced from models, design disciplines could create design documents faster in Project-A. Although the changes are automatically reflected in the design documents with the possibility of model-based design, comprehensive annotation-dimension and detailing studies are carried out to produce design documents from the models. Nevertheless, almost 2.5 times more documents have been created from the models (Fig. 5.20) in the same duration for Project-A with the proposed system.

When the proposed system is examined in terms of design documents produced from models, design disciplines can create design documents faster. Although the changes are automatically reflected in the design documents with the possibility of model-based design, a serious annotation-dimension and detailing studies are carried out to produce design documents from the models. Nevertheless, almost 2.5 times more documents have been created from the models (Fig. 5.20) in the same duration for Project-A with the proposed system.

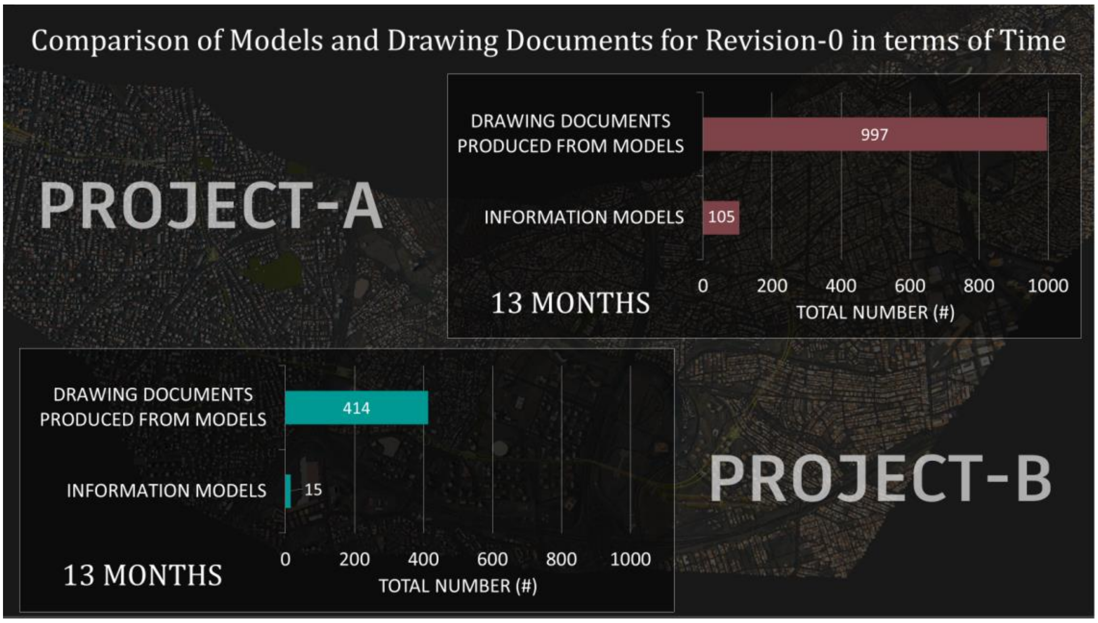

Figure 5.20. Comparison of Produced Information Models and Drawing Documents Produced from Models for Revision-0 of Each Project in terms of Time

In case the published design documents for Project-A are approved, the possibility of completing two projects at similar times demonstrates the benefits of the collaboration system in terms of time, although Project-A consists of 11 stations and the Project-B consists of 3 stations.

5.1.4. Comparison of Cost

In general, engineers, architects and technical draftspersons are actively involved in the design studies. The number of engineers, architects, and technical draftspersons involved in the design of Project-A was nearly the three-quarters of the designers in Project-B, thanks to automation solutions. It was expected that this would result in a very serious man-hour gain.

In the beginning, a man-hour cost analysis study was planned to be conducted for comparing Project A and Project B in terms of cost. Then, man-hour cost tables were prepared, and some problems were noticed in extracting statistical data. There were some factors affecting the reliability of the data.

First, a healthy comparison could not be made by using man-hour data since the design teams was working on multiple projects at the same time. Secondly, the data was not reliable since the members of the design teams entered the time that they worked in the project into the work monitoring system manually. This applied to both projects.

As a result, it has been decided to make a cost-based comparison according to the progress payment earned. Since there is a 2-year difference between Project-A and Project-B, the progress payment earned from Project-A has been converted into the equivalent value of today. The comparison results are shown in Figure 5.21.

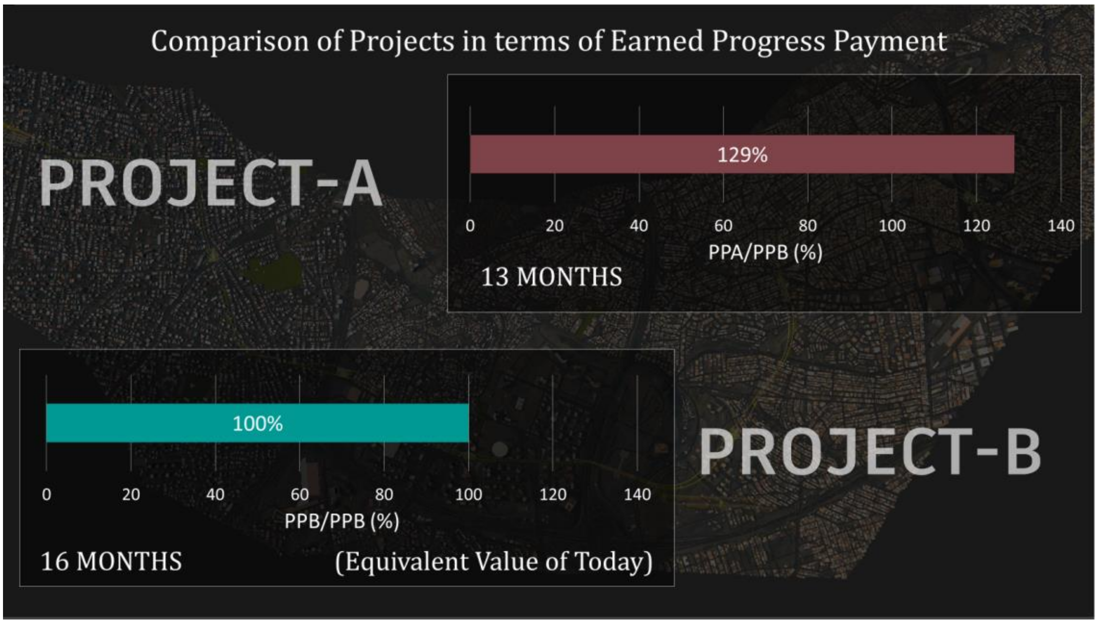

Figure 5.21. Comparison of Projects in terms of Earned Progress Payment

Although the company worked for a shorter period of 3 months, the design firm prepared the work that would deserve 29% more of the total progress payment it received under Project-B. While making these calculations, in addition to the official employer presentation, the design documents that have been completed but not have been submitted to the employer were also taken into consideration.

If the remaining works for Project-A are completed within a period of 3 months, the design of the 15 km line will be completed within the same period of Project-B and it will be possible to earn nearly 1.5 times more progress payments in the same period.

5.1.5. Other Comparison Results

The proposed system has also been examined in terms of two other expected benefits, which are reducing the number of disputes between design disciplines and minimizing errors in file sharing. Unfortunately, there was no statistical data for Project-B according to the number of errors in file sharing and disputes between design disciplines from two years ago. But still, due to the fact that no such problem was encountered among the disciplines during the file sharing in Project-A, it may be accepted as a benefit of the proposed system in this regard. The same applies to the number of disputes between design disciplines.

5.2. Benefits of the Proposed System

The proposed collaboration system enabled the integration of different disciplines, including Architecture, Structural, Landscaping, HVAC, Plumbing, Electrical, Electronic, Fire, Underground Utilities, Geotechnical, Traffic, Survey, and Route.

Firstly, the proposed system reduces the total duration for the preparation of design documents. Some examples are explained in detail below.

- Over 100 models in Project-A have been produced in similar time as compared to the total of 15 models produced in Project-B.
- The preparation of the structural tunnel models for the whole line was completed within two days. Although this process is expected to take a shorter time, it was prolonged due to slow hardware processing. With powerful hardware, this process can be reduced to one day.

- Almost all models were prepared for an area of 16 km in 13 months (Fig. 5.22).

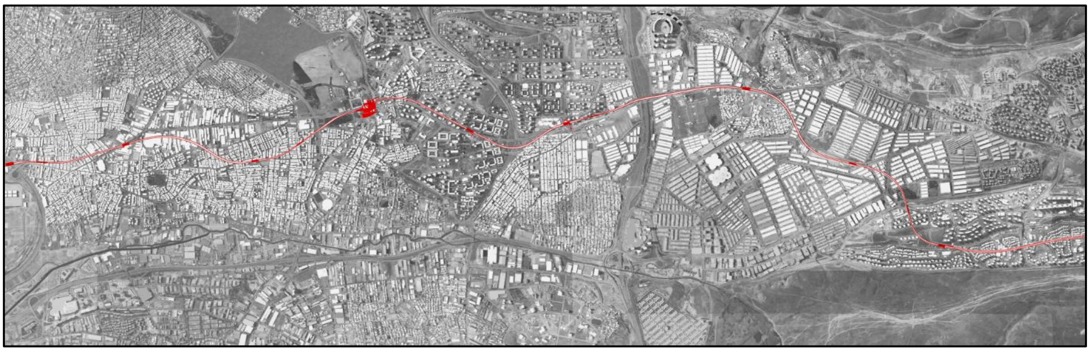

Figure 5.22. Sample Image of Virtual Project Model for the Project-A (Combination of 100+ models)

- For the aesthetic design studies, the employer presentation was prepared for different aesthetic design alternatives in 1.5 months for different stations. It is one of the fastest accepted aesthetic designs of the firm. Also, the difference between the renders and the architectural plans, which was encountered in the previous projects, has been prevented with the proposed system.
- Although no employer presentation was made, the design teams produced tunnel and station mass models for different route alternatives during the preliminary design stage by using the automation solution. At the end of the one-day study, mass models were created for three different alternatives. Along with 3D modeling of existing structures, the interaction of existing structures with the metro line can be examined in 3D instead of 2D.
- In the project, different than any other infrastructure projects held in Turkey before which have been designed simply relying on national and international standards, further optimization was requested. Value engineering was one of the main objectives requested by the client, as well as further improvements in aesthetic design. It was a great chance to test the benefits of the proposed system. In particular, the rapid production of different design alternatives provided the basis for these studies. The graphical and non-graphical data

obtained from models have enabled studying different alternatives very quickly. Many engineering simulations have been performed using models as a reference such as CFD, lighting, electroacoustic, pedestrian, etc. With integrated engineering analysis solutions for MEP systems, designers have a chance to carry out these studies in the model without the risk of errors and data loss.

It is assessed that the number of documents produced in the BIM environment has increased with the proposed system. According to the study results, there has been a significant increase in the number of documents produced from 3D information models. The rate has been increased from 30% (Project-B) to 57% (Project-A). It is expected to reach 65% at the end of Project-A. Moreover, a significant amount of time is saved since document production from 3D models is faster than preparing from CAD environment.

To reduce disputes between design disciplines, the entire process has been recorded following the information management processes as proposed in the system. Although there have been no disputes between the disciplines within the project, this approach could be used to solve the disputes. It is possible to use the information in which all the review processes have been recorded.

To minimizing errors in file sharing, the whole process has been carried out with the help of an automation solution. Because files are automatically shared in the corresponding area, human-made mistakes have been prevented. In addition, since the cleaning of the contents of the shared models have been also carried out by the automation solution, the situation of over or missing information have been prevented.

It is easier for the designers to follow the reference documents of the related station with the opportunity to access all the shared design documents of that structure through the study files in the WIP area. With file sharing automation, disciplines were able to access the reference information quickly without any conversion process since the relevant files are shared according to the file format (*.dwg, *.dgn, *.rvt *.ifc, etc.) used by the discipline.

Furthermore, quality control processes have been managed through automated solutions for the models. Therefore, errors in the model can be easily identified. Previously, these studies were carried out manually by the designers before sharing the model with the other disciplines or publishing with the employer. By making this control within the automated solutions, it is ensured that errors in the model have been prevented.

Due to metro projects are working in an extensive area, it is always expected to encounter significant revision needs in the project. At the beginning of the system proposal, it is foreseen that revision needs that are caused by modeling and drawing errors made by designers can be reduced with using automation solutions in the design process. Yet, no definite conclusions could be drawn on this issue since the answers to the official presentations were not transmitted for Project-A.

5.3. Limitations of the Proposed System

In this section, the limitations of the proposed system are discussed in detail.

The study has been prepared for the Turkish AEC industry. The system proposal has been made by taking into consideration the criteria of the metro projects that have been tendered in Turkey. If it is integrated into the design process in a different country, the same benefits may not be encountered depending on the various regulations, project delivery methods and the content of different tender packages.

The study has been prepared to use for metro projects. If the station is underground, at-grade, or viaduct, it will not cause any problems. However, it is foreseen that a few minor adjustments might be needed in the workflows if the line structure is above the ground or viaduct since there is a different working systematic for both viaduct and at-grade line structures. For example, interaction with existing structures is more critical for these types of line structures.

Even so, it has been tried to ensure that the system can able to operate independently of the software used by the design team, while developing the system proposal, software packages preferred to be used in metro projects by the employers has been taken into consideration since the system is Turkish AEC industry-specific. The software used in the company during the case study did not pose a problem since it coincided with the demands of the employer. However, if different software tools are preferred, it is possible to encounter various issues or other advantages in the process.

Since all the metro projects have been tendered in Turkey as DBB, the system has been proposed according to DBB method. The applicability of a different project delivery method has not been tested. In addition, a system proposal may be applied for the design process of a metro project that has gone through the construction process. Yet, it has not been tested that efficiency can be obtained as predicted.

The study has been carried out in one of the biggest design companies, which is actively involved in the design of metro projects. Some steps in the process are foreseen on a firm basis. If the system is used in another company, it may be necessary to make additions to the system. In addition, the case study has been carried out in a company that has all design teams within a single company, and there may be a need to revise some processes in a project where disciplines are from different firms. A company with different disciplinary definitions may need some revision in the system integration.

Design documents of some disciplines are still produced in a 2D CAD environment in the proposed system. There is a need for solutions that can help create these drawings through models. This led to a decrease in the efficiency of the process of creating drawings.

The proposed system involves software development studies’ integration into a design company’s processes. Most of the software solutions have been created by making all the coding from scratch. In today's Turkish construction companies, there are not many experts in the software development field. Up to a particular stage, automation processes can be realized with more user-friendly AAD tools or by choosing the 3rd party software solutions, which is the most suitable option for the proposed system, as a result proper operation can be provided with the configuration of this software.

The same efficiency cannot be achieved if the automation processes are removed, and the system is manually executed. In order to use the system effectively, the design team needs to master a certain level of BIM processes, standards and model-based design processes.

5.4. Road Map

For the design companies that are actively involved in the design of the metro systems in the Turkish AEC industry, the suggested road map for integrating the proposed system into their companies is described in Figure 5.23.

5.5. Future Studies

The future studies which could be solicited from this research are listed below. Planned studies specified in the system proposal but not completed in the case study should be completed as part of a future research study that will be carried out.

- BIM-based design collaboration system should be revised considering the identified limitations.
- The proposed collaboration system should be generalized to be applicable to all design firms that are actively involved in the design of the metro systems in Turkish AEC Industry.
- Information management automation should be provided, including client sharing and published phases.
- Design automation solutions capable of 3D modeling including all elements for tunnel structures should be studied.
- Process should be studied to ensure that all engineering analysis and simulations are resolved within the proposed system.

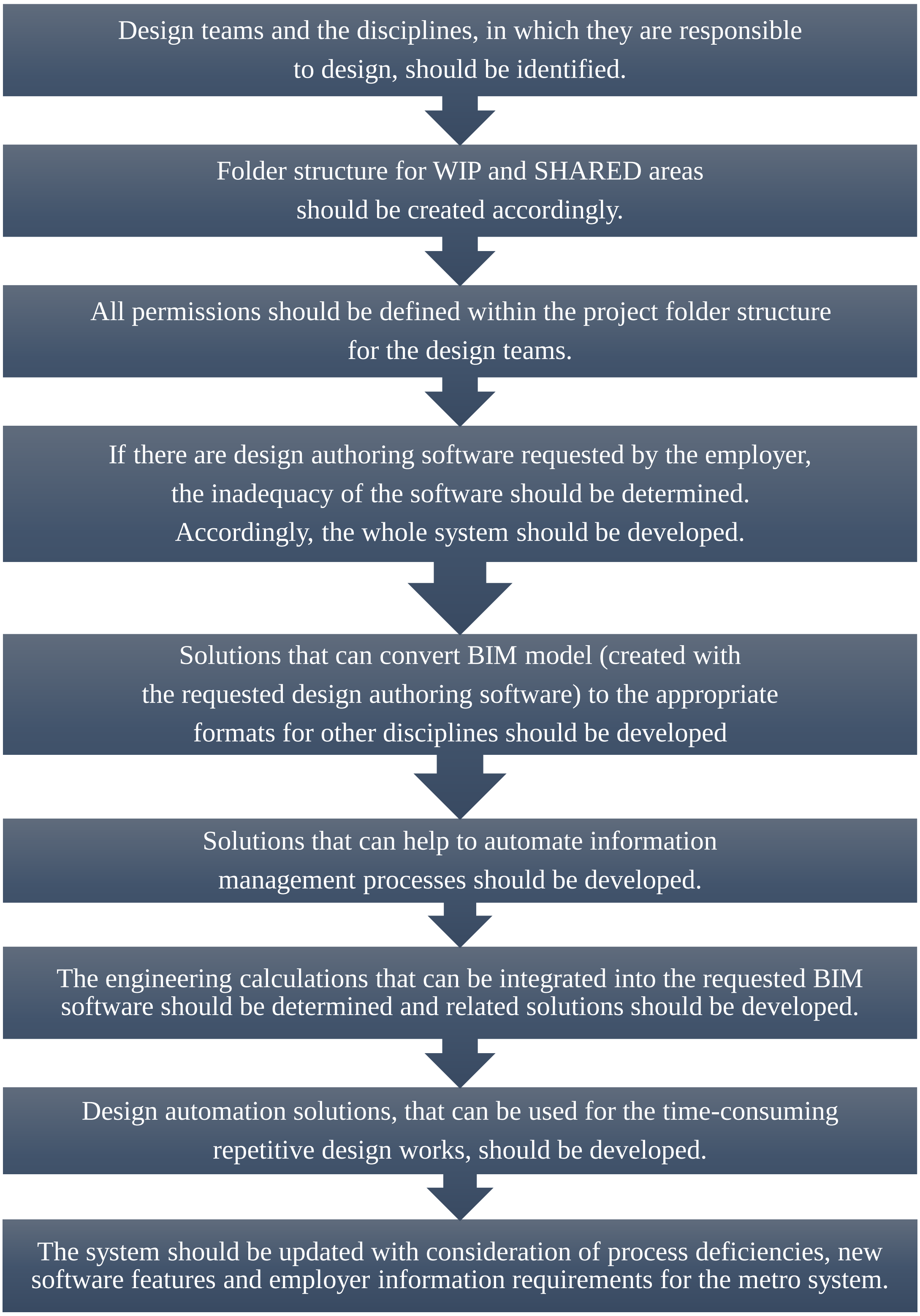

Figure 5.23. Road Map for Design Firms

CHAPTER 6

CONCLUSION

In recent years, metro investments have been made on a large-scale in Turkey. Metro projects have become one of the most important investments that keep the Turkish AEC industry alive. Almost all of these projects have been carried out with BIM, as it has been specified in the technical specifications. The main goal of this research was to develop a BIM-based design collaboration system to be used in the design phase of metro projects. Although several design firms in Turkish AEC Industry have already begun to make good use of BIM for the design of metro projects, there is still a need for an integrated collaboration system supporting information management, design automation, and engineering analysis processes to overcome various barriers in fully benefiting from this promising approach.

The research in this thesis covers the design phase of metro projects, designed with BIM and tendered with DBB, in the Turkish AEC Industry. The approaches that should be at the center of this collaboration system were identified as design automation, information management, and integrated engineering analysis. The expected benefits of the design collaboration system, that centralizes these approaches, were determined as increasing collaboration between design disciplines, increasing the number of documents produced in the BIM environment, reducing total duration for the generation of design documents, reducing project revisions, reducing the number of disputes between design disciplines, reducing man-month costs incurred in the project, enabling easy access to reference documents shared by other disciplines, minimizing errors in file sharing. The comparison was made between the project in which the design documents were prepared with the proposed system (Project-A), and another project, developed by the design firm in the past without the use of the collaboration system (Project-B), to test the accuracy of the expected benefits. In the end, the information obtained from the Project-A were analyzed and compared it with Project-B in terms of time, cost, numbers of design revision, number of documents produced in the BIM environment, number of disputes between design disciplines, and number of errors in file sharing process.

Relevant literature, publications, standards, and guidelines were reviewed to gain in-depth knowledge on the use of BIM in the design phase, design collaboration, design automation, information management, and the use of BIM for railway and metro projects in particular. Besides, some background information regarding metro systems and BIM were also reviewed and covered.

First, a general framework of stations and line structures forming the metro systems was drawn. In addition, the current status of the metro systems in Turkey was examined. As a result of this, it was observed that serious investments had been made in the last five years and this will progress further in the future. Then, EKAP system was examined regarding the metro projects, and it was observed that all metro projects in Turkey had been tendered by DBB method. In addition, the scope of the tender documents defined for metro projects was extracted using the technical specifications downloaded from EKAP system.

Some BIM definitions related to the study were also discussed in detail. They were as follows: BIM uses, BIM standards, level of development, BIM software, information management. Since the CDE approach was planned to be used at the center of the information management system, the CDE approach was examined and covered in this section.

Although there were studies covering the design phase, metro projects, and collaboration related to BIM separately, a research study related to BIM collaboration system covering all design disciplines during the design phase of the metro project was not encountered. In addition, there were very few research studies in which all disciplines are actively involved. Since the case study was conducted for the whole metro line, unlike many other studies, it increased the importance of the research. This study was carried out to fill these gaps in the literature.

Subsequently, a BIM-based design collaboration system, including design automation, information management, and integrated engineering analysis, was developed by considering the needs of the metro system design in Turkey.

First of all, an information management approach, covering the process from the WIP to the beginning of the client sharing, was constructed for the design phase by adhering to CDE principles. In order to standardize the information management process, it was determined that there should be automated solutions behind it. The related disciplines involving in the design studies of the metro project in Turkey were determined. The contents of the design documents and general delivery requirements of these disciplines were examined, and their file format requirements were specified. After determining the file formats that each discipline would work on, algorithms for how to automate file sharing process were identified. In addition to integrating all disciplines into CDE processes for the design phase by providing automated file sharing, information management solutions were developed to enable file sharing in different formats to ensure that shared files can be used directly by other disciplines in the corresponding file format.

In order to determine the scope of integrated engineering analysis studies at the center of the collaboration system, all engineering analysis and simulations performed by the design teams were determined. For these studies, the capabilities of the most preferred analysis and simulation programs to be used in the design of a metro system were considered. First, the ones that can be realized in BIM models were determined. In addition to the calculations that can be performed already in the design authoring software, the calculations that can be included in the design authoring software such as ventilation flow calculation, domestic-water calculation were specified. At this stage, the analyzes that will continue with the traditional methods such as traction power simulation, vibration analysis, and the analysis that should be done using the model data such as CFD simulation, fire evacuation simulation, pedestrian dynamic simulation were determined. It was predicted that the conversion might be required for the analysis and simulations to be performed using model data, and the model conversion processes that can be automated were identified and solutions have been developed for it. While determining the studies that would continue with traditional methods, it was decided that it would be more appropriate to carry out these studies since they can usually be done by a few experts.

It was envisaged that design automation solutions have an important role in performing repetitive and time-consuming studies. Due to these reasons, design automation solutions were included in the proposed collaboration system. Repetitive and time-consuming design studies were identified, and solutions were developed to automate these studies. The proposed design automation solutions were modeling underground structural tunnels, generating the tunnel and station mass models for different route alternatives, creating 3D existing condition models for the metro corridor, creating RDS, placing architectural finish elements for different alternatives, controlling and modifying room dimensions in compliance with metro design criteria, and converting information model to suitable content for some analysis and simulation studies. Consequently, disciplinary process maps for the collaboration system were prepared.

After system development studies were completed, the proposed system was adapted to the design of a real metro project consisting of 15 km, which includes 11 stations and 12 line structures. The duration of the design was estimated as 18 months and 13 months had passed since the start of the project. Its applicability was tested by conducting a case study, which was carried out in one of the biggest design company actively involved in the design of metro projects in Turkey.

Afterward, the design of another metro project completed by the same company two years ago with BIM processes was compared with the outputs of the case study. Projects were compared in terms of time, cost, numbers of design revision, number of documents produced in the BIM environment, number of disputes between design disciplines, and number of errors in file sharing process, as suggested. As a result, it was observed that the proposed system reduced the total duration for the preparation of design documents. It was assessed that the number of documents produced in the BIM environment has increased with the proposed system. It was easier for the designers to follow the reference documents of the related station with the opportunity to access all the shared design documents of that structure through the study files in the WIP folder. Unfortunately, there was no statistical data to compare some expected benefits. For example, no data was available according to the number of errors in file sharing and disputes between design disciplines for Project-B. But still, the fact that no such problem was encountered among the disciplines during the file sharing in Project-A so it was accepted as the benefits of the proposed system in this regard, and the same applies to the number of disputes between design disciplines. In addition to these, no data regarding design revisions were collected in Project A since the project had not been completed.

Within the scope of the research, some of the envisaged issues might not be compared; however, in general, the measurable results obtained from the case study revealed the positive effects of the proposed system on the design of a metro project.

It should be noted that it is not clear that the same benefits can be obtained in a different metro project or a different design firm. However, the findings of this study indicated that more design documents could be produced in less time with the proposed system since the number of documents produced through the model increased. In addition, it enabled the creation of more information models in a shorter time. And together with information management automation, it allowed more controlled management of file sharing processes.

Finally, it can be concluded that an effective design collaboration system was proposed within this research. It was developed for the design firms that can take as a sample in their studies, considering the limitations explained.

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