A FRAMEWORK FOR BIM-BASED CONSTRUCTION PLANNING AND SIMULATION IN UNDERGROUND METRO PROJECTS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

SAMİ BATUHAN KALPAKÇI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

NOVEMBER 2023

Approval of the thesis:

A FRAMEWORK FOR BIM-BASED CONSTRUCTION PLANNING AND SIMULATION IN UNDERGROUND METRO PROJECTS

submitted by **SAMİ BATUHAN KALPAKÇI** in partial fulfillment of the requirements for the degree of **Master of Science** i**n Civil Engineering, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences** _____

Prof. Dr. Erdem Canbay
Head of the Department, **Civil Engineering** _____

Assist. Prof. Dr. Aslı Akçamete Güngör
Supervisor, **Civil Engineering, METU** _____

Examining Committee Members:

Prof. Dr. Rıfat Sönmez
Civil Engineering, METU _____

Assist. Prof. Dr. Aslı Akçamete Güngör
Civil Engineering, METU _____

Assoc. Prof. Dr. Güzide Atasoy Özcan
Civil Engineering, METU _____

Assist. Prof. Dr. Saman Aminbakhsh
Civil Engineering, Atılım University _____

Assist. Prof. Dr. Gözde Bilgin
Civil Engineering, Başkent University _____

Date: 30.11.2023

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name: Sami Batuhan Kalpakçı

Signature:

ABSTRACT

A FRAMEWORK FOR BIM-BASED CONSTRUCTION PLANNING AND SIMULATION IN UNDERGROUND METRO PROJECTS

Kalpakçı, Sami Batuhan
Master of Science, Civil Engineering
Supervisor: Assist. Prof. Dr. Aslı Akçamete Güngör

November 2023, 110 pages

Building Information Modeling (BIM) is an information management process that involves creating and using an intelligent 3D model to design, integrate, manage and visualize the construction process throughout the lifecycle of a construction project. As the value gained from BIM has been realized, underground metro projects carried out with BIM have been becoming more and more common due to the necessity of an effective project management. BIM-based progress tracking and scheduling are two useful practices which utilize both spatial and non-spatial information contained in BIM model. These two applications play an important role in more effective construction management since visualization of real-time progress and schedule simulation facilitates decision-making and detection of possible problems. However, metro projects are obviously different from conventional superstructure buildings which BIM tools are generally convenient for; therefore, BIM has a slightly limited use for railway systems. In addition, inconsistency between data gathered on site and BIM models is another issue that leads to a decreased efficiency and reliability of BIM use in the construction projects. In this study an ongoing metro construction project in Türkiye has been investigated by focusing on the issues mentioned. The objective of this research is to examine the implementation of the BIM-based

progress tracking and scheduling of metro projects, then propose a framework for progress monitoring and scheduling in geotechnical and structural construction of underground metro projects based on the findings of the investigated project. An interview questionnaire has been conducted to evaluate the proposed framework via one-on-one interviews with the industry experts. Questionnaire results demonstrates that the proposed framework has the potential to significantly improve the process of creating project schedule simulation and progress tracking models in metro projects.

Keywords: Building Information Modeling, Progress Tracking, 4D Modeling, Phase Planning Simulations

ÖZ

YER ALTI METRO PROJELERİNDE BIM TABANLI İNŞAAT PLANLAMASI VE SİMÜLASYON ÇERÇEVESİ

Kalpakçı, Sami Batuhan
Yüksek Lisans, İnşaat Mühendisliği
Tez Yöneticisi: Dr. Öğr. Üyesi Aslı Akçamete Güngör

Kasım 2023, 110 sayfa

Yapı Bilgi Modellemesi, bir inşaat projesinin yaşam döngüsü boyunca inşaat sürecini tasarlamak, entegre etmek, yönetmek ve görselleştirmek için akıllı bir 3D model oluşturmayı ve kullanmayı içeren bir bilgi yönetimi sürecidir. BIM'den kazanılan değerin fark edilmesiyle birlikte, etkin bir proje yönetimini ihtiyacı sebebiyle BIM ile yürütülen yeraltı metro projeleri giderek yaygınlaşmaktadır. BIM tabanlı ilerleme takibi ve iş planlaması, BIM modelinde yer alan hem uzamsal hem de uzamsal olmayan bilgileri kullanan iki faydalı uygulamadır. Gerçek zamanlı ilerlemenin görselleştirilmesi ve iş programı simülasyonu, karar vermeyi ve olası sorunların tespit edilmesini kolaylaştırdığından, bu iki uygulama daha etkili inşaat yönetiminde önemli bir rol oynamaktadır. Bununla birlikte, metro projeleri, BIM araçlarının genellikle uygun olduğu geleneksel üst yapı binalarından oldukça farklıdır; bu nedenle, BIM'in demiryolu sistemleri için biraz sınırlı bir kullanımı vardır. Ayrıca, şantiyede elde edilen veriler ile BIM modelleri arasındaki tutarsızlık, inşaat projelerinde BIM kullanımının etkinliğinin ve güvenilirliğinin azalmasına yol açan başka bir konudur. Bu çalışmada Türkiye'de bulunan ve devam eden bir metro

inşaatı projesi, bahsedilen konular üzerinde durularak incelenmiştir. Bu araştırmanın amacı, BIM tabanlı ilerleme takibi ve iş planlaması uygulamasını incelemek ve incelenen projeden elde edilen bulgulara dayanarak yeraltı metro projelerinin geoteknik ve yapısal inşaatında ilerleme takibi ve iş planlaması için bir çerçeve önermektir. Önerilen çerçeveyi değerlendirmek için sektör uzmanlarıyla birebir görüşme yoluyla bir mülakat yapılmıştır. Mülakat sonuçları, önerilen çerçevenin metro projelerinde proje takvimi simülasyonu ve ilerleme izleme modelleri oluşturma sürecini önemli ölçüde iyileştirme potansiyeline sahip olduğunu göstermiştir.

Anahtar Kelimeler: Bina Bilgi Modellemesi, İlerleme Takibi, 4B Modelleme, Faz Planlama Simülasyonları

Dedicated to my family

ACKNOWLEDGMENTS

The author wishes to express his deepest gratitude to his supervisor Dr. Aslı Akçamete Güngör for her guidance, advice, criticism, encouragements and insight throughout the research.

The author would like to thank his family for their worthwhile supports.

The author is also grateful to Serhat Kaş for providing the opportunity to conduct the research and for his unwavering support and guidance throughout the research.

TABLE OF CONTENTS

ABSTRACT v

ÖZ vii

ACKNOWLEDGMENTS x

TABLE OF CONTENTS xi

LIST OF TABLES xiv

LIST OF FIGURES xv

LIST OF ABBREVIATIONS xviii

CHAPTERS

1 INTRODUCTION 1

2 BACKGROUND AND LITERATURE REVIEW 7

2.1 Background 7

2.1.1 Rail Transit and Metro Systems 7

2.1.2 Building Information Modeling 16

2.2 Relevant Studies in the Literature 20

3 METHODOLOGY 27

3.1 Research Method 27

3.2 Project Characteristics 28

3.3 Investigated Project Documents 29

3.3.1 BIM Models 29

3.3.2 Project Schedule 31

3.3.3 Progress Reports 32
3.3.4 Progress Tracking Models and Phase Planning Simulations 34
3.3.5 Phase Planning Reports 37
3.4 Interview Questionnaire 38
3.4.1 Target Population 38
3.4.2 Questionnaire 38
3.4.3 Interview with Experts 39
4 FINDINGS AND DISCUSSION 41
4.1 BIM Model 41
4.1.1 Model Detail 42
4.1.2 Modeling Technique 47
4.2 Project Schedule 50
4.2.1 Detail Level of Project Schedule 51
4.2.2 Schedule Errors 55
4.2.3 Additional Findings 58
4.3 Progress Report 59
5 BIM-BASED CONSTRUCTION PLANNING AND SIMULATION FRAMEWORK 63
5.1 Creating BIM models 65
5.1.1 Model Detail 65
5.1.2 Modeling Technique 68
5.2 Phase Planning Simulation 69
5.3 Progress Tracking Models 71
6 EXPERT ASSESSMENT 77

6.1 Demographic Information 77
6.2 Experience Details 78
6.3 Framework Evaluation Results 79
7 CONCLUSION 85
REFERENCES 91
APPENDICES 99
A. Interview Questionnaire 99
B. Human Subjects Ethics Committee Approval 110

LIST OF TABLES

TABLES

Table 3.1 Content of Geotechnical Model Elements 29
Table 3.2 Sample Part of the Project Schedule 32
Table 3.3 Sample Part of the Progress Report 32
Table 3.4 Parameters Used for Progress Tracking Data 34
Table 3.5 Example Problem from Phase Planning Report 37
Table 4.1 Sample for Activity Breakdown 52
Table 4.2 Example Activities and Their Planned Dates 58
Table 5.1 List of Progress Tracking Parameters 72
Table 6.1 General Information of the Respondents 77
Table 6.2 Respondent Evaluation for Section 4 80
Table 6.3 Respondent Evaluation for Section 5 80
Table 6.4 Respondent Evaluation for Section 6 82

LIST OF FIGURES

FIGURES

Figure 2.1. Sample Image for Rapid Transit System (Tompagenet, 2006) 8
Figure 2.2 Metro System Openings per Decade (International Association of Public Transport, 2021)..... 9
Figure 2.3 Total Line per Region (km) 2013-2020 (International Association of Public Transport, 2021) 10
Figure 2.4 Global Ridership (million) (International Association of Public Transport, 2021)..... 10
Figure 2.5 Sample Image for Cut and Cover Method (Civilverse, 2021)..... 12
Figure 2.6 Sample Image for NATM (Structurae, 2016)..... 12
Figure 2.7 Sample Image for TBM (Amberg Engineering, n.d.)..... 13
Figure 2.8 Distribution of Construction Models for Metro Stations (International Association of Public Transport, 2018) 14
Figure 2.9 Schematic View of a Station Box (Wikipedia, 2013) 14
Figure 2.10 Four Key Elements of the BIM Concept (Bradley et al., 2016)..... 16
Figure 2.11 Top Five BIM Benefits for Contractors (Autodesk, 2021) 17
Figure 2.12 Distributions of Publications by Industry Sector (Bradley et al., 2016) 21
Figure 3.1 Research Methodology..... 28
Figure 3.2 Project Stakeholders 29
Figure 3.3 Sample Images for Geotechnical BIM Model Elements: (a) Excavation (b) Shotcrete (c) Support Systems)..... 30
Figure 3.4 Sample Images for Structural BIM Model Elements 30
Figure 3.5 Sample Image of the Progress Report 33
Figure 3.6 Sample Images for Progress Tracking Models of Tunnel-type Stations: (a) Shoring and (b) Structural Work 35

Figure 3.7 Sample Images for Phase Planning Simulations: (a) Geotechnical Construction of Tunnels (b) Geotechnical Construction of Tunnels (c) Structural Construction of Shafts (d) Completed Construction 36
Figure 4.1 Categorized Findings 41
Figure 4.2 Sample Structural Tunnel Elements 42
Figure 4.3 Coloring of 40 m Single Model Element 43
Figure 4.4 Coloring of 1 m Model Elements 44
Figure 4.5 Distribution of Progress Data in meters 45
Figure 4.6 Distribution of Average Progress Amounts: (a) Progress Amounts Frequency (b) Progress Amounts for Each Tunnel Type 45
Figure 4.7 Distribution of Minimum Progress Amounts: (a) Progress Amounts Frequency (b) Progress Amounts for Each Tunnel Type 46
Figure 4.8 Distribution of Maximum Progress Amounts for Each Tunnel 46
Figure 4.9 Final Stage of the Tunnel Connection 48
Figure 4.10 Screenshot of the Problem in the Simulation 48
Figure 4.11 Modeling Example Incompatible with Project Schedule 49
Figure 4.12 Modeling Example Compatible with Project Schedule 49
Figure 4.13 Cause of Issues in Phase Planning Simulations 51
Figure 4.14 Screenshot of the Tunnel Model 52
Figure 4.15 Screenshot of the Simulation Before Revision 53
Figure 4.16 Screenshots of the Simulation After Revision: (a) Tunnel Construction (b) Shaft Construction 53
Figure 4.17 Screenshots of the Clashing Items 55
Figure 4.18 Screenshot of the Tunnel and Shaft Model 56
Figure 4.19 Screenshots from the Simulation Before Revision: (a) Constructed Shaft (b) Line 2 Construction Starts (c) Line 1 Construction Starts (d) Line 2 Construction Ends 57
Figure 4.20 Screenshots from the Simulation After Revision: (a) Constructed Shaft (b) Line 1 Construction Start (c) Line 2 Construction Starts (d) Line 1 Construction Ends 57

Figure 4.21 Plan view in Progress Report and Geotechnical BIM Model 60
Figure 4.22 Geotechnical Tunnel Elements 61
Figure 4.23 Plan view of Progress Report and Structural BIM Model 62
Figure 5.1 Summary of Topics 63
Figure 5.2 Proposed process of BIM-based Scheduling and Construction Planning 64
Figure 5.3 Sample Images for Shotcrete, Excavation and Structural elements 67
Figure 5.4 Sample Parameters for a Shotcrete Element 67
Figure 5.5 Defined Sample Global Parameter 73
Figure 5.6 Matched Sample Global Parameter 73
Figure 5.7 Sample Image for Rule-based Coloring 74
Figure 5.8 Sample Image for Model Element Coloring 75
Figure 5.9 Sample Image for the Parameters 75
Figure 6.1 Respondents Experience in BIM 78
Figure 6.2 Respondents Experience in BIM Software Packages 78
Figure 6.3 Distribution of Company Fields 79

LIST OF ABBREVIATIONS

ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
4D	4 Dimensional
AEC	Architecture, Engineering and Construction
BEP	BIM Execution Plan
BIM	Building Information Modeling
CAD	Computer Aided Design
CIM	Civil Information Modeling
GIS	Geographic Information System
IFC	Industry Foundation Classes
LOD	Level of Development
NATM	New Austrian Tunneling Method
O&M	Operation and maintenance
TBM	Tunnel Boring Machine
UAV	Unmanned Aerial Vehicles
WBS	Work Breakdown Structure
VPS	Virtual Prototyping Simulation

CHAPTER 1

INTRODUCTION

Transportation infrastructure can be regarded as a valuable asset that contributes to a country's economy, welfare and development. A well-established transport network is key to maintain the economic and social interactions. As the population density increases especially in urban areas, the need for expanding these networks arises. However, considering the fact that there is already an established city layout, improving the existing transportation structure may not be a feasible solution in general. Moreover, lack of space restrains building new transportation infrastructure above the ground. Underground transportation systems; on the other hand, is a sustainable, safe and effective solution to meet the needs of new transportation network since there is more comprehensive options in underground compared to above ground. In addition, with the advances in tunneling techniques, underground transportation infrastructure has evolved rapidly and become more and more common. Two well-known methods developed for modern tunnel design and construction are shield tunneling and New Austrian Tunneling Method (NATM). These two methods execute the tunnel construction in a more cost-effective and high-performance manner.

The main characteristic of infrastructure construction, including both above and underground, is that they are longitudinal compared to buildings being vertical. There is a significant distinction in the process of planning, designing and construction between horizontal and vertical projects. In general, infrastructure projects have multiple construction sites, involving multiple stakeholders, spread across the project scope's terrain. In addition, horizontal constructions are mostly government-funded with legal and financial restrictions. Infrastructure projects are complex by their nature, therefore it is important to effectively manage the

construction process by integrating all the information and data analysis (Cheng et al., 2016). As a result, the necessity of efficient management of infrastructure projects paved the way for the utilization of Building Information Modeling (BIM) in this type of construction.

As technology continues to be developed, reforms are made in the construction sector one of which is the concept of BIM. The U.S. National Building Information Model Standard Project Committee defines Building Information Modeling as "a digital representation of physical and functional characteristics of a facility". It serves as an information management technique that encourages collaboration between the stakeholders through the lifecycle of a facility. Some of the common BIM uses are producing design drawings, quantity/cost estimation (5D estimation), clash detection (3D coordination), construction sequencing (4D scheduling), energy analysis etc. Considering the benefits of BIM, there has been a significant push towards the promotion of implementing BIM in the Architecture, Engineering and Construction (AEC) industry for the last few decades.

As the value gained by using BIM in infrastructure have been realized, the adoption of BIM in infrastructure sector has escalated. The United States is already known for the heavy use of BIM, on the other hand implementation rate of BIM in infrastructure sector has increased in many European countries such as Germany, France and the UK. In Europe, while the infrastructure implementation rate was 20% in 2012, it went up to 52% in 2017 (The business value of BIM for infrastructure SmartMarket report, 2017).

However, shifting from traditional methods to BIM is not a straightforward process. While the building sector has greatly benefited from BIM by widely adopting it, infrastructure sector lags behind this adaptation (J.U. Kim et al. 2016). Bradley et al. (2016) states that there is nearly 3-year gap between the use of BIM in infrastructure and buildings. As the name implies, Building Information modeling has been initially proposed for building sector. Consequently, initial standards and software developed for BIM are mostly convenient for building structures which makes the

adaptation of BIM in infrastructure sector harder. Nonetheless, implementation of BIM plays an important role in achieving desired efficiency especially in project management. Project management aims to meeting the deadlines of project ensuring the quality of the construction without exceeding the project budget. Reliable and effective planning of construction project is crucial to achieve these targets (Chen et al., 2013).

Construction planning consists of establishing and controlling the schedule when the design of the project is approved, meaning that the design is more or less clear. Schedule plan is established by analyzing the activity relations, durations, resource and schedule constraints (Shi & Ouyang, 2017). On the other hand, schedule control is monitoring the progress of construction activities and making necessary adjustments based on the progress. If these processes can be carried out effectively, the overall quality of project is enhanced by optimizing the construction activities, resources and project duration. However, traditional methods used for schedule management such as Gannt Chart has limitations. Since they consist of charts and diagrams, it is harder to track the activity relations based on solely 2D designs, and as projects become more and more complex, efficiency and reliability of these methods decreases (Kastor & Sirakoulis, 2009). The amount of effort put into monitoring the progress and adjusting the schedule is quite high, and this has a potential to produce faulty schedules. What is more, if there is a mistake made in the schedule, it is even harder to detect it. Going over thousands of activity relations is a tedious and exhaustive process which decreases the accuracy of the schedule plan.

Traditional methods used for schedule management are rather inefficient compared to BIM (Mawlana et al., 2015). However, if BIM and traditional methods are combined together schedule management can be improved to a great extent (Zhou & Wang, 2009). 4D building information modeling is a technique of visualizing the stepwise construction sequencing simulation by integrating 3D BIM model and project schedule. This schedule simulation helps the project staff comprehend the construction activities. Moreover, BIM can be used for progress monitoring. Progress data is collected from site and these data can be represented in BIM models

by adding the progress data to intelligent BIM objects. Color codes can be implemented to BIM objects to specify the status of construction based on the data available in the BIM objects. As a result, integrating schedule with BIM models can have a positive impact on the project by detecting possible mistakes, improving decision making process and optimizing the schedule (Shi & Ouyang, 2017). The accuracy of the BIM models, in terms of representing the construction onsite, is crucial to fully benefit from BIM integration. Furthermore, the progress data collected from jobsite needs to be properly represented for BIM-based progress monitoring. However, 4D BIM models are not ensured to be 100% accurate especially in underground metro projects due to several reasons. Various factors that hinder accurate models of underground metro construction are the followings:

- Inconsistency between data gathered on site and BIM models
- Lack of modeling standardizations for BIM objects to be compatible with construction logic (LOD definitions)
- Lack of predefined procedure for control mechanism of BIM-based progress tracking and scheduling

The goal of this study is to develop a framework BIM-based progress monitoring and scheduling in geotechnical and structural construction of underground metro projects. The study aims to standardize the 4D simulations and progress tracking in a systematic way to get the highest benefit from the utilization of BIM in metro projects. A framework to support fully utilizing benefits of BIM can enhance the integrity between BIM model and construction schedule and increasing the consistency between data gathered on site and BIM models which as a result could:

- Reduce errors in the scheduling and planning
- Increase the efficiency of decision making
- Improve the optimization of construction schedule
- Increase efficiency of the collaboration between the parties involved
- Enable comprehension of tunnel construction activities

In the study, implementation of BIM-based progress tracking and scheduling in an ongoing metro construction is examined and a framework is developed based on literature review and investigation of a real metro project. Proposed framework will enhance the overall integrity of BIM model with the construction schedule and progress.

This thesis is constructed as the followings. Chapter 1 introduces the characteristics of infrastructure, concept of BIM, definition of problem, goal and the method of the study. Chapter 2 includes detailed information about the metro systems and its construction, BIM and 4D modeling, related studies and the discussion of gap in the literature. Chapter 3 consists of the method of research, questionnaire data collection method, its target population and questionnaire design. Investigated project is also presented in this chapter. Chapter 4 presents the findings of the investigation and discussion of findings. Based on the findings, proposed framework is described in Chapter 5. Chapter 6 presents the experts' assessments of the proposed framework. Chapter 7 contains the conclusions and future works.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Background

2.1.1 Rail Transit and Metro Systems

Rail Transit is a general term used for the different types of rail systems for transportation purposes. Tram, light rail, rapid transit, monorail, funicular are the main types of rail systems. Rail systems are classified based on their technical and system characteristics. Subdivisions of rail systems can intersect with each other because some aspects of subdivisions may belong to different types of railway systems.

Rapid transit system, also known as metro, is a common type of public transportation in urban areas. It is also called “Heavy Rail” to differentiate it from light rail. Most of the time, metro systems go below the ground and for this reason, it is also named as “Underground” and “U-bahn” (stands for underground rail) in London and Germany, respectively. Metro systems going underground provides favorable transportation infrastructure solution due the lack of space in highly urbanized areas. Metro systems provide an efficient solution to move high number of passengers in an exclusive designated track (Fouracre et al., 2003).

2.1.1.1 History of Development

London’s steam-hauled railway was the first attempt that can be regarded as rapid transit. The London underground was opened in 1863 and it was the oldest

underground railway in the world. In 1890, electric-traction rapid transit railway was introduced for the first time, and it was named as “City and South London Subway”. The term “Subway” was used as terminology since the railway was fully below the ground.



Figure 2.1. Sample Image for Rapid Transit System (Tompagenet, 2006)

With the advancements in the technology, spread of rail transit systems had escalated in different regions of the world by 1960s. In 2010s, the number of metro system openings almost doubled compared to previous decade (Figure 2.2). Total of 193 metro systems extending 17,221 km length are present across the world as of 2020 (International Association of Public Transport 2021).

In Figure 2.2, the distributions of metro systems categorized based on the regions can be seen. Considering the lack of space and overpopulated cities in Asia-Pacific region, it is no surprise that these cities resort to metro systems for efficient transportation such that 78% of the metro system openings are located in Asia-Pacific region in 2010s.

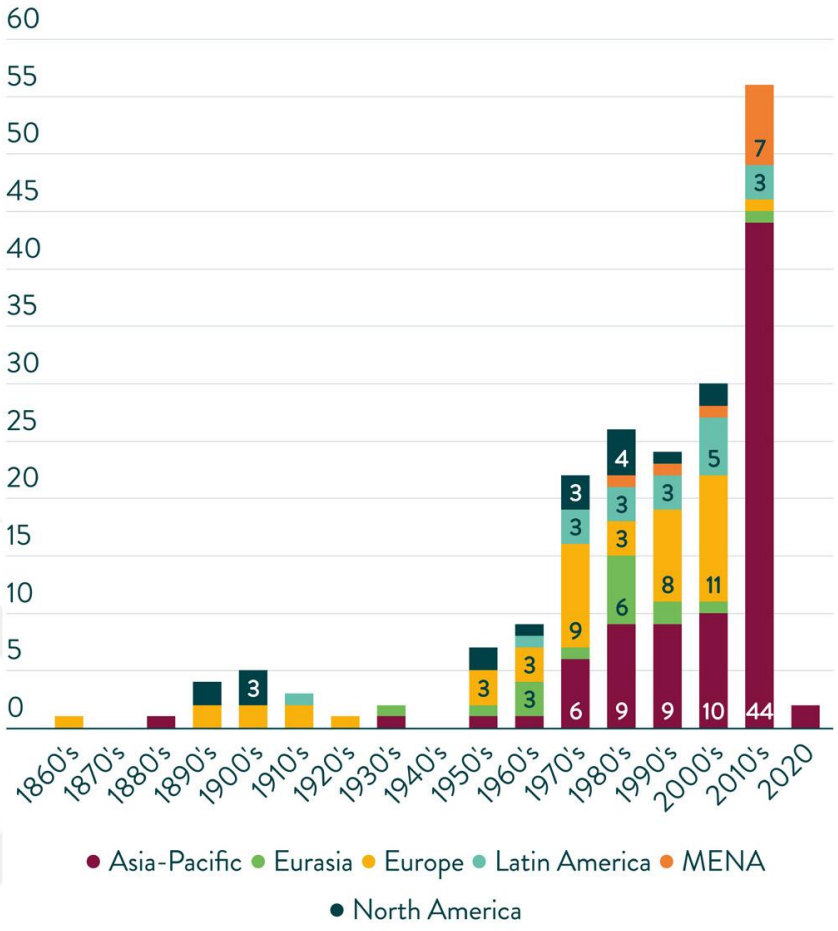


Figure 2.2 Metro System Openings per Decade (International Association of Public Transport, 2021)

Between 2013 and 2020, total length of metro lines has increased significantly in Asia-Pacific region compared to other regions (Figure 2.3). 5 of 10 cities with the longest metro systems are in China and India, making them the leading countries investing in metro systems.

Daily volume of passenger transport has increased %20 in 8 years period of time (Figure 2.4). There is a major drop in the number of daily ridership in 2020 due to COVID 19 pandemic. Therefore, 2020 was excluded from the analysis presented in Figure 2.4 not to cause irregularities in the data caused by unusual events.

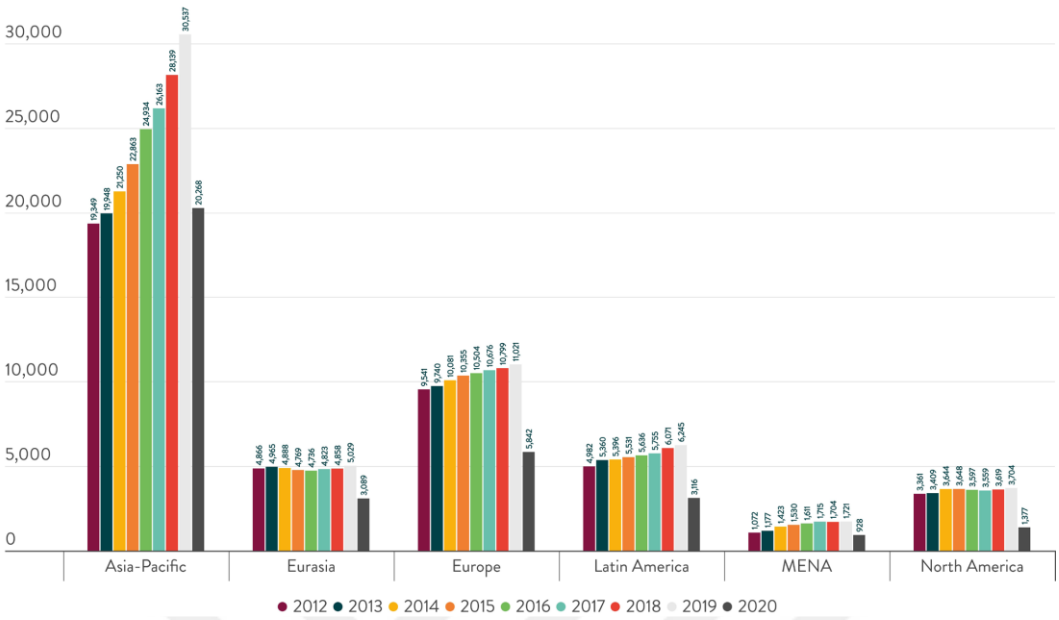


Figure 2.3 Total Line per Region (km) 2013-2020 (International Association of Public Transport, 2021)

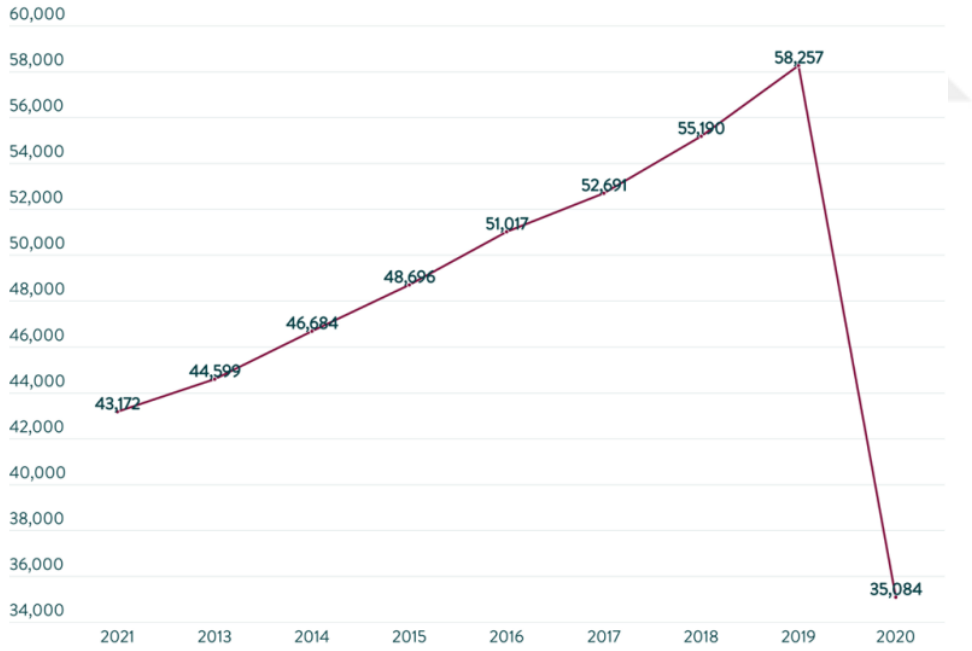


Figure 2.4 Global Ridership (million) (International Association of Public Transport, 2021)

2.1.1.2 Components of Metro Systems

Stations, line structures, trains and rail tracks are the main components of metro systems. Stations are the checkpoints where passengers can board and get off trains. Trains move along the rail tracks in line structures that provides a connection between the stations.

Since each project has distinct characteristics, it is essential to select the suitable construction method based on these characteristics. There are three main construction methods used for metro systems which are Cut and Cover Method, New Austrian Tunnelling Method (NATM) and Shield Tunneling Method.

2.1.1.2.1 Line Structures

Cut and cover is a simple and economic method where excavation works starts from the surface and it continues down to the elevation of tunnel construction (Figure 2.5). Then the tunnel is constructed in the excavated trench from bottom to top. Lastly, the trench is filled, and the surface is restored back to its original state. Relocation of utilities under the ground should be done carefully not to damage the utilities. Furthermore, cut and cover is a better choice if there are no restrictions on the ground such as traffic or residential areas because traffic may be blocked and, the residential areas may be affected from the vibrations caused by excavation works in cut and cover method.



Figure 2.5 Sample Image for Cut and Cover Method (Civilverse, 2021)

In New Austrian Tunneling Method (NATM), tunnel is excavated in stages, then the excavated section is supported by temporary lining such as shotcrete or rock bolts (Figure 2.6). By this way, surrounding rocks are used to provide additional support. NATM can adapt different geological conditions in the excavation area. However, applicability of NATM should be assessed properly as there are numerous collapses reported in the history of NATM constructions (Karakuş & Fowell, 2004).



Figure 2.6 Sample Image for NATM (Structurae, 2016)

Shield tunnelling is a technologically advanced method for constructing tunnels deeper in the ground with long distances without disturbing what is on the surface. Tunnel boring machines (TBM) are used for both excavation and construction of tunnel (Figure 2.7). TBM has a rotating cutting wheel at the front of it which excavates and removes the soil. TBM excavates continuously by moving forward, then precast concrete lining segments are assembled. Shield method is commonly used in the underground tunnel construction because it ensures a fast and safe construction of tunnels (H. Guo, 2019). Once TBM is installed, it creates the line structure by going along the line and passing through the stations.



Figure 2.7 Sample Image for TBM (Amberg Engineering, n.d.)

2.1.1.2.2 Stations

Figure 2.8 shows the distribution of metro stations based on the design features. It can be observed that underground stations are the majority in this distribution. (International Association of Public Transport 2018).

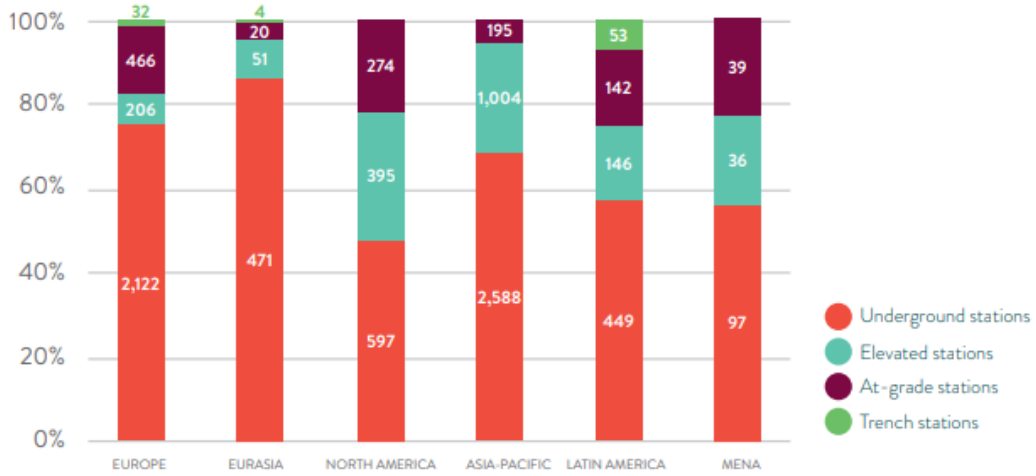


Figure 2.8 Distribution of Construction Models for Metro Stations (International Association of Public Transport, 2018)

Underground Metro stations have two types of structure namely box and tunnel type. Station box is the term used for the former to describe the box-like underground structure that is similar to conventional superstructure buildings in terms of main structural components such as columns, beams, walls and slabs. The lowest level is called the "platform level" where the passengers board and alight from the train. "Concourse level" is on the top of platform level that contains technical rooms, station facilities, security room, offices and ticket machines. From the concourse level, passenger can reach to street level using entry-exit structures. Schematic view of a station box is shown in Figure 2.9.

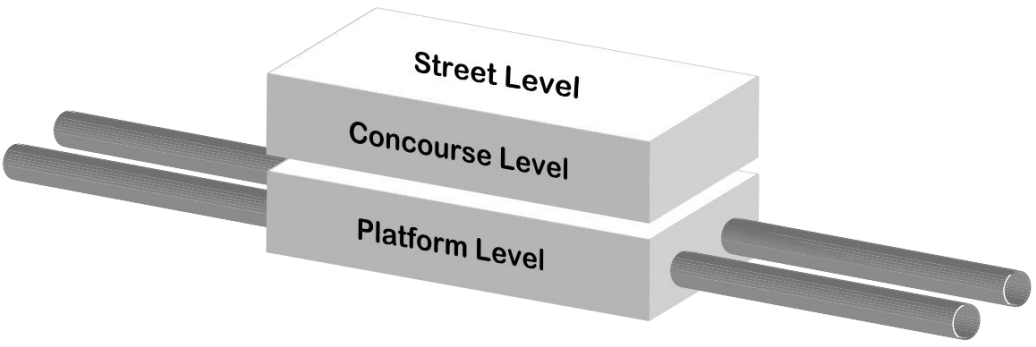


Figure 2.9 Schematic View of a Station Box (Wikipedia, 2013)

Box type is usually chosen for the stations at the start, middle and end of the metro line, because when building a metro system, TBM is mainly installed and removed at these stations for the construction of line structures due to the availability of space. Tunnel type stations consists of shafts and various small tunnel network connected to each other. In some cases, these two types of stations can be mixed together such that box type is constructed from ground level to concourse level, then the rest of the station is formed with tunnels.

In general, NATM and Cut & Cover method are used for the construction of metro stations (Guo, 2019). Shield tunneling is not suitable for construction of stations because, the cross section of tunnels for station and line structures are different in terms of size. In addition, TBM is quite large and not flexible for station tunneling (S. Wang et al., 2021). NATM is used for the construction of tunnel type deep stations, and the construction procedure for station is the same as line structure construction. Shafts are opened to access the different levels of the station that are deep in the ground. Excavation vehicles and equipment are transported to the bottom level of the shaft to carry out the excavation works.

There are two cut and cover construction methods which are top-down and bottom-up, and they are used for box type stations. In the top-down method, structural elements of station are built as the excavation progress from top to bottom. Firstly, retaining walls are installed and the soil is excavated. Then, Struts are installed to support the retaining walls, and the roof slab is casted below the strut level. After that, the soil is excavated down to next slab level followed by the casting of slab. This process is repeated until the bottom level of station is reached. Top-down method is generally preferred when the aboveground is required to be used for traffic or construction purposes. In the bottom-up method, the excavation works are performed to the bottom level of station. Once the excavation is completed, underground structure is constructed from bottom to top unlike top-down method. Bottom-up is simple and conventional construction method compared to top-down, consequently contractors generally choose bottom-up method if it is not necessary to use the ground.

2.1.2 Building Information Modeling

2.1.2.1 Definition and General Uses

Architecture, Engineering and Construction (AEC) is one of the densest industries in terms of information. (Ingram, 2020). Considering that the construction industry usually relies on the conventional methods, managing this dense information is not an easy task. BIM emerged from this need in the industry. BIM is a process of creating 3-dimensional digital model of a building which consists of graphical and non-graphical information, and using these models to design, manage and visualize the construction projects throughout its lifecycle. BIM should not be seen as the 3D models of a building only, because BIM is more about the information that these models contain, and 3D model is just a tool to represent this information. It provides a facility for different phases of the project such as design, construction and maintenance by increasing the overall efficiency of the project (Minagawa & Kusayanagi, 2015). In Figure 2.10, four key elements that forms the BIM concept and their relationships are demonstrated. Bradley et al. (2016) indicated that the interaction of these elements which are collaboration, representation, process, and lifecycle, enables an efficient and productive project environment.

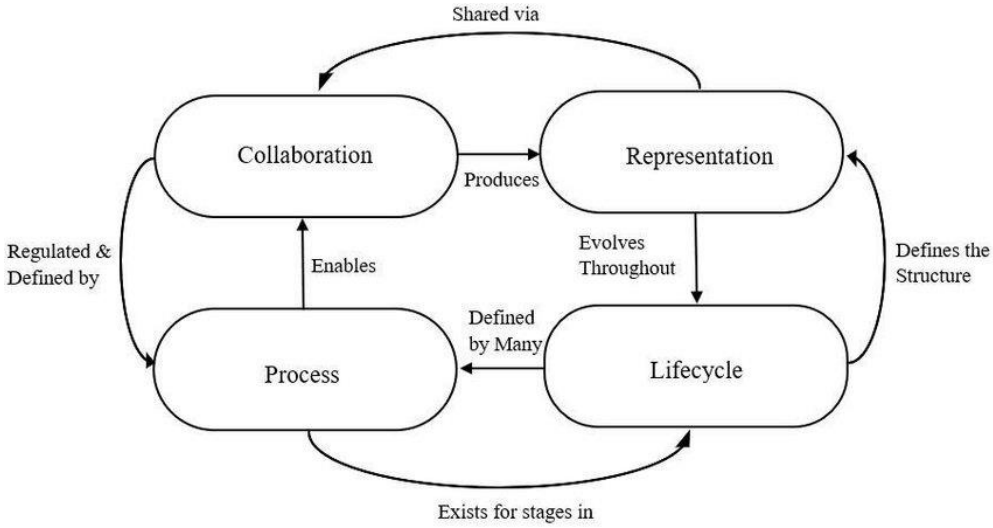


Figure 2.10 Four Key Elements of the BIM Concept (Bradley et al., 2016)

The concept of BIM has been suggested in the 1970s; however, it was not until 2000s that BIM has been widely recognized and the development of BIM has escalated. BIM can provide significant benefits for the construction projects if implemented properly. Findings in SmartMarket report by Autodesk (2021) shows the top five positive impacts on the construction projects from the contractor point of view by implementing BIM with different densities (Figure 2.11). These positive impacts are the improvement of cost control, reducing the number of constructability issues onsite and defects at handover and nonrecoverable costs, and increasing the percentage of successful projects. It can be interpreted that the more BIM is used, the more benefits it provides.

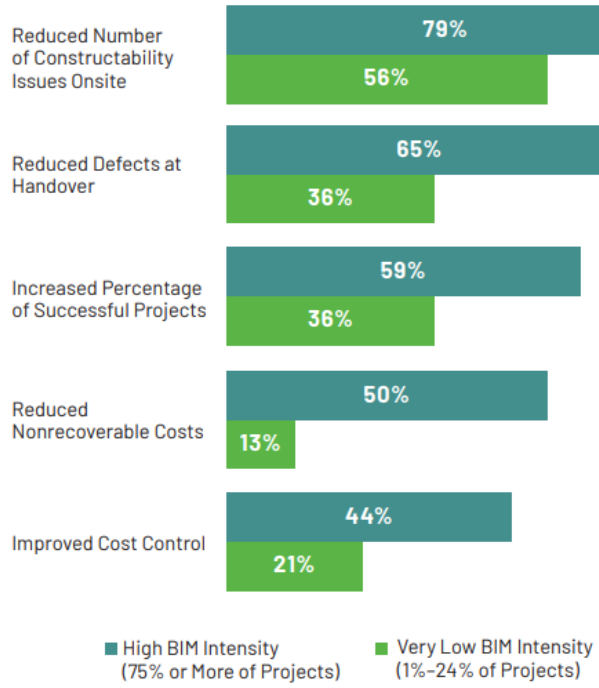


Figure 2.11 Top Five BIM Benefits for Contractors (Autodesk, 2021)

BIM models can be used for various purposes that contributes different aspects of the construction projects. Creation of design and BIM models using BIM-based software tools is considered to be the first step of BIM system. These models provide transparency between the parties involved in the design process. BIM enhances the quality of design by providing a visual representation of building and promoting

effective collaboration between these parties (Shim et al., 2011). BIM models created separately by different disciplines are combined in a federated model via dedicated software such as Navisworks to detect the incompatibilities in the design. This process is called 3D coordination, and it is one of the essential uses of BIM models as it decreases the number of flaws in the design before the construction phase.

From BIM models, design documents can be created and modified easily by using BIM-based software since they have the feature of automatically reflecting the changes in the design to all related views. Hereby, it saves considerable amount of time in the design process and also enables consistency of information.

BIM models can also be used for quantity takeoff and cost estimation. Elements in the model can be listed in the created schedules with the quantity information. Quantity information allows to perform cost analysis for different work breakdowns.

Level of Development (LOD) is a term to define the complexity of geometry and attached information of 3D objects in BIM model. LOD specifications provide a systematic way to create 3D objects so that every user has the consensus view about the level of detail of 3D objects. These are prepared by BIM forum and its interpretation of LOD definitions are the followings.

- LOD 100 elements are not geometric presentations. They may be symbols or other generic representations of information that can be derived from other model elements. Any information derived from LOD 100 elements must be considered approximate.
- LOD 200 elements are represented graphically but are generic placeholders, e.g., volume, quantity, location, or orientation. Any information derived from LOD 200 elements must be considered approximate.
- LOD 300 elements are graphically represented as specific systems, objects, or assemblies from which quantity, shape, size, location, and orientation can be measured directly, without having to refer to non-modeled information such as notes or dimension callouts.

- LOD 350 elements are enhanced beyond LOD 300 by the addition of information regarding interfaces with other building systems. For example, an LOD 350 masonry wall element would include jamb conditions, bond beams, grouted cells, dowel locations, and joints – information that enables the model user to coordinate the wall element with other systems in the structure.
- LOD 400 elements are modeled at sufficient detail and accuracy for fabrication of the represented component.

Depending on the project phase and requirements, different LOD can be applied for different elements.

2.1.2.2 Construction Sequencing and Progress Tracking

Construction sequencing, also known as 4D modeling, is the process of adding time factor to 3D BIM model. In other words, it is a BIM-based scheduling where 4D simulation is the visual output obtained by linking construction activities in a project schedule to 3D objects in a BIM model. By establishing the project schedule, work breakdown structure (WBS) and their codes are also defined for each construction activity in the schedule. Then, these WBS codes are entered to 3D objects in BIM model based on the definition of activities. 4D model is produced by matching the WBS information of 3D objects with the WBS codes included in the schedule so that the time information (start and finish date of activities) will be integrated with 3D objects in a dedicated software. Synchro, Fuzor and Navisworks are some example BIM-software to run 4D simulations.

In AEC industry, application of 4D modeling has started to gain interest in recent years (Hartmann et al., 2008). This is mainly because 4D simulation can offer many benefits for the project. Visualization of construction schedule is the key element of 4D model as it helps project members comprehend the construction process (Zhou et al., 2013). Before the construction phase, constructability issues can easily be

detected compared to traditional methods (Abdelwahab, 2018). Although, there are thousands of construction activities in the schedule, inconsistencies among the construction activities can be effectively noticed by examining the 4D simulations (Koo & Fisher, 2000).

As for progress tracking, construction progress data obtained from the site are inserted into 3D models during the construction phase. The data for a specific 3D object may contain the followings:

- Individual completed amount
- Cumulative completed amount
- Individual completed percentage
- Cumulative completed percentage
- Total amount to be constructed

Then, according to information available in the 3D model, visualization of progress is done via BIM-based software such as Navisworks, and the visualized model is presented to owner of the project and project stakeholders. By this way, the awareness of the progress in the construction increases for the parties involved in the project. Progress tracking models is presented in a predetermined frequency such as once or twice in a month.

2.2 Relevant Studies in the Literature

In this section, studies related to BIM and infrastructure applications, 4D modeling in general and in infrastructure, and in metro system applications were examined.

In order to establish a framework for using BIM in construction projects and assess the usefulness of BIM, various studies have been carried out in different types of case projects. For the last decade, the effort put into adopting BIM in infrastructure sector has been increasing. 32% of the BIM related publications between 2008 and 2015 (not complete year) had focused on infrastructure sector (Bradley et al., 2016). This 32% includes mainly highway, bridges and roads (Figure 2.12).

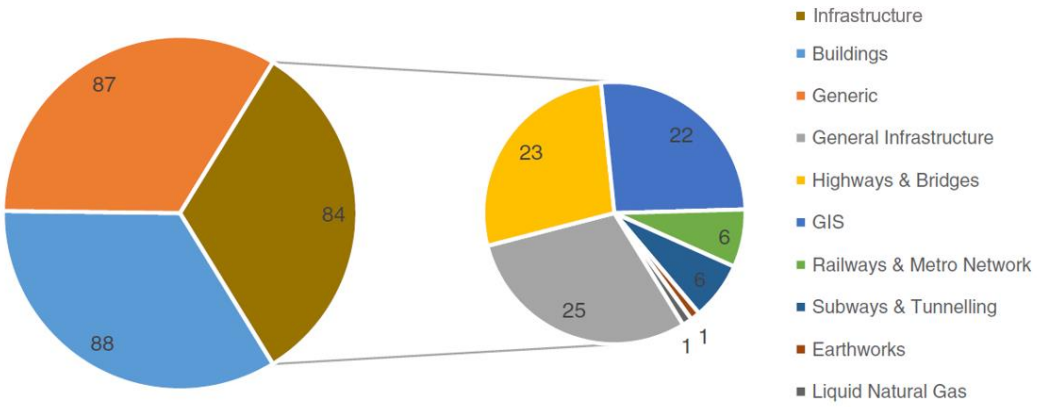


Figure 2.12 Distributions of Publications by Industry Sector (Bradley et al., 2016)

Fanning et al. (2015) compared two structurally similar bridge construction projects (one with BIM, the other one without BIM) to assess the impact of implementing BIM in infrastructure projects. The findings suggest that BIM have provided potentially 5-9% cost savings during the construction. Reducing change orders and rework is the main contribution of BIM. Implementing BIM has allowed the project to be finished within the deadline by meeting the specific requirements.

In a motorway improvement project, BIM has been utilized to determine the benefits of BIM and expand the knowledge for wider adoption of BIM on infrastructure projects. Based on the findings, Kumar et al. (2017) stated that value production has increased due to improvements in information exchange between the stakeholders. Moreover, the amount of effort put into design review works dropped to one-fifth of traditional methods in terms of duration.

H. Kim et al. (2014) used object-oriented 3D visualization modeling to compare different alignment alternatives and identify the optimum solution. With the proposed method designing highway alignment process becomes less costly and time-consuming compared to traditional way of designing.

Virtual Prototyping Simulation (VPS) can be used to evaluate construction scenarios in bridge construction. By visualizing the temporary platforms, equipment and

vehicles including time aspect, Li et al. (2012) proposed an approach for resource allocation and construction planning.

Civil Information Modeling (CIM) is another definition occasionally encountered for the applications of Building Information Modeling for horizontal infrastructure projects (F. Guo et al. 2014). Sankaran et al. (2016) evaluated integration of CIM in a case study Horseshoe project for the design and construction phase. They stated that, the competence of the participants is an essential element for the proper integration of BIM in the infrastructure sector.

BIM can also be used for bridge inspection which is required to maintain its operability. Dibernardo (2012) proposed a framework for data management system which includes data collection, analyzing and storing. It was stated that potential for BIM utilization in bridges during the operation phase has the potential to facilitate the inspection process, and decreasing the costs related to operation and maintenance.

BIM can be used in the operation and maintenance (O&M) phases of infrastructure projects. Wang and Zhang (2021) studied the strategies to overcome the challenge of implementing BIM in underground rail transit projects during handover management for operation and maintenance phase. They noted that the involvement of O&M personnel in the early stage was helpful to investigate the requirements for O&M. By this way, BIM requirements, such as determining LOD, have been properly defined before the O&M stage which led to effective operation and maintenance performance for rail transit project. Yin et al. (2020) proposed a BIM-based framework for the O&M phase of utility tunnels to enhance the conventional O&M practices in terms of information integration and visualization. BIM and GIS can be integrated to enhance the application possibilities. Geographic information system (GIS) is a computer system to store visualize and interpret geographic data. Lee et al. (2018) developed a BIM and 3D GIS based system for maintenance management of utility tunnels. It was reported that this integration provides

feasibility and efficiency in maintenance of utility tunnels according to the tunnel operators' feedback.

BIM can increase the efficiency in the calculations for tunnel constructions during design process. Zhang et al. (2023) combined numeric model and BIM model with schedule information to perform numerical analysis. This method decreased long durations related with the calculation operations for hydraulic tunnel construction. Osello et al. (2017) proposed a BIM methodology for creating tunnel model and performing geotechnical analysis via interoperability. The study aimed to develop the methodology by analyzing LOD, objects library and information exchange as it was stated that BIM tools are not yet proper for the design of infrastructure projects. It was reported that information included in BIM database improves the design process of infrastructures. Borrmann et al. (2015) created a multi-scale model for shield tunnels and their components. It was reported that this model aids the data exchange by conducting the necessary relation between semantic and geometric details of shield tunnel. Providakis et al. (2019) developed an BIM-based approach for the prediction of settlement risk of buildings caused by tunneling. J. Wang et al. (2022) calculated the carbon emissions during construction of tunnels by parameterization.

In order to address the complexity and varied data in the construction of tunneling, Koch et al. (2017) presented a framework for the development of integrated tunnel models to simulate mechanized tunnelling projects. It was stated that level of geometric details of 3D objects should be considered because it may have a negative impact on the applicability of the simulations.

Baraibar et al. (2022) implemented BIM in a tunnel extension project to evaluate the BIM methodology in the execution of underground works. It was stated that establishing a contractual framework that promotes collaboration between the parties involved is essential for the adaptation of BIM in underground projects.

Sharafat et al. (2021) proposed a BIM-based framework for drill-and-blast tunneling projects including Industry Foundation Classes (IFC) standards and LODs. It was

stated that BIM cannot be directly implemented in tunneling projects since building and tunnel construction projects have distinct standards in terms of process and engineering. It was noted that such frameworks improve the quality of project; nonetheless, the challenge of BIM technology being immature in the tunneling industry still remains.

Ding et al. (2012) carried out a study to determine the BIM capabilities in city rail transit construction based on nD model which may contain information regarding time, cost safety and quality. In the study, it was emphasized that gathering and managing of information was a challenging task due to lack of efficient workflow for these tasks.

Zhou et al. (2013) proposed a visualization framework for the 4D modeling process to be used in site safety management of metro projects. Ding indicated that considering the complex activities in metro construction, 4D models should be used to for accurate and successful safety assessment. It was reported that the proposed approach is a proper tool for virtual analysis of risk levels, and collaboration between the parties involved in the project.

In the literature, 4D related studies mostly focus on the capturing the progress data on-site and updating the 4D models. IFC is an international standard schema that enables the BIM model data exchange between different software programs. Hamledari et al. (2017) stated that 4D models should be updated regularly for effective progress tracking and proposed IFC-based procedure to for automated updating the progress data in BIM models. Park and Cai (2017) presented a framework that synchronizes the information in daily progress reports to automatically update 4D models in a Web environment. Teizer (2015) studied the image processing technique for progress tracking. Similarly, Han et al. (2018) presented geometry and appearance-based method for detecting construction progress. Image-based 3D point clouds and laser-scanned point clouds were studied, and it was reported that reasoning accuracies were about 90% and 68%, respectively. Advancements in technology offers new ways to collect information from site. Han

and Golparvar-Fard (2017) used UAV (unmanned aerial vehicles) with an attached camera to document the progress data to develop more affordable, simple and short method for data gathering. Kopsida and Brilakis (2020) presented an automated framework for progress monitoring by comparing as-build and as-planned data via using a mobile device called Microsoft HoloLens with an accuracy about 95.2%. It was stated that such technologies are more effective compared to current practices being manual and labor intensive.

Although there is a growth in the number of research focusing on the adoption of BIM in infrastructure, where majority of them contains roads, highways and bridges, implementation of BIM for metro systems is still limited (G. Wang and Zhang 2021). Furthermore, only a small percentage of these research concerns the 4D modeling application in metro systems (Costin et al., 2018). It can also be observed that 4D modeling related studies mainly focuses on the data gathering and updating of 4D models. Modeling standards to have the desired 4D simulations are rather unexplored especially in infrastructure sector. A study where the main focus is defining workflow and modeling standards regarding BIM-based progress tracking and scheduling of underground metro projects have not been found. Therefore, there is a need of a framework for BIM-based progress tracking and scheduling in underground metro projects.

CHAPTER 3

METHODOLOGY

In this chapter, research method of the study is described, examined project characteristics and project documents are demonstrated.

3.1 Research Method

Following research approach is implemented in this study, and it is also demonstrated in Figure 3.1. Firstly, relevant studies are reviewed. Secondly, an ongoing metro construction project has been investigated to observe the implementation of BIM in an infrastructure project. Data to be analyzed contains 4D models, phase planning reports, project schedule, progress reports and BIM models, which are obtained from the phase planning simulations and progress tracking models that have been carried out as part of the scope of the project. So far, 65 phase planning simulation and progress tracking models have been submitted during the 2.5-year construction period of the project, and 4D model submissions will continue until the end of the agreement. These inputs have been analyzed in depth to identify the flaws and strengths of the process in the current practice. Thirdly, identified problems have been categorized in terms of definition, cause and solution. Then a framework has been proposed based on the findings. Lastly, the efficacy of the framework has been assessed by interviewing the experts of the industry.

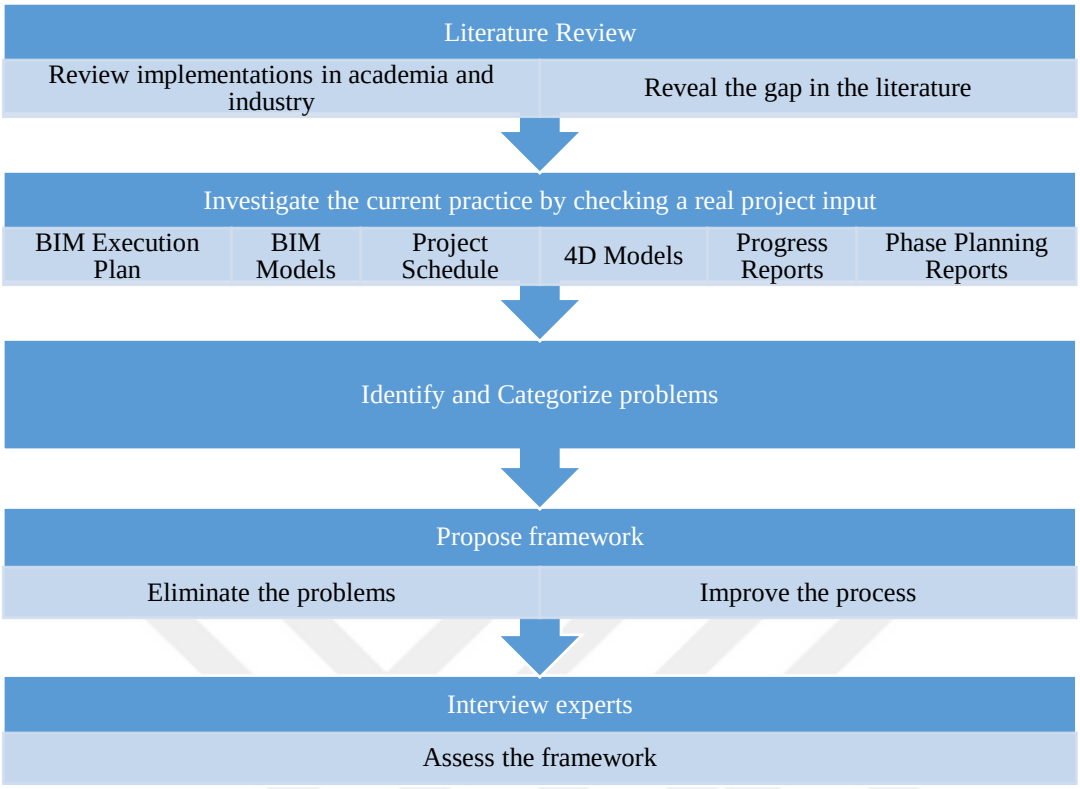


Figure 3.1 Research Methodology

3.2 Project Characteristics

The Metro project investigated in this study is currently under construction and it is located in Türkiye. The project involves a 13 km underground rail transit line, 11 underground metro stations and one maintenance depot. Line structures are constructed with NATM and TBM methods. Three of the stations are box type stations to be constructed using cut-cover method, and the rest of the stations are tunnel type stations to be constructed using NATM. In this project, BIM models are created for each discipline which consists of structural, geotechnical, architectural, electrical and mechanical. Every line structure and station have a separate model for the disciplines mentioned. At the time the project is inspected, geotechnical and structural construction works are in progress. Therefore, in order to inspect the processes of progress tracking and phase planning simulations, this study focuses on

the geotechnical and structural discipline models of tunnel type stations and line structures.

There are four parties involved in this project as participants. These are client, consultant, contractor and designer. Relationships of these parties are shown in Figure 3.2.

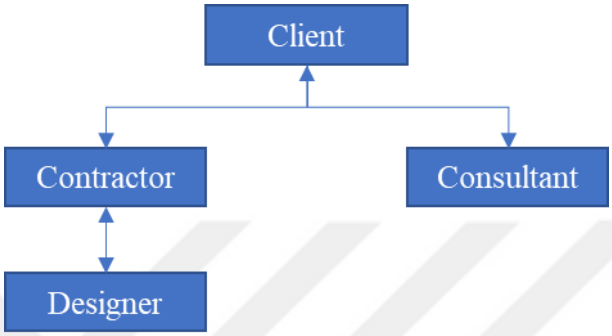


Figure 3.2 Project Stakeholders

3.3 Investigated Project Documents

3.3.1 BIM Models

- Stations

Geotechnical models consist of three categories which are excavation, geotechnical and support systems. Contents of these categories are explained in Table 3.1.

Table 3.1 Content of Geotechnical Model Elements

Category	Content of model elements
Excavation	Excavated soil volume
Geotechnical	Shotcrete lining, bored pile, strut, bracing beam
Support systems	Anchorage, rock bolt, soil nail

Geotechnical model elements for tunnels are divided into 1-meter pieces instead of a single element for the whole tunnel since there is no specific length for the tunnel elements unlike structural components. BIM elements related to shotcrete lining and excavation are modeled such that they comply with the excavation steps at the site. Figure 3.3 shows the sample geotechnical model elements used in the project.



(a) (b) (c)

Figure 3.3 Sample Images for Geotechnical BIM Model Elements: (a) Excavation (b) Shotcrete (c) Support Systems)

Structural models include concrete work items. Top and bottom part of tunnels are modeled separately for each tunnel segment based on the design so that LOD 300 requirements are met (Figure 3.4). Top part is called “arch concrete”, and bottom part is called “invert concrete”.

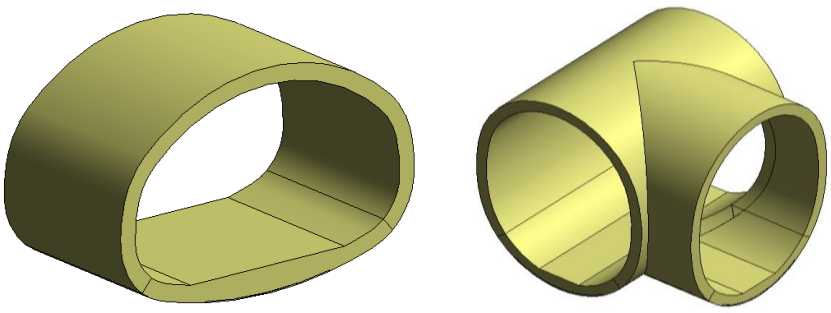


Figure 3.4 Sample Images for Structural BIM Model Elements

- Line Structures

For line structures, only shotcrete and inner lining components are modeled for geotechnical and structural models, respectively. Similar to stations, shotcrete lining elements are divided into 1-meter pieces.

3.3.2 Project Schedule

Project schedule is constructed in a dedicated software called Microsoft Project based on the construction activities in the established work breakdown structure. Planner provides project schedule to be used for phase planning simulations. Project schedule contains information for each construction activity, and the followings are used to create phase planning simulations.

- WBS Code
- Definition of construction activity
- Planned start date
- Planned end date
- Actual start date
- Actual end date

For some activities, scope of a defined construction activity can be comprehensive while for some activities, it can be more specific. Construction activities related to reinforcement works include all tunnel elements located on a floor in the station. For example, there is a single reinforcement works activity for the tunnels on the platform level. On the other hand, construction activities for formwork and concrete works are specific to each tunnel. Furthermore, construction activities can be changed or added to project schedule as the design of the project can change through the lifecycle of the project.

A sample from the project schedule is given in Table 3.2.

Table 3.2 Sample Part of the Project Schedule

WBS	Activity Name	Planned Start Date	Planned End Date	Actual Start Date	Actual End Date
4.11.6.4.1.7	Concrete production and pouring	19.09.2020	1.08.2023	6.10.2020	9.10.2023
4.11.6.4.1.7.3	Concrete production and pouring of Invert in tunnels	19.09.2020	3.06.2023	6.10.2020	25.06.2023
4.11.6.4.1.7.3.1	Platform tunnels	19.09.2020	21.04.2021	19.09.2020	2.06.2021
4.11.6.4.1.7.3.1.1	Invert concrete LINE 01 (L1-101)	8.02.2021	21.04.2021	8.02.2021	23.05.2021
4.11.6.4.1.7.3.1.2	Invert concrete LINE 02 (L1-102)	19.09.2020	2.09.2020	19.09.2020	3.08.2020

3.3.3 Progress Reports

Progress reports are acquired from the site, and they include progress data regarding the actual construction made until that date. There are two documents, one containing visual and the other numerical data, provided in the form of PDF and Excel, respectively. Visual data makes it easy to comprehend where the c is, while numerical data provides quantitative value about the construction. Sample images and parts from the report are shown in Table 3.3 and Figure 3.5.

Table 3.3 Sample Part of the Progress Report

Activity Name	Unit	Total Amount	Total Progress	Remaining Amount	Percentage of Completion (%)
D2 Tunnel Excavation & Shoring					
Top Part Stage 1	mt	243,5	181,2	41,5	74,4
Top Part Stage 2	mt	243,5	183,1	39,6	75,2
Bottom Part Stage 3	mt	243,5	184,42	38,28	75,7
Bottom Part Stage 4	mt	243,5	184,42	38,28	75,7
D2 Tunnel Concrete					
Invert Concrete	mt	243,5	69,05	153,65	28,4
Arch Concrete	mt	243,5	0	243,5	0,0

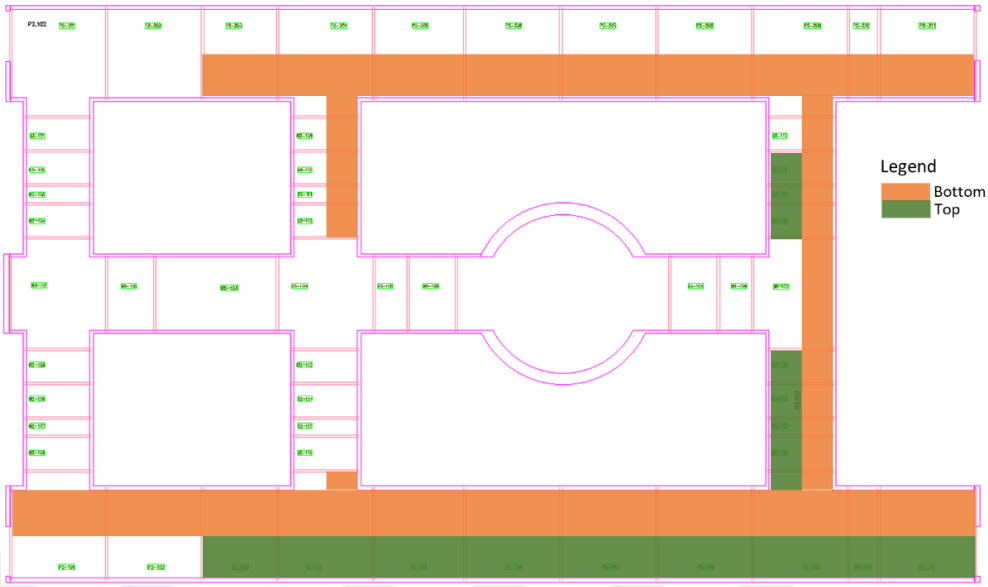


Figure 3.5 Sample Image of the Progress Report

Progress data is categorized based on the construction activities. In the sample report, four main construction activities are observed which are geotechnical and structural construction activities of each NATM tunnel type namely “T” and “B5”. Sub-activities cover the geotechnical and structural construction works for top and bottom part of the tunnels. Numerical values are the cumulative construction data of each tunnel type in a specific station. The table contents are as follows, in order:

- Construction Activity
- Unit
- Total Amount
- Total Progress
- Remaining Amount
- Percentage of Completion

In the visual report, horizontal tunnel construction is demonstrated on a plan view, and these views are divided into levels where necessary. Vertical tunnel construction, on the other hand, is demonstrated via section views. In addition, information regarding the progress distance of each tunnel is provided for geotechnical construction.

3.3.4 Progress Tracking Models and Phase Planning Simulations

Within the scope of the project, phase planning simulations and progress tracking models are produced once or twice a month depending on the project decision.

Progress information in the daily progress reports are inserted into related parameters of BIM objects to create progress tracking model. Although progress reports are created daily, the most recent daily report, that is created a day before data entry begins, is used in order to have the most accurate progress representation of site. For example, if the data insertion of BIM objects starts on Wednesday, the progress report created on Tuesday is used. In this project, following parameters shown in Table 3.4 are used (PT: Progress Tracking).

Table 3.4 Parameters Used for Progress Tracking Data

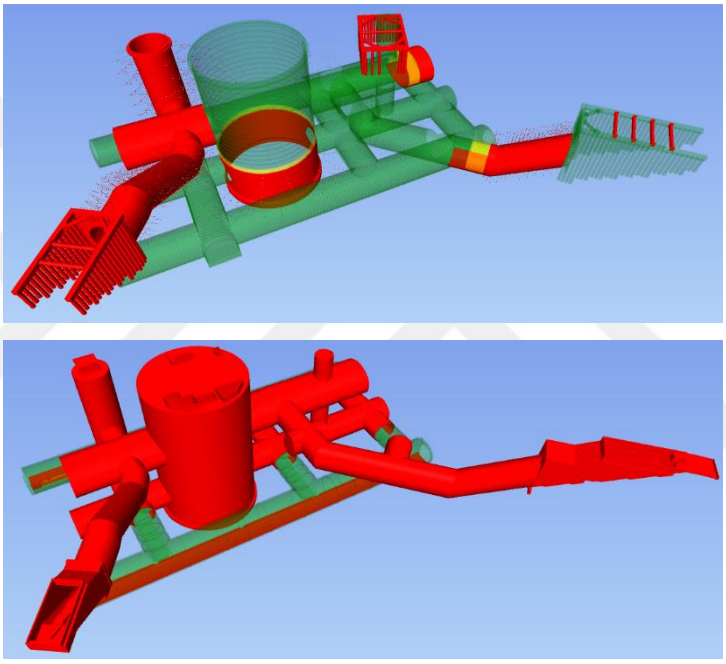
Parameter Name	**Description**
PT_Progress Status	Construction status that shows whether the model element is completed (C) or in progress (I/P)
PT_Progress "Y/N"	Construction status with a check box (Yes/No)
PT_Completed Amount "m"	Completion amount of model element
PT_ Completed Percentage "%"	Percentage of completion of model element
PT_Project Amount "m, m^3"	Total project amount of model elements. Appropriate parameter is used according to the unit of the relevant pose number.
PT_ Cumulative Completed Amount	Total completion amount of model elements
PT_ Cumulative Completed Percentage "%"	Completion percentage of model elements based on total completion and project amount

Progress tracking model is created by visualizing the model elements as a result of matching the color coding of the data processed to the model elements. Geotechnical and structural progression of each structure is demonstrated in a single progress tracking model by means of viewpoints. Viewpoints are categorized in terms of geotechnical and structural construction. For box-type stations, excavation and shoring works are included in geotechnical construction, while for tunnel-type

stations, only shoring works are included. Example illustrations for a tunnel-type station are shown in Figure 3.6.

Construction statuses and color codes used to display the progress are as follows:

- Progress status: Not started (Red)
- Progress status: In progress (Yellow)
- Progress status: Completed (Green)
- Existing Structures (Gray)



(a)

(b)

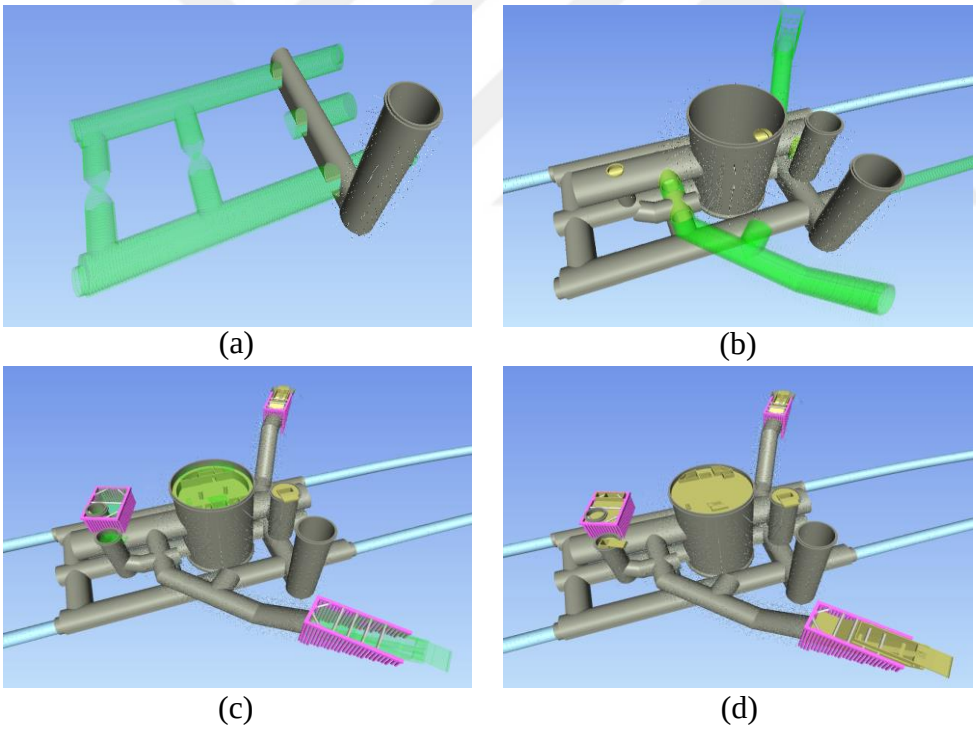
Figure 3.6 Sample Images for Progress Tracking Models of Tunnel-type Stations: (a) Shoring and (b) Structural Work

Phase planning simulations are obtained by associating the planned start and end dates of each construction activity in the project schedule with the corresponding elements in BIM models. Three parameters are used to hold the information regarding the construction activities (PL: Planning).

- PL_WBS 1: Concrete, Excavation & Shoring
- PL_WBS 2: Formwork
- PL_WBS 3: Reinforcement

WBS codes in the project schedule are inserted to relevant elements in BIM models based on the definition of construction activities. There are three activities for the structural construction which are concrete, formwork, and reinforcement. These three activities are associated with the relevant parameters. Unlike structural construction, there is only one activity for the geotechnical construction that covers the excavation and shoring works.

Geotechnical construction works of tunnels, shafts and entry-exit structures are represented by the elements in geotechnical and support system categories. In Figure 3.7, sample images are shown for the phase planning simulations for a station. At a specific timestamp, model elements are colored green if they are in progress and the original model color if they are finished. Model elements are not displayed if the construction activity has not started yet.



(a) (b)

(c) (d)

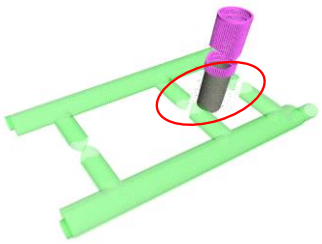
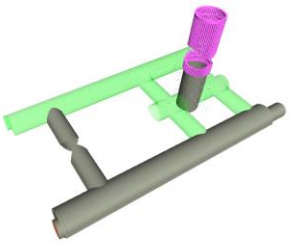
Figure 3.7 Sample Images for Phase Planning Simulations: (a) Geotechnical Construction of Tunnels (b) Geotechnical Construction of Tunnels (c) Structural Construction of Shafts (d) Completed Construction

Phase planning and progress tracking models are presented in the same information model within the determined schedule.

3.3.5 Phase Planning Reports

Within the scope of the project, phase planning simulations are checked based on certain constructability rules, and phase planning reports are generated for the detected problems. For each problem, necessary information is provided and required action is suggested or requested for the resolution of the problem. Then the report is transmitted to the planner for review to get feedback on the problems. A sample problem detected as part of the report is shown in Table 3.5.

Table 3.5 Example Problem from Phase Planning Report

<table>
<tr><td>Structure:</td><td colspan="3">Station 4</td></tr>
<tr><td>Discipline:</td><td colspan="3">Geotechnical</td></tr>
<tr><td>Item:</td><td colspan="3">D1-103</td></tr>
<tr><td>Cause:</td><td colspan="3">Project Schedule Date</td></tr>
<tr><td>Related Activities Names</td><td>WBS Code</td><td>Start Date</td><td>End Date</td></tr>
<tr><td>Shaft 7 Excavation & Shoring Works</td><td>01.1.7.2.1.7</td><td>26.11.2020</td><td>8.02.2021</td></tr>
<tr><td>D1 Type Tunnel Excavation & Shoring Works (D1-103)</td><td>01.1.7.2.4.1.3</td><td>1.04.2021</td><td>20.05.2021</td></tr>
<tr><td>D3 Type Tunnel Excavation & Shoring Works (D3-101)</td><td>01.1.7.2.4.3.1</td><td>11.12.2020</td><td>28.06.2021</td></tr>
<tr><td>D3 Type Tunnel Excavation & Shoring Works (D3-102)</td><td>01.1.7.2.4.3.2</td><td>17.03.2021</td><td>3.05.2021</td></tr>
<tr><td>Image 1</td><td colspan="3">Image 2</td></tr>
<tr><td></td><td colspan="3"></td></tr>
<tr><td>Explanation</td><td colspan="3">Request</td></tr>
<tr><td>In the simulation, the excavation and shoring works of D1-103 tunnel should start after the excavation and shoring works of Shaft 7 are finished and before the excavation and shoring works of D3-101 and D3-102 tunnels start.</td><td colspan="3">Activity relations and dates should be checked in order to solve the problem.</td></tr>
<tr><td>Reply</td><td colspan="3"></td></tr>
<tr><td>The problem was solved by revising the project schedule.</td><td colspan="3"></td></tr>
</table>

3.4 Interview Questionnaire

The aim of this interview questionnaire is to evaluate the proposed framework for improving the process of creating a BIM-based schedule simulation and progress tracking model in metro projects by industry professionals.

3.4.1 Target Population

The interview was conducted in Türkiye and its targeted respondent group was experts who have experience working in the transportation infrastructure industry and have used BIM in these projects. The respondents were selected so that the companies they work for operate in different fields such as design, consultancy and construction with varying experience levels ranging from highly experienced to less experienced. By this way, it was possible to get opinions from people with different perspectives. In order to get proper feedback from the experts it was ensured that selected experts were knowledgeable about 4D modeling.

3.4.2 Questionnaire

The questionnaire consists of six sections. Section 1 collects general information about the respondent, Section 2 has questions about experience details of the respondent, Section 3 asks company details of the respondent. Section 4 contains the challenges in BIM implementation at 4D level in metro projects. Section 5 comprises of the challenges identified in the case study project while the proposed solutions for these challenges are presented in Section 6. A sample of the questionnaire is provided in Appendix.A.

Section 4, 5 and 6 are the main sections of the questionnaire regarding the assessment of the proposed framework. In Section 4, respondents were asked to rate the listed challenges in terms of their importance using a 5-point Likert scale ranging from “not at all important” to “very important” (1 = not at all important, 2 = slightly

important, 3 = important, 4 = fairly important, and 5 = very important). In Section 5, identified problems which are related to the challenge items in Section 4 are presented with explanatory details and figures, and respondents were asked to rate these problems in terms of their importance using a Likert scale, similar to previous section. In Section 6, respondents were asked to rate their agreement on the proposed solutions for the identified problems using Likert scale ranging from "strongly disagree" to "strongly agree" (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree).

3.4.3 Interview with Experts

One-on-one interviews were held with experts through the questionnaire. A total of five experts were interviewed. By having one-on-one interviews with a small number of respondents who have a specific background, it was aimed that the respondents could better understand the subject and make an accurate evaluation of the proposed framework. In the framework assessment section, the explanations and figures in each item listed were clearly explained to the respondents one by one, and the respondents were asked to rate the listed items after the explanations. The interview was conducted after it was submitted to the METU Human Subjects Ethics Committee for approval. A copy of the approval is provided in the Appendix.B.

CHAPTER 4

FINDINGS AND DISCUSSION

This section presents the findings from the project documents under the following categories shown in Figure 4.1. Some of these findings are identified from the reports created within the scope of the project and others are identified while the project documents are investigated. There are five topics under three main categories that will be discussed and elaborated with examples.

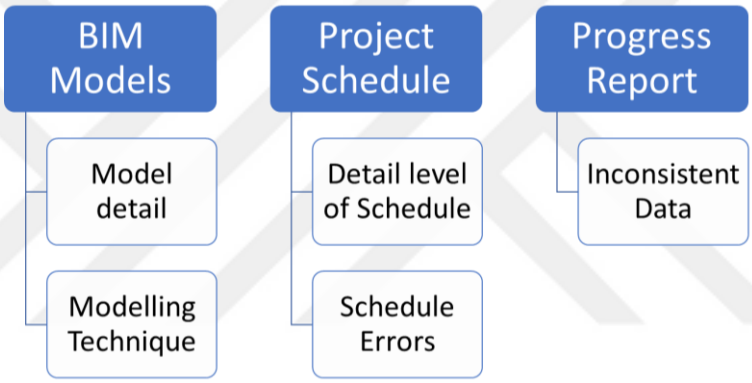


Figure 4.1 Categorized Findings

4.1 BIM Model

In this section, findings related to BIM model are discussed. BIM is implemented by following the guideline BIM Execution Plan (BEP), but modeling techniques may change depending on the assumptions made by BIM staff based on the project characteristics as these guidelines do not specifically address the way of modeling. Sometimes this modeling assumptions may not meet the requirements for all BIM uses, which is 4D modeling in this case. The model elements were created by meeting LOD 300 requirements and following BEP, but there are still model related

problems although the requirements stated in the guidelines are followed. Hence, model detail and modeling techniques need further clarifications.

4.1.1 Model Detail

In the phase planning simulation, activities are assigned to elements as a whole. For instance, every model element in the tunnel named as D1-103 would have the same WBS values in their parameters because the scope of the activity is defined for the tunnel D1-103 as a whole. However, every model element could have different progress information in their parameters depending on the progress. Therefore, it is essential to create each model element separately with enough geometric detail based on the design. LOD 300 elements are key to have a precise progress tracking model, as they are required to be modeled directly referring to design documents. For structural elements, a tunnel consists of divided tunnel parts, and these tunnel parts are modelled separately to meet LOD 300 requirements. LOD 200 elements would be a single model element without any separation between tunnel parts. In this project, LOD 300 elements are used because having separate model elements allows inserting progress information specific to model elements. An example for the part of the structural tunnel segments with 2 cm spacing between each based on the design documents is given in Figure.4.2.

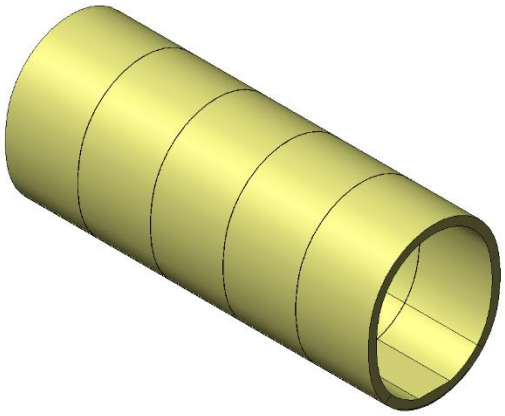


Figure 4.2 Sample Structural Tunnel Elements

For geotechnical elements, total lengths of the tunnels are specified in the design documents as they are continuous activities unlike structural elements. However, geotechnical model elements for tunnels were divided into 1-meter pieces as project decision, since having separate model elements are necessary to have precise progress information. By this way, geotechnical and structural construction progress can be demonstrated precisely. Otherwise, progress onsite cannot be properly visualized, and it would be difficult to comprehend the progression of these construction works. To illustrate, 40-meter tunnel is modeled as a single model element in Figure 4.3, and 1-meter elements in Figure 4.4. In this example case, geotechnical works of upper part of this tunnel is 70% finished. While visualizing the progress, the model element would be colored yellow for the 40-meter tunnel element, because construction is still in progress (Figure 4.3). In the case where the tunnel is modeled as 1-meter elements, total of 28 (70% of 40) pieces of 1-meter tunnel elements are colored green based on the progress because construction works of these elements are finished (Figure 4.4). Both model element colorings are correct, however, the precision of progress visualization differs for these two different modeling techniques. When the geotechnical construction for this tunnel is started, the progress status of the 40-meter single model object will be “in-progress” until the geotechnical construction of the whole tunnel is completed. Therefore, which parts of the tunnel is actually excavated cannot be exactly shown. Also, the amount of progress made is indicated in BIM object’s parameters, yet this amount is not observed in the coloring of BIM model elements. As a result, it can be clearly stated that the progress of the tunnel is shown more precisely in the Figure 4.4.

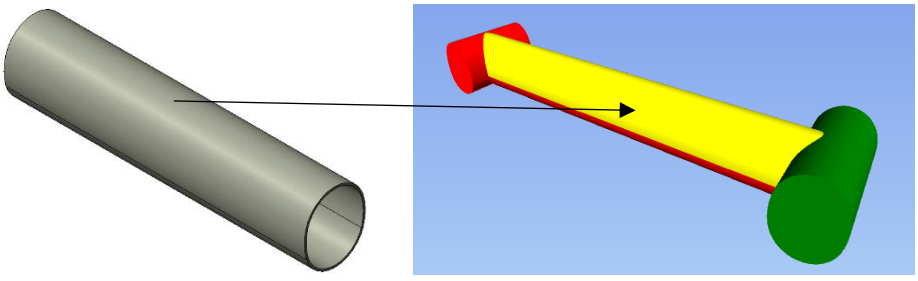


Figure 4.3 Coloring of 40 m Single Model Element

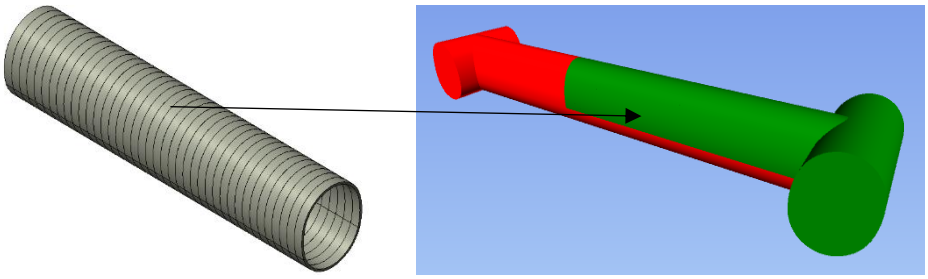


Figure 4.4 Coloring of 1 m Model Elements

Although it is suitable to model geotechnical tunnel elements in 1-meter pieces for 4D applications, no statement for applying such a method regarding the level of detail of geotechnical model elements has been found in any BIM-related document.

In order to examine the lengths of geotechnical tunnels more systematically, progress data obtained from the field were analyzed. For this purpose, geotechnical tunnel construction data included in a total of 65 consecutive progress reports submitted for progress tracking models were compiled. In this way, it is aimed to establish a relationship between the amount of construction in the field and the length of geotechnical tunnel elements. The average submission frequency of reports is 2 weeks, and this period may sometimes change depending on field conditions or public holidays. In general, it can be assumed that the analyzed progress data covers approximately 14 days of manufacturing process.

A total of 1161 geotechnical tunnel progress were recorded in 65 reports. The chart below shows the distribution of these progress data in meters (Figure 4.5). As can be seen from this graph, progress amounts are mostly in the range of 0-10 and 10-20 meters. The average of these recorded progress values is 14.8 meters. This means that an average of 14.8 meters of excavation is carried out in a tunnel in approximately 14 days. The maximum recorded construction amount is 112.7 meters, and the minimum is 0.23 meters.

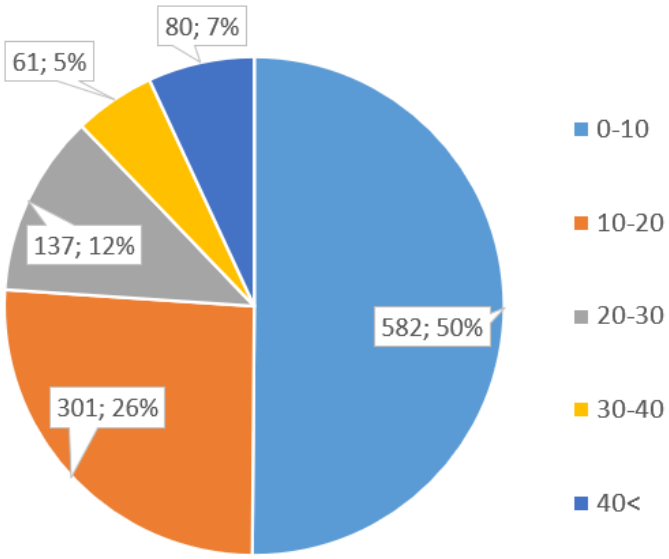
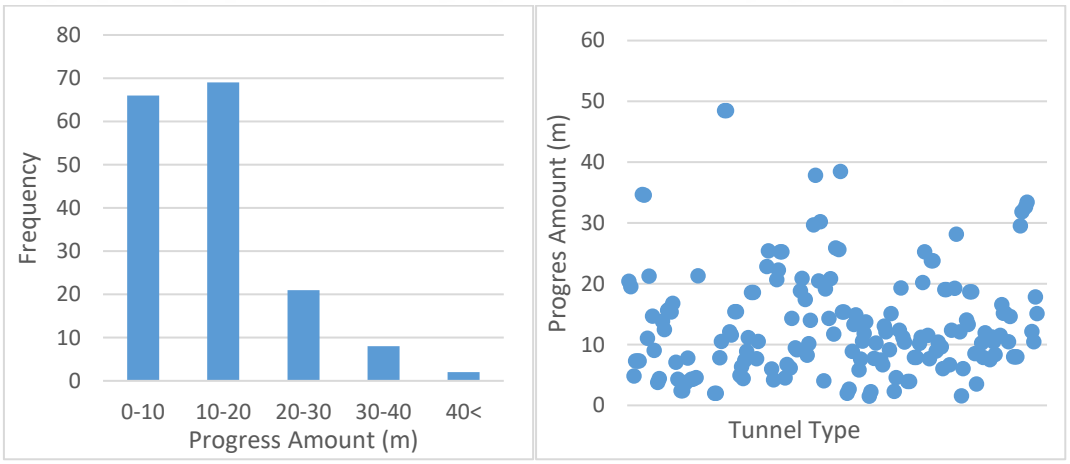


Figure 4.5 Distribution of Progress Data in meters

The graphs below show the distribution of average progress amounts for each tunnel type at each station (Figure 4.6). Similar to Figure 4.5, The distribution of progress amounts is concentrated around 0-20 meters, and the distribution are almost even for 0-10 and 10-20 meters.

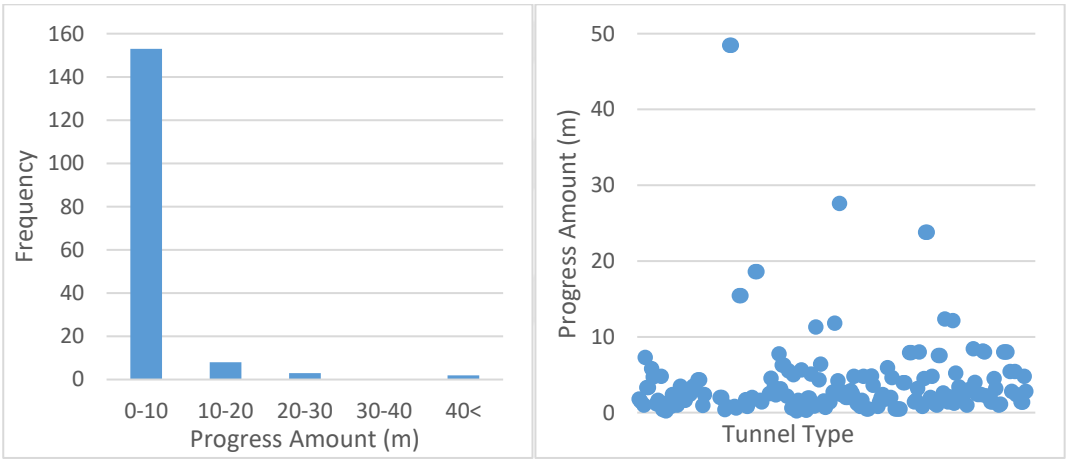


(a) (b)

Figure 4.6 Distribution of Average Progress Amounts: (a) Progress Amounts Frequency (b) Progress Amounts for Each Tunnel Type

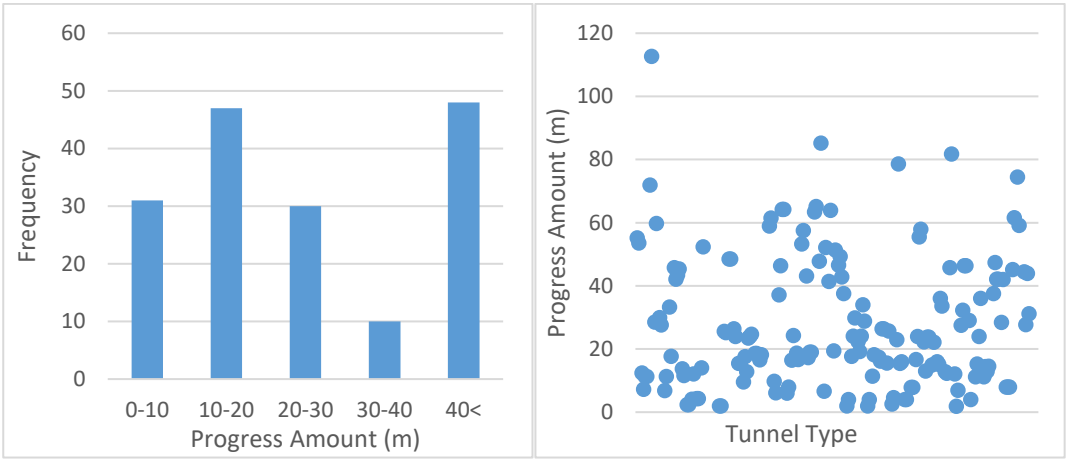
Considering the general average of the progress amount, which is 14.8 meters, it seems appropriate to model the tunnel elements as 10-meter pieces, but when the distribution graph of the average values is examined, it is observed that the

construction quantities are mostly between 0-10 meters. Construction progress cannot be shown in a precise way, if the tunnel elements are modeled with 10 meter length pieces. Moreover, the distribution of minimum values for construction amounts in Figure 4.7 indicates that the minimum construction amounts are mostly within the range of 0-10 and more specifically in 0-5, which means that there is at least 0-5 m amount of construction in majority of the tunnels. As for the maximum construction amounts, there is a varying distribution for each range, and there are maximum values within the range of 0-10m. As a result, it can stated that it is not convenient to have a model element longer than 10 meters.



(a) (b)

Figure 4.7 Distribution of Minimum Progress Amounts: (a) Progress Amounts Frequency (b) Progress Amounts for Each Tunnel Type



(a) (b)

Figure 4.8 Distribution of Maximum Progress Amounts for Each Tunnel

Moreover, the data included in the progress report covers the progress in all tunnels of a tunnel type within a station. For example, a tunnel with type B section can be used in four different tunnels in one station, and in this report the progress amount is given cumulatively, covering the progress in four tunnels. From this it can be inferred that the average progress amount can be expected to be slightly lower for each tunnel segment.

In addition to the amount of construction done on site, the tunnel designs should also be taken into account to determine the tunnel lengths. When the designs of the stations were examined, it was observed that there were tunnels that are 4-5 meters long.

As a result, based on the progress data and project design documents, it was concluded that it is appropriate to model the length of the geotechnical tunnel elements as 1-meter pieces in order to represent progress adequately.

4.1.2 Modeling Technique

In this project, only shotcrete lining model elements were included in the phase planning simulations and progress tracking models to represent the geotechnical construction of tunnels which are excavation, installation of shotcrete and installation of rock bolts. Shotcrete linings are the outer shell of the excavation boundary. When the excavation works of tunnel is completed, the connecting tunnels starts being excavated by breaking and removing the part of shotcrete at the connection point. Therefore, shotcrete lining elements are not continuous in the model as it is modelled by referring the final stage of the geotechnical construction (Figure 4.9).

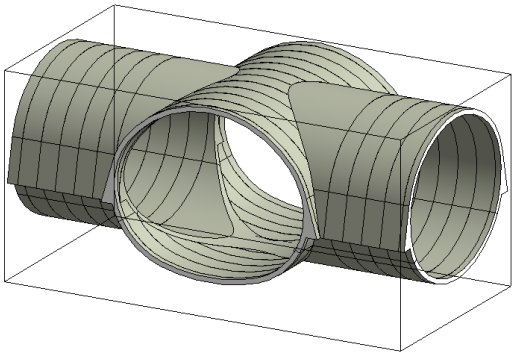


Figure 4.9 Final Stage of the Tunnel Connection

Discontinuity in the model elements results in incorrect visualization of the excavation works (Figure 4.10). In practice, excavation of tunnel should be continuous at the connection of tunnels.

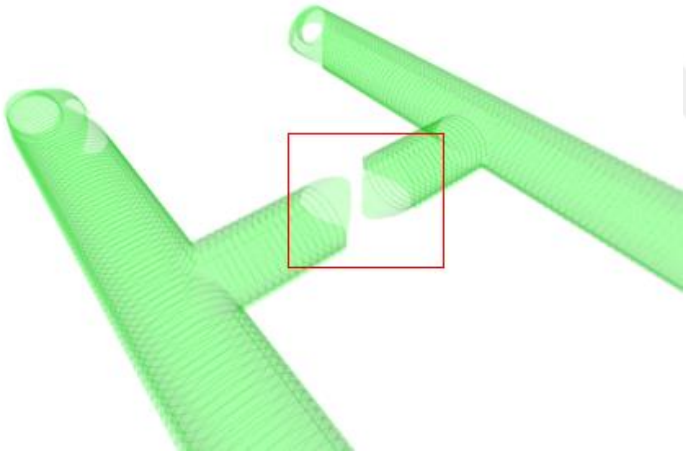


Figure 4.10 Screenshot of the Problem in the Simulation

Including excavation elements in the phase planning simulation instead of shotcrete lining elements can solve this problem. Excavation elements do not have any alteration in the geometric form during the construction of the tunnels. For this reason, they can be used to represent the geotechnical construction of the tunnels. However, when the excavation elements are inspected, it was realized that they are not generally modelled by considering the construction order of tunnels i.e., project schedule. In terms of construction logic, if a tunnel is excavated before the other

tunnels connecting to it, excavation elements of this tunnel should be continuous, and the other tunnels should be partially divided by the tunnel (Figure 4.12).

If excavation elements were to be used for the issue demonstrated in Figure 4.10, this would be wrong visualization of excavation because excavation elements of B6-201 tunnel, which is excavated after B3-101 is finished, is continuous and divides B3-101 into two pieces (Figure 4.11). On the contrary, B3-101 should be continuous and there should be a hole in B6-201 as shown in Figure 4.12.

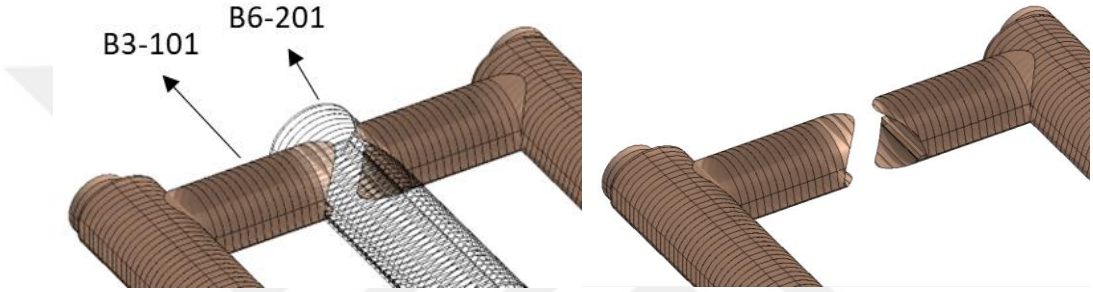


Figure 4.11 Modeling Example Incompatible with Project Schedule

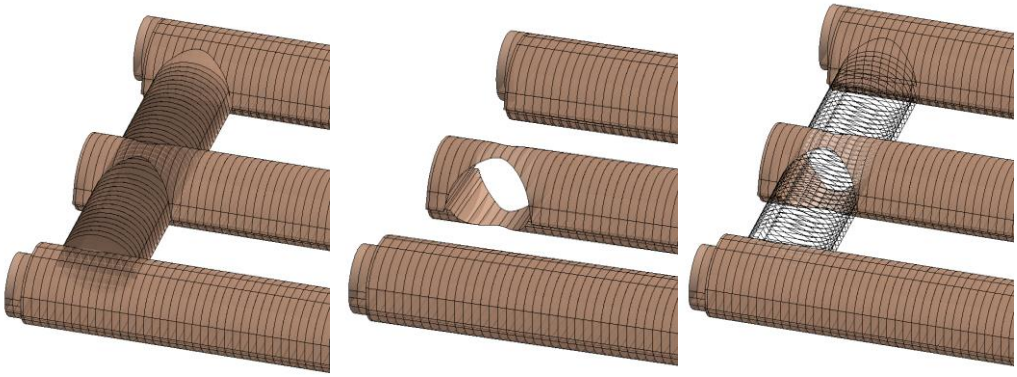


Figure 4.12 Modeling Example Compatible with Project Schedule

This causes a problem for the progress tracking model as well. There are no excavation model elements regarding B3-101 tunnel at the connection of B3-101 and B6-201 if it is not modelled according to construction order. Since there are no such elements, progress information cannot be inserted, and the progression of B3-101 excavation cannot be shown in the progress tracking models.

4.2 Project Schedule

In this section, problems indicated in the phase planning reports within the scope of phase planning simulation controls will be discussed.

Phase planning simulation controls were performed based on certain predefined rules. These rules are determined by considering the concepts of metro construction methods. The main rules taken into account in the simulation controls are listed below:

- Structural construction of tunnels, shafts and other underground structures must start after geotechnical works are completed/started.
- For the excavation and shoring of NATM tunnels, top part is completed first, then the bottom part is completed.
- For the construction of NATM tunnels, invert concrete (bottom part) is completed first, then arch concrete (top part) is completed.
- On the platform level of the stations, NATM construction of invert concrete in the parts where TBM passes through must be completed before TBM reaches that station.
- In order to start excavation of NATM tunnels, these tunnels must have a connection to shafts or tunnels.

In the phase planning simulation reports, total of 74 issues were reported, and it is observed that there are three main reasons for the issues related to relationship between project schedule and BIM models. Figure 4.13 shows the distribution of main reasons of the issues which are the detail level of project schedule, errors in the project schedule and minor modeling mistakes. Modeling mistakes were not discussed because they are simple errors related to BIM models that are not relevant to project schedule.

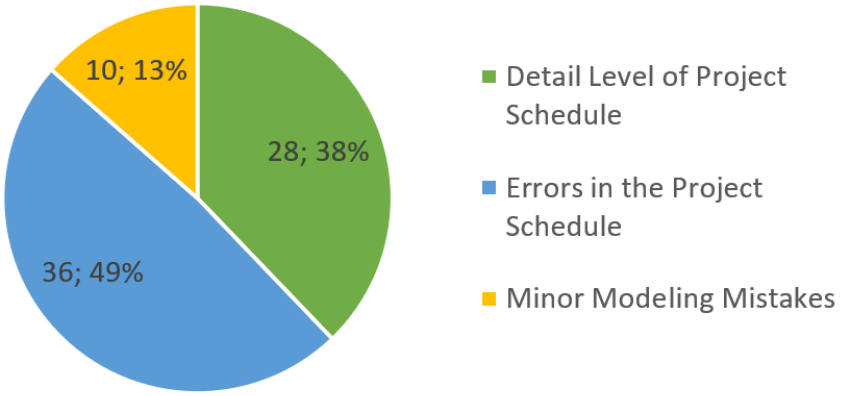


Figure 4.13 Cause of Issues in Phase Planning Simulations

4.2.1 Detail Level of Project Schedule

Among 74 detected issues, 28 (38%) of them are caused due to inadequate detail level of project schedule, i.e., lack of activities defined in project schedule meaning that there is no matching activity for the particular set of model elements to be defined. At first, these issues were tried to be solved by assigning higher level activity to the model elements with no matching activity. Higher level activity is a general activity that contains sub-activities. For example, higher level activity covers a specific type of NATM tunnels to be constructed in a station, while sub-activities included in that general activity covers this specific type of NATM tunnels to be constructed in the different parts of the station. In Table 4.1, there is a main activity called “B3 Type Tunnel Excavation Works” and five sub-activities for the same tunnel type in different parts of the station. It can be seen that the time information (start and end date) of the general activity represents the whole construction period of this specific type of tunnel; therefore, it is dependent on the sub activities. It is evident that assigning higher level activity can cause inconsistencies in the simulation because the start and end dates of this activity are too generic for a specific activity, thus causing the simulation not to reflect the real case.

Table 4.1 Sample for Activity Breakdown

WBS	Activity Name	Planned Start Date	Planned End Date
02.1.15.4.9.1.3	B3 Type Tunnel Excavation Works	13.04.2021	28.05.2023
02.1.15.4.9.1.3.1	B3 Type Tunnel Excavation Works (B3-201)	13.04.2021	25.06.2021
02.1.15.4.9.1.3.2	B3 Type Tunnel Excavation Works (B3-202)	4.09.2021	12.02.2023
02.1.15.4.9.1.3.3	B3 Type Tunnel Excavation Works (B3-203)	19.06.2021	28.05.2023
02.1.15.4.9.1.3.4	B3 Type Tunnel Excavation Works (B3-204)	6.07.2021	19.10.2021
02.1.15.4.9.1.3.5	B3 Type Tunnel Excavation Works (B3-205)	21.07.2021	9.12.2021

For example, construction activities for tunnels with marks B1-204 and B1-205 were not included in the project schedule (Figure 4.14). These tunnels were assigned to "B1 Type Tunnel Construction" which is the higher-level activity for B1 tunnels. Such activity assignment resulted in these two tunnels to be constructed without any connection to other tunnels or shafts in 4D simulation, which is not possible in terms of constructability (Figure 4.15).

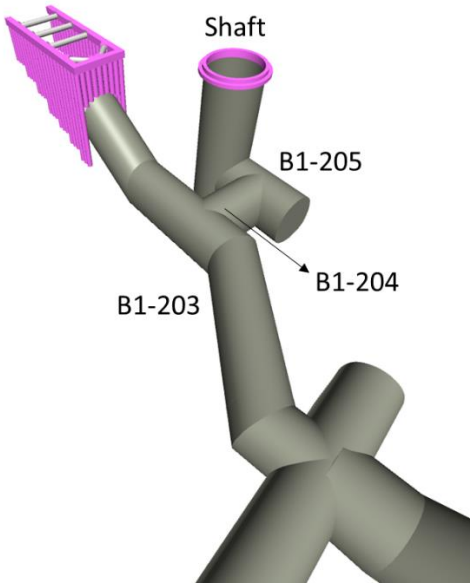


Figure 4.14 Screenshot of the Tunnel Model

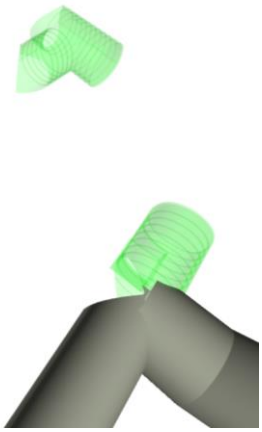
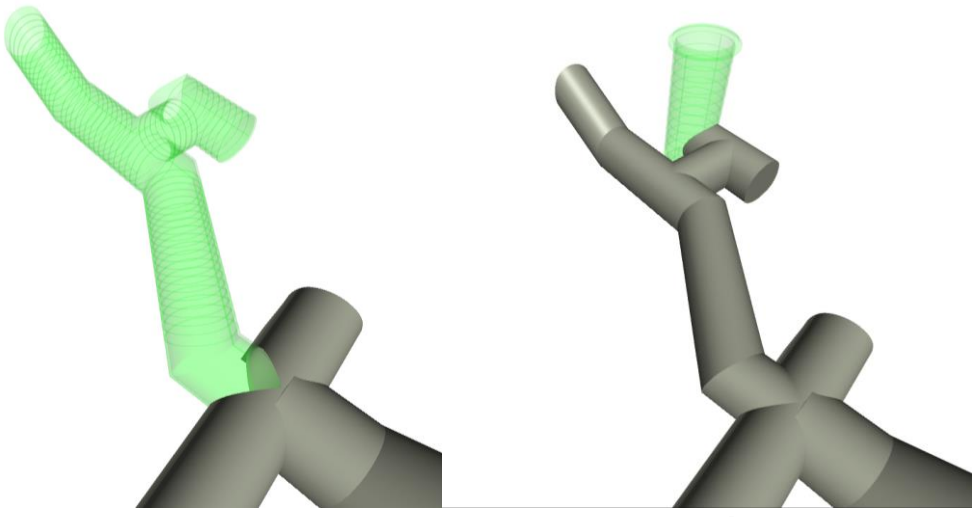


Figure 4.15 Screenshot of the Simulation Before Revision

In order to solve these issues, different activities were assigned to model elements so that the phase planning simulation is consistent with the construction logic. In general, model elements with no specific activities are assigned to adjacent structure activities. In the example case, the planner confirmed that excavations of B1-204 and B1-205 are to be started when the excavation progression reaches the junction between B1-203 and B1-204. Therefore, excavation works of B1-204 and B1-205 are assigned to activity of B1-203 excavation works so that these three tunnels start and end simultaneously in the simulation (Figure 4.16).



(a) (b)

Figure 4.16 Screenshots of the Simulation After Revision: (a) Tunnel Construction (b) Shaft Construction

Although in the simulation the problem seems to be solved after such assignment, other potential problems may be missed because the start and end date of construction works for these two tunnels does not reflect the reality. These dates belong construction of the B1-203. Such assignments were done in order to solve the problem for the time being. Later, the project schedule was revised progressively according to feedback from the phase planning report, and once the missing activities were added to the project schedule, they were assigned to corresponding model elements. As for the example case, construction activities for B1-204 and B1-205 tunnels were added to project schedule and assigned to the model elements. By this way, model elements with no matching activity have relevant start and end dates for the construction.

Another example of this type of issue is caused by the activities regarding the construction of slabs, columns and walls inside the tunnels which were not yet included in the project schedule. Assigning to higher-level activity or different activity did not solve the problem because there is no such activity that shows a proper sequence for the construction of these structures as they are constructed way after the construction of tunnels. For this reason, model elements of these structures were excluded from the simulation until relevant activities were added to project schedule.

Last example is the activities related to removal of shoring items. After the excavation is completed, some of the shoring elements are removed because they are not required anymore. In the example case, struts and bracing beams are removed before the structural construction of entry-exit structure. Since there is no specific activity regarding the removal of these shoring items, they do not disappear in the simulation although they are actually removed on the site. This results in views of clashing shoring items and structural elements which is not the real case (Figure 4.17). Moreover, the removal of shoring items can be crucial to structural construction of entry-exit structure in terms of construction sequence. The problem can be prevented by having a separate construction activity regarding the removal of shoring items in the project schedule. By this way, related shoring items disappear

in the simulation at the time when it is planned to be removed before the structural construction.

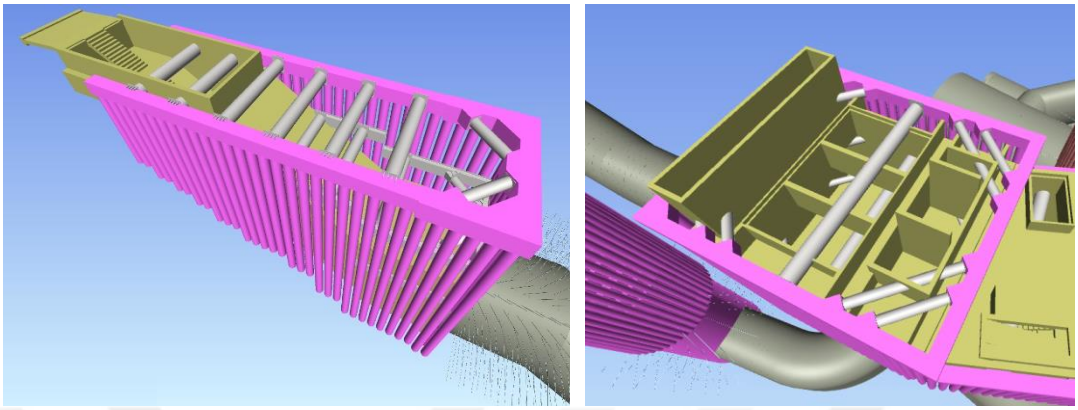


Figure 4.17 Screenshots of the Clashing Items

4.2.2 Schedule Errors

36 (%49) out of 74 the detected issues are related to errors in the project schedule, and there can be various reasons behind it. Kandregula and Le (2020) stated that it is essential to detect the reasons for human errors in 4D modeling and taking precautions against these errors. Findings in their research indicate that some of the activities most prone to human error are identifying the activities of the project, setting logics/dependencies between activities, and estimating the durations of the activities. Top three causes of these human errors are reported to be knowledge shortage, complexity of the project, incorrect information from stakeholders. Considering that the metro projects are complex in their nature, it is unavoidable that these mistakes are most likely to occur while preparing the project schedule. As a result, faulty project schedule leads to faulty 4D simulations.

When the project schedule was checked, some of the activity relations are not compatible with the design of the project which leads to unconstructable sequences in the simulation. Moreover, while some activity relations seem appropriate at first look, they are not appropriate if other relevant activities are taken into account in terms of construction logic when checking the sequences in 4D simulation.

As an example, detected problem for the tunnels in Figure 4.18 is explained.

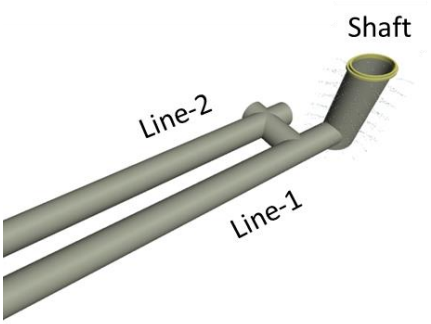
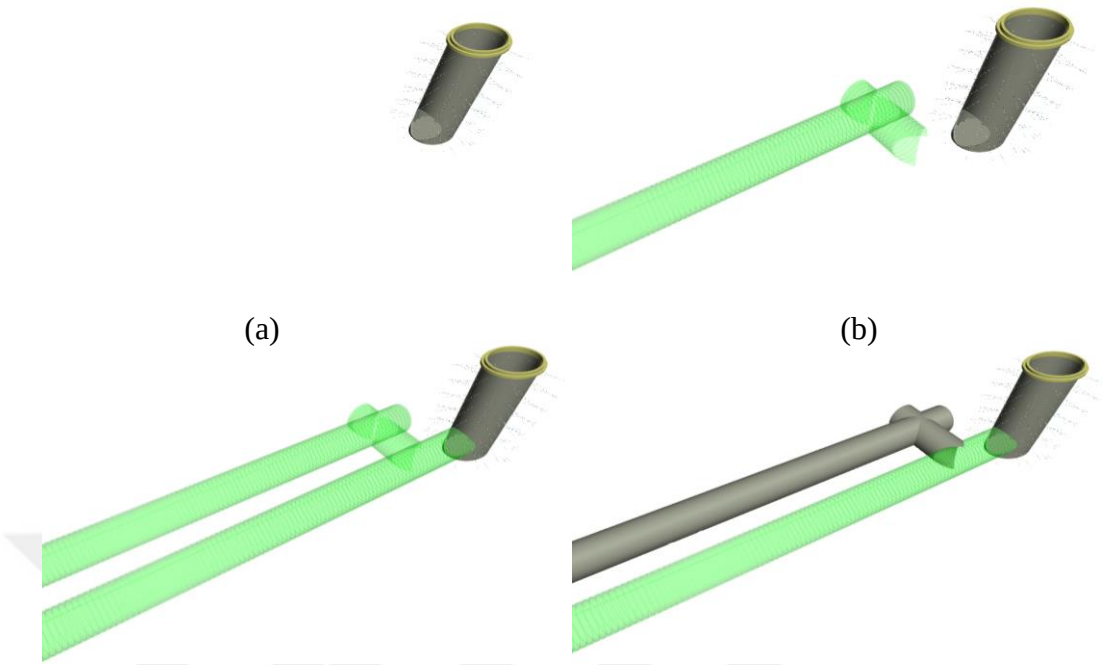


Figure 4.18 Screenshot of the Tunnel and Shaft Model

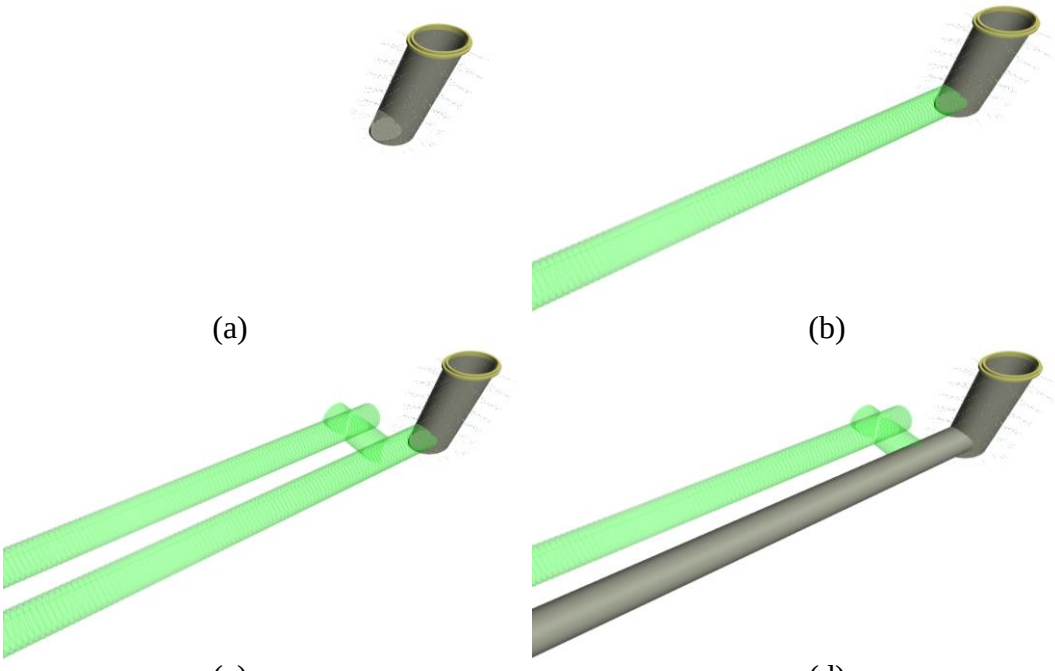
In the schedule, construction shaft is opened at first. Then the excavation of NATM tunnels is proceeded along two lines called Line-1 and Line-2. Line-1 is directly connected to construction shaft, and Line-2 is derived from Line-1 as seen in Figure 4.20. Logically, Line-1 must be excavated first, so that excavation works for Line-2 can start. However, the construction sequence is opposite of the real case in 4D simulation. Line-2 excavation starts without any connection to shaft, then Line-1 starts (Figure 4.19). This problem occurred due to incorrect start and end dates of the related activities for these model elements. In the project schedule, relationship between the excavation works of Line-1 and Line-2 were not defined properly. For this reason, project schedule had to be revised to solve the issue. After the revision of project schedule, excavation of Line-1 starts before Line-2 as it is supposed to be (Figure 4.20).



(a) (b)

(c) (d)

Figure 4.19 Screenshots from the Simulation Before Revision: (a) Constructed Shaft (b) Line 2 Construction Starts (c) Line 1 Construction Starts (d) Line 2 Construction Ends



(a) (b)

(c) (d)

Figure 4.20 Screenshots from the Simulation After Revision: (a) Constructed Shaft (b) Line 1 Construction Start (c) Line 2 Construction Starts (d) Line 1 Construction Ends

According to the feedback on the phase planning report, project schedule had been revised, and then integrated with the BIM models to see if the problems are solved. Some of the revisions resulted in new problems in 4D simulations, which was reported again to revise the project schedule.

4.2.3 Additional Findings

There is also an additional finding other than the issues stated in the phase planning reports. Although there are three (concrete, formwork, reinforcement) activities related to construction of structural elements in the station, it was decided that only one (concrete) of them considered for the simulation of the project. When the project schedule is inspected, reinforcement activities do not separately cover each specific tunnel, unlike concrete and formwork activities. They rather cover parts of the station as a whole, such as platform tunnels, shafts, concourse tunnels, etc. Hence it is not reasonable to include reinforcement activities in the simulation because start and end dates would be too generic which is similar to assigning model elements higher-level activity case. The relationship between formwork and concrete is dependent on each other. It was observed that concrete pouring activities starts 3 days after the start of the formwork activity and ends 3 days after the end of formwork activity. When only concrete pouring activity is considered, 3 days of work before the concrete works will not be taken into account. These 3 days are vital for the simulation because there could be problems such as clashing activities or incorrect activity relations that would go undetected otherwise. As an example, activities and their planned dates are shown in Table 4.2.

Table 4.2 Example Activities and Their Planned Dates

Activity Name	Planned Start Date	Planned End Date
Platform Tunnel Invert Concrete LI 01	9.06.2023	23.06.2023
Platform Tunnel Invert Formwork LINE 01	6.06.2023	20.06.2023
Platform Tunnels Reinforcement	30.03.2023	20.06.2023

4.3 Progress Report

There are some incompatibilities with the geotechnical BIM model elements and the data stored in the progress report transmitted from the field. In general, the tunnel lengths included in the progress report do not match the lengths of the tunnel elements in the BIM models. For example, the length of the geotechnical construction of the B2-102 tunnel shown in Figure 4.21 is given as 10.45, but this length does not match the total length of the tunnel elements in the BIM model. This is because the reference to the tunnel length given in the progress report is not clear. As can be seen from the same image, the upper excavation works completed in the B2-101 tunnel is given as 6.40 m, but since it is not clear between which two points this length is, this construction amount data cannot be processed correctly into the BIM model element. These progress amounts transmitted from the field are measured according to the progress payment method in the field and it may be correct to serve this purpose. However, these data do not match the model elements, because the method of collecting the actual field data is not compatible with geotechnical BIM models. As a result, the progress in the field could not be accurately reflected in BIM models, relying solely on 2D visuals and numerical field data.

Furthermore, excavation works of B2-102 start from Line-1 and ends in Line-2 according to schedule plan, which means that the excavation elements should be continuous. However, in the progress report this tunnel is divided into two parts with lengths of 10.45 m. Such demonstration is not compatible with the actual case at the site.

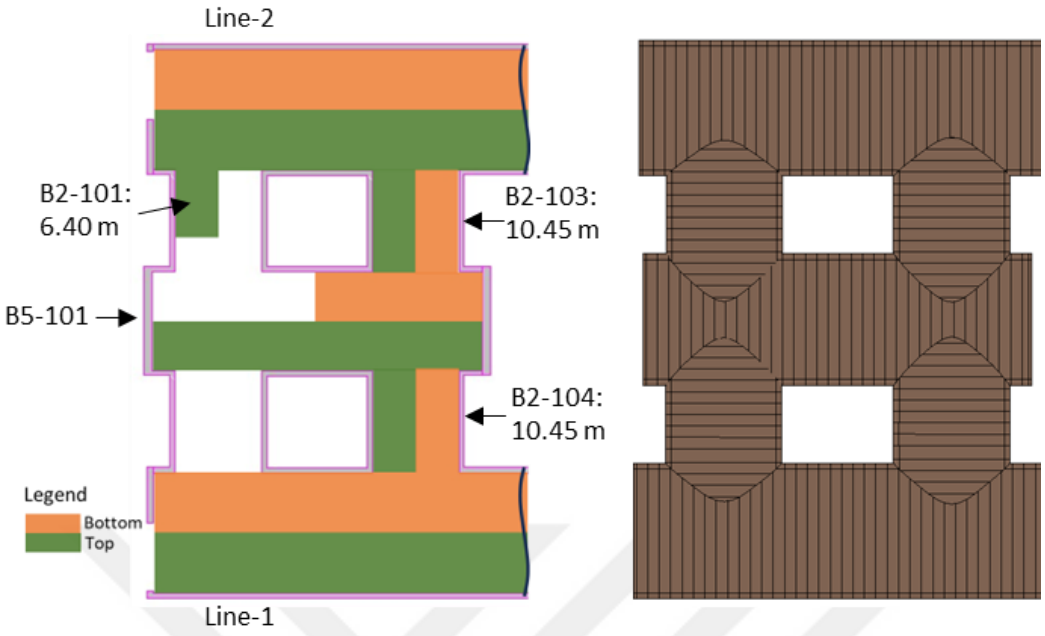


Figure 4.21 Plan view in Progress Report and Geotechnical BIM Model

This problem occurs in connection tunnels. Since the beginning and end of the main tunnels are exact, the data in the progress report can be processed correctly. On the other hand, connection tunnels are connected to the main tunnels, for this reason the starting and ending points of these tunnels are not like the main tunnels as can be seen from the Figure 4.22. Tunnels A and C are each main tunnel, and their length is 30 meters. Tunnel B is a connection tunnel between tunnels A and C. Geotechnical construction of tunnel B starts from tunnel A and ends in tunnel C. Unlike tunnel A and C, the length of tunnel B is not exact as it is defined based on the distance between connection points from A to C, and it can be given approximately.

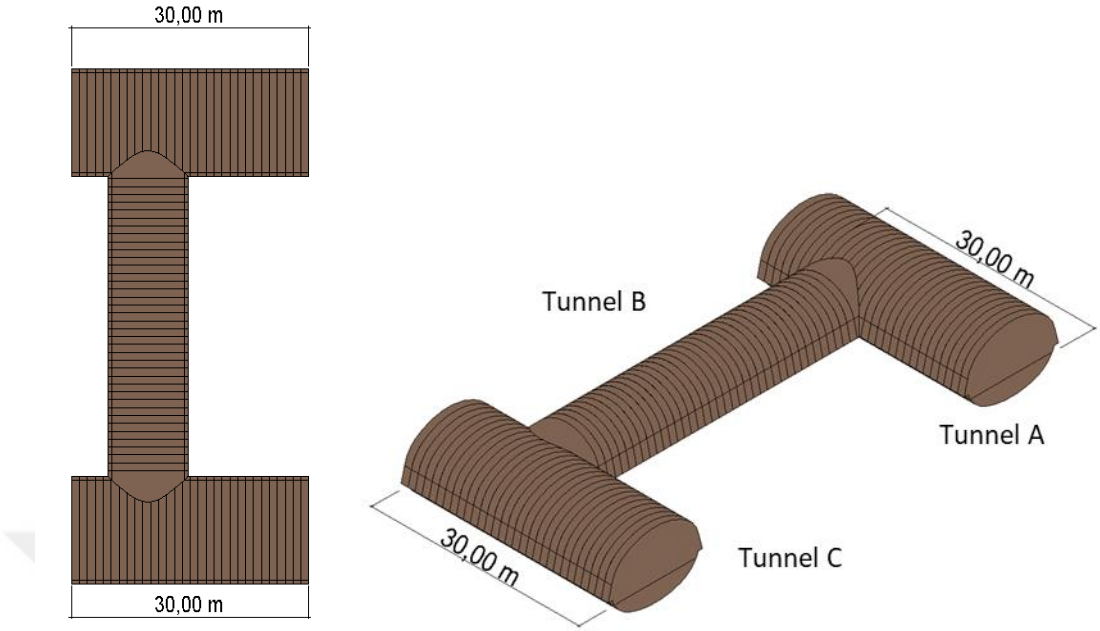


Figure 4.22 Geotechnical Tunnel Elements

Inconsistency between progress data gathered on site and BIM models could be prevented if the method of collecting data would be BIM model based. Having 1-meter model elements become quite useful for this task. Indication of which elements are completed, and which elements are in progress with the percentage in the progress report can facilitate the process of inserting progress information into the BIM model elements, thus leaving no room for errors and inconsistencies in progress tracking models. With the consistent data in BIM model elements, the progress on site can be visualized in a correct way.

As for the structural BIM model elements, there is no such inconsistency in the progress data. Structural tunnel components are constructed part by part based on the design documents unlike geotechnical components being continuous as already explained in the previous sections. In Figure 4.23, each part in the document is also a model element. Therefore, it is straightforward to indicate which structural components are constructed, and the progress on site can be easily matched with the BIM model elements.

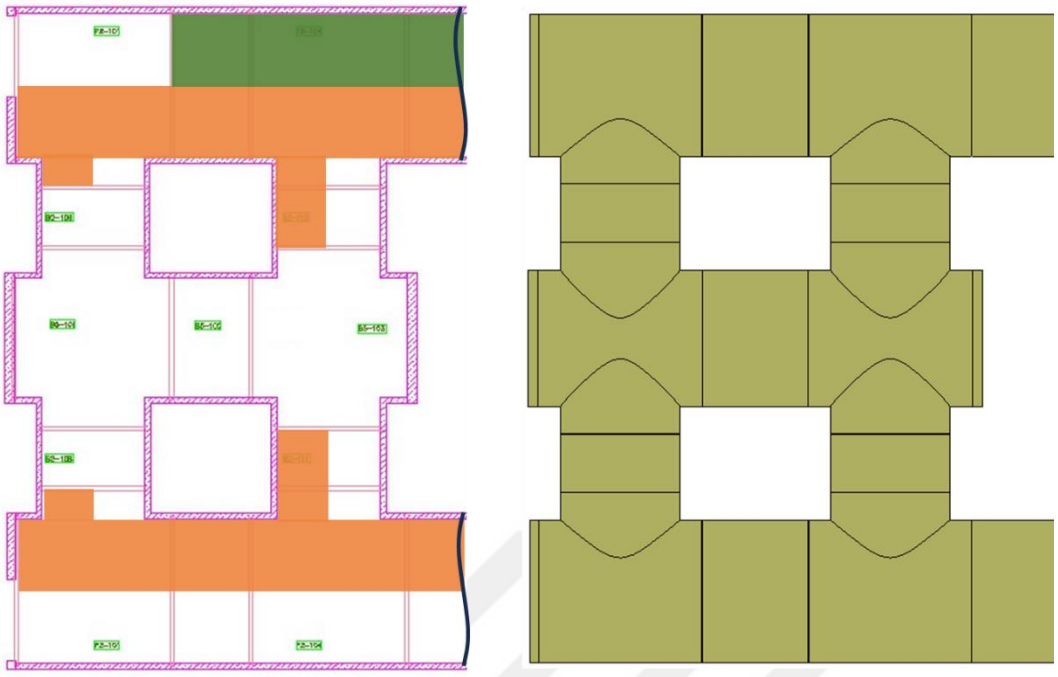


Figure 4.23 Plan view of Progress Report and Structural BIM Model

CHAPTER 5

BIM-BASED CONSTRUCTION PLANNING AND SIMULATION FRAMEWORK

In this chapter, BIM-based construction planning and simulation framework is described based on the categorized findings in CHAPTER 4. Topics that will be addressed are summarized in Figure 5.1

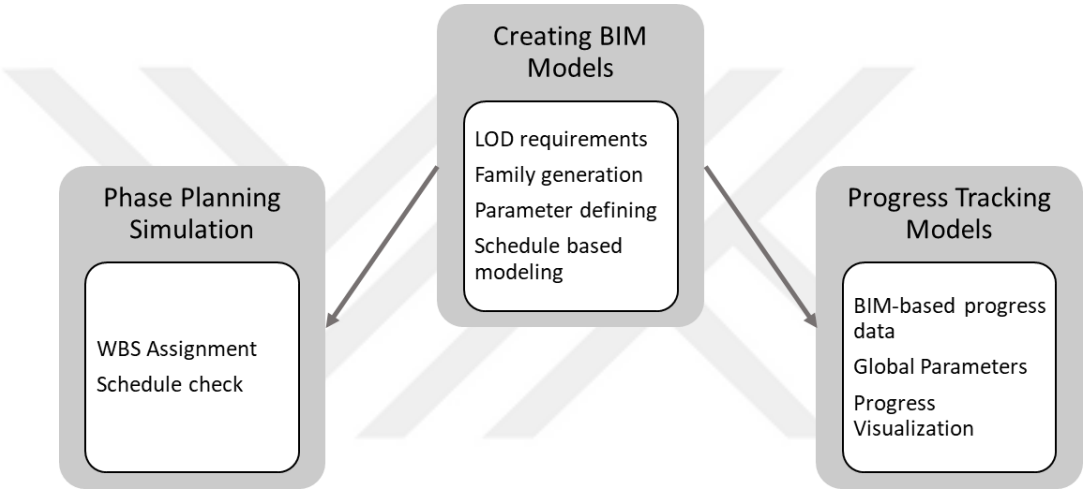


Figure 5.1 Summary of Topics

The purpose of BIM-based construction planning and simulation framework is to produce standardized phase planning simulation and progress tracking model which are well integrated with actual site data and construction schedule. The framework is demonstrated in Figure 5.2. The underlined bold statements are the improvement propositions indicated within the framework. In the following sections, these propositions will be explained in detail.

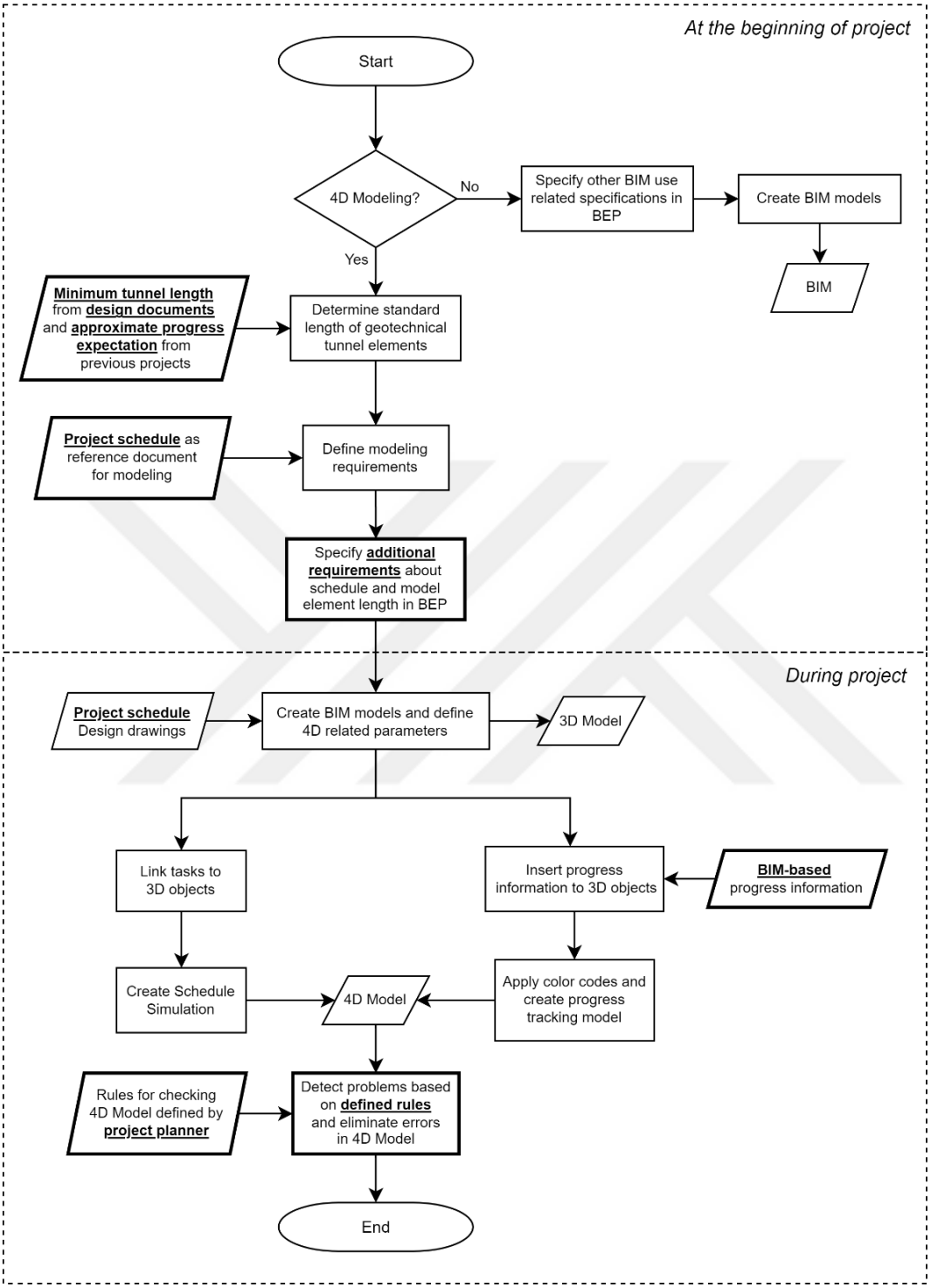


Figure 5.2 Proposed process of BIM-based Scheduling and Construction Planning

5.1 Creating BIM models

Determining model requirements is the first step to consider prior to creating BIM models. BEP includes most of the details regarding the BIM models, however there should be additional requirements to achieve proper 4D and progress tracking models.

5.1.1 Model Detail

Most of the model elements have a geometric detail of LOD300 in construction phase, and since progress tracking models are produced during the construction phase, LOD300 is sufficient to have a precise model for 4D modeling and progress tracking models. BIM software mostly supports building project and there are no built-in families for the tunnel components. Therefore, these families should be created once the tunnel sections are designed. By referring to cross section details, families are created for each part of (i.e., arch, invert) each different tunnel type. Created families should be editable via changing the parameters (length, slope etc.) so that these families can be repeatedly used for different design alternatives. Metro projects have multiple sites on distinct locations meaning that there will be multiple BIM (projects) models created for each station, lines and other auxiliary structures. It is quite important that all these BIM models are consistent with each other by obeying the regulations. Created families should follow the same naming convention and they should be stored and managed properly. Stored families should be utilized in BIM models. Every tunnel segment in structural and geotechnical model should be separately modelled based on the design documents. For geotechnical elements, there is no specific length in the design documents due to the continuous nature of geotechnical construction. Geotechnical construction is considered as a whole for the tunnels. Therefore, geotechnical items can be modeled as a single model object for each tunnel. Although, modeling single model objects for each tunnel does not violate LOD300 requirements, it is not adequate to have precise information

regarding the progress. If the whole tunnel is modeled as one single geotechnical model element, the progress status of this model element would be “in-progress” until the geotechnical construction of the whole tunnel is completed. Hence, the which parts of the tunnel is actually excavated could not be precisely indicated in the progress tracking models. Therefore, the length of the geotechnical elements regarding the tunnels should be standardized at before starting modeling. To determine the length of tunnel elements, construction progress amounts and project design documents should be examined. However, it will not be possible to examine construction progress amounts since construction will not have started while modeling requirements are determined. For this reason, analysis of progress report values obtained from the case study project can be taken as reference while keeping in mind that these values can change depending on the project characteristics. In addition, approximate progress expectation can be estimated from the previous project values as well. In the case study project, 1-meter length pieces are observed to be suitable for having precise progress information and visualization. Decreasing the length would result in more accurate model, but the workload increases as the density of model also increases, so the accuracy of model should be optimal for the applications. If BIM models are to be used for 4D applications, such standardizations regarding the detail level of model elements should definitely be included in BIM execution plan (BEP). Including the standardization of model elements in the BEP ensures that the process of creating BIM models for 4D applications is managed in an accurate and systematic way. Examples for the created tunnel families are shown in Figure 5.3.

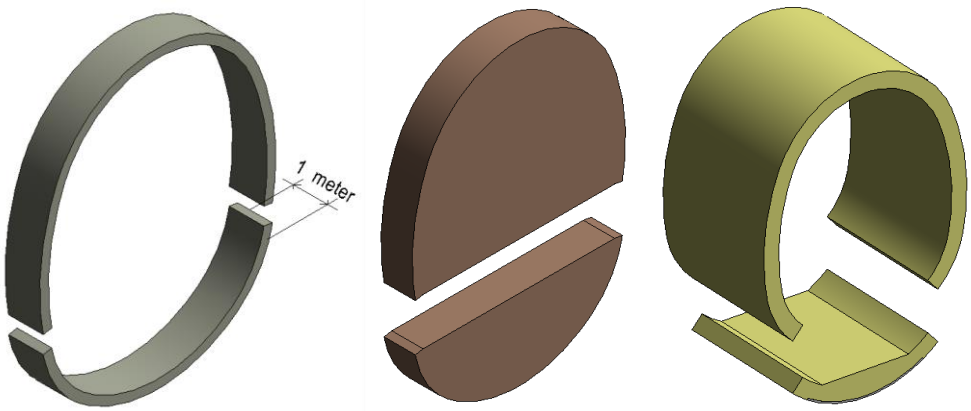


Figure 5.3 Sample Images for Shotcrete, Excavation and Structural elements

Upon creating families, parameters to be used for phase planning simulations and progress tracking models are defined. These parameters should be uniform across all the BIM models in the project. This can be achieved by using “shared parameters” in the Revit software. Shared parameter is a parameter type that can be used in multiple families or models. Shared parameter definitions are created and stored as a file independent of family file or Revit projects. With the uniform parameters across all the BIM models, necessary information can be contained in these parameters to be used for creating 4D models (Figure 5.4).

Construction	
Completed Amount "m"	0.600000
Completed Percentage "%"	60.000000
Cumulative Completed Amount "m"	19.200000
Cumulative Completed Percentage "%"	40.000000
Progress "Y/N"	☑
Progress Status	I/P
Project Amount "m"	48.000000
WBS_1	4.11.6.4.1.7.3.1.1
WBS_2	4.11.6.4.1.6.3.1.1
WBS_3	4.11.6.4.1.5.1

Figure 5.4 Sample Parameters for a Shotcrete Element

5.1.2 Modeling Technique

According to examples in section 4.1.2, it is evident further details regarding the way of modeling is required. Observations have indicated that modeling technique have an impact on both phase planning simulations and progress tracking models. When BIM elements are not created in accordance with the actual construction sequence, there are disconnections within the model elements of tunnels and shafts which is not the real case on site. Disconnections are caused by the connecting tunnels crossing the main excavation tunnel. In other words, connecting tunnels are excavated once the excavation of main tunnel is completed up to junction point and for this reason connecting tunnels cannot divide the geometrical form of the main tunnel. Model elements of main tunnel should be continuous in the phase planning simulation. Furthermore, if the connecting tunnel divides the main tunnel, the model elements of main tunnel would be absent at the junction point. Since the main tunnel is excavated initially, the progress information should be available in the model elements of main tunnel at the junction point. While the model elements are absent, progress could not be represented properly. In order to decide which tunnel is the connecting tunnel and or the main tunnel, excavation order of these tunnels should be examined before modeling. Excavation order can be examined from project schedule by comparing the start and finish dates of excavation activities of tunnels. Once the main tunnels and connecting tunnels are determined, model elements at the junction points can be created in the correct form. It should be noted that the main tunnel and connecting tunnel relationship is specific to each pair of tunnels. The tunnel determined as the connecting tunnel on a junction can be the main tunnel on another junction which is a natural outcome of the tunnel network.

If BIM models are to be used for such applications, its references must definitely include project schedule plan in addition to design documents, and this should be stated in the BEP documents. Models are created in compliance with the construction sequence because it is essential to have a model that is consistent with the actual site conditions.

5.2 Phase Planning Simulation

After creating BIM models, WBS codes of construction activities included in the established schedule are assigned to related parameters of model elements based on the activity definitions. Every construction activity that has a corresponding construction value should be assigned to model elements, and these model elements are included in the phase planning simulations. Both structural and geotechnical related items should be displayed in the simulation because these two types of construction are related to each other, and the examination of their relation is essential to detect problems on site beforehand and optimize the schedule. Depending on the project characteristics, geotechnical elements such as shotcrete items can be excluded in the phase planning simulations, instead excavation items can be considered, since these two items are generally represented by the same construction activity and the visibility in the simulation would be more consistent with the actual site conditions. A model element can have more than one corresponding construction activity such as concrete pouring, formwork placement and reinforcement for structural items. In this case, all the corresponding construction activities should also be taken into account because they have an impact on the construction sequence.

Assigning related construction activities should be performed in interaction with the planner who is responsible for establishing project schedule. If there is an unclear situation about which construction activity to assign to certain model elements, they should be assigned by the instruction and confirmation of the planner.

Detail level of project schedule is a key factor to obtain a phase planning simulation that accurately reflects the site. It is important to match every model element with the correct construction activity. For this reason, detail level of project schedule should be mature enough to create a proper phase planning simulation. Nonetheless, there can be some missing activities due to uncertainties in the design or other reasons. In such case, every model element may not have a corresponding construction activity defined in the project schedule. In order to solve this kind of

problems, different construction activities are assigned under certain assumptions considering the construction sequences with the approval of the project planner. It is vital that it should be avoided assigning higher level activities to model elements when there is no corresponding construction activity. Later in the project, when the missing construction items are added to project schedule, they are assigned to proper model elements. Moreover, specific construction activities that have an impact on the construction sequence in the phase planning simulation should also be included in the project schedule. Removal of shoring items such as struts and bracing beams is an example of this type of specific activities.

Once the necessary information for the phase planning simulations is defined in BIM models, 4D model is created by linking the construction activities in project schedule with the WBS information inserted into model elements. 4D model demonstrates the whole construction sequence, and it is used for detecting problems in both models and project schedule, and that is why control mechanism is essential part of 4D modeling.

Checking project schedule via phase planning simulation on regular basis have great benefits that traditional methods such as Gantt Chart and 2D CAD drawings could not provide. Having a graphical representation of project schedule enhances the controls in terms of efficiency and accuracy. These controls should be performed based on certain rules which are defined before starting the control of 4D model. Rules are defined by considering the construction sequences. Rules can contain basic concepts such as listed below.

- For the construction of NATM tunnels, invert concrete (bottom part) is completed first, then arch concrete (top part) is completed.
- On the platform level of the stations, NATM construction of invert concrete in the parts where TBM passes through must be completed before TBM reaches that station.
- In order to start excavation of NATM tunnels, they must have a connection to shafts or tunnels.

Also, they can contain more specific rules that should be paid attention to if it is crucial for the construction sequence. An expert planner must guide while defining these check rules. Detected problems are categorized based on their estimated source of error and explained in a report. Then, the report submitted for the feedback of the planner. Problems are eliminated by revising project schedule and BIM models. Once the revisions are done, controls are performed again to check if there is a new occurrence of problems. This process is repeated until all the problems are solved. By this way, phase planning simulations become mature enough to show proper construction sequence of the metro projects.

5.3 Progress Tracking Models

Progress tracking models are created within a frequency which is stated in the BEP documents. Although this frequency may vary depending on the project characteristics, it is usually 2 weeks. During this period, construction progress on site is captured and reported. There are various methods to gather data on site and store them in pictures, daily report, weekly report etc. Examination of the project has indicated that, excluding BIM models while gathering the data leads to incompatibility between the progress information and BIM models. For this reason, using solely 2D images and progress values is not a proper approach for creating progress tracking models. BIM models should be taken into consideration while gathering progress information, and this progress information are inserted into related parameters of BIM model elements. Progress tracking models contain various information for various uses. These parameters are defined in BEP at the beginning of creating progress tracking models (Table 5.1).

Table 5.1 List of Progress Tracking Parameters

Parameter Name	**Description**
Progress Status	Construction status that shows whether the model element is completed (C) or in progress (I/P)
Completed Amount	Completion amount of model element
Completion Percentage "%"	Percentage of completion of model element
Project Amount	Total project amount of model elements.
Cumulative Completion Amount	Total completion amount of model elements
Cumulative Completion Percentage "%"	Completion percentage of model elements based on total completion and project amount
Production No	Indicates what period it was constructed

Autodesk Revit has a parameter type called "Global Parameters" which can improve the processing of progress data in a timely and efficient manner. Global parameters are created specific to a BIM model, and they hold simple values that can be used to establish parametric relationships in a model. Global parameters can be used to control and edit many model elements at one time instead of selecting all elements one by one and editing parameter values which can be quite useful considering that there can be thousands of model elements contained in a BIM model. Global parameters can be defined per tunnel, and they can be attached to progress tracking parameters of related model elements. Global parameters are suitable for the parameters created for cumulative progress. They cannot be applied to parameters such as "progress status" and "completed percentage" since they are defined individually for model elements. For instance, in order to collectively enter data regarding the excavation of the upper part of a tunnel, global parameters with a descriptive name must first be created and matched with the parameters related to the cumulative progress of these tunnel elements (Figure 5.5). The matching process is done only once before entering any progress data. After the global parameter matching is done, the cumulative progress data transmitted from the field is entered

through the relevant global parameters, and parameter values of all elements to which the global parameters are connected are edited at once (Figure 5.6). The value of the cumulative completion percentage can be formulated based on the cumulative completion amount and the project quantity and is automatically calculated when the cumulative completed amount is edited (Figure 5.5).

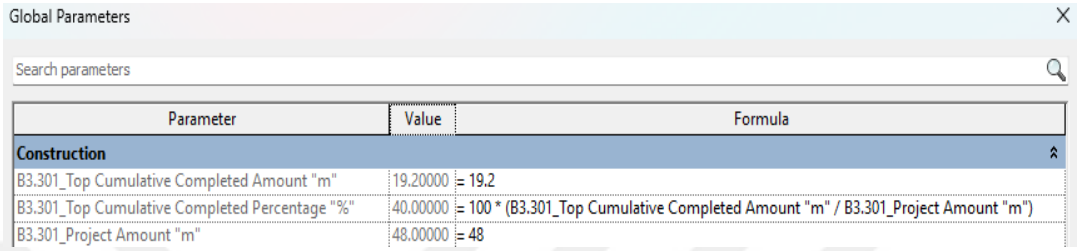


Figure 5.5 Defined Sample Global Parameter

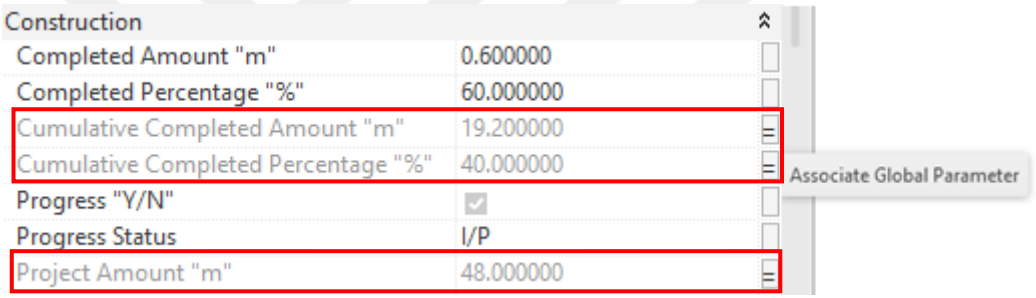


Figure 5.6 Matched Sample Global Parameter

After processing the progress data obtained from the field into the BIM model elements, the visualization of the progress in the field can be started. Visualization can be done with project review software such as Navisworks. These software tools provide the opportunity to work on the BIM models produced by other BIM authoring software. Tens of BIM models are produced in metro projects, and these produced models should be combined in a common model as the first step. For each model included in the combined model, viewpoints should be created for each discipline, specific to the stations, line structures and other auxiliary structures. After viewpoints are created, coloring is performed according to the progress status based on the information in the parameters of BIM model elements. With the help of the tool named as “Appearance Profiler” in Navisworks, rule-based coloring can be done

with ease. These rules are defined to match the data in the parameters. Sample rules used for coloring process of progress are given in Figure 5.7.

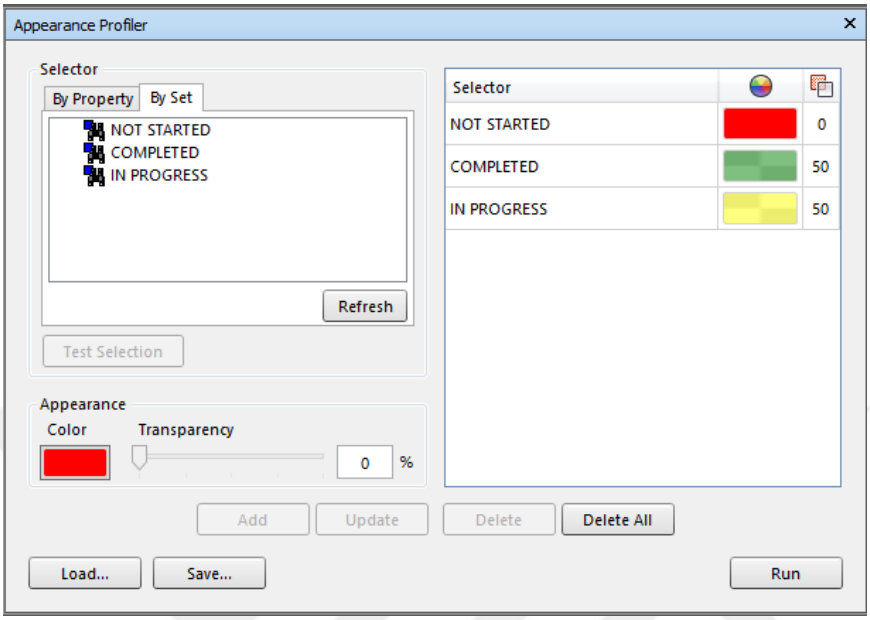


Figure 5.7 Sample Image for Rule-based Coloring

The green color represents the model elements whose construction works has been completed, and the progress status parameter is entered as "C" for these elements, that is, completed. The yellow color represents the model elements that are still under construction, and the progress status parameter is entered as "I/P" for these elements, that is, in progress. The red color represents model elements whose progress status parameter are neither "C" nor "I/P", and whose construction has not started yet. Sample colored model elements are given in Figure 5.8. Coloring configurations can be tweaked as desired to suit project requirements.

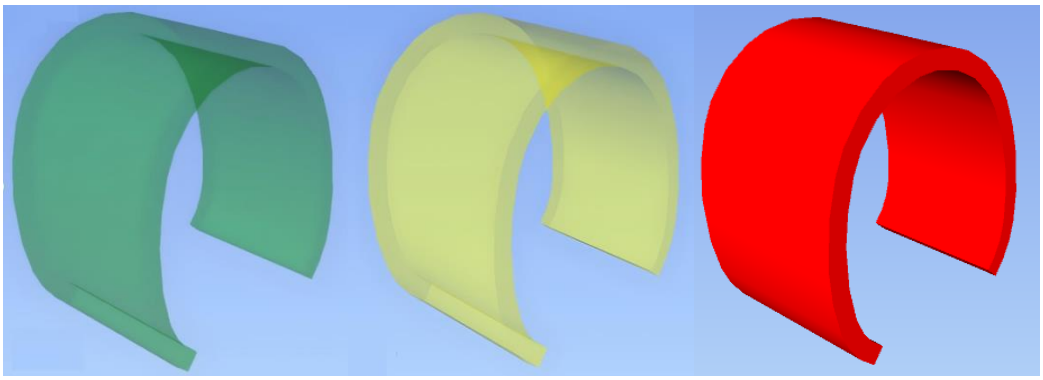


Figure 5.8 Sample Image for Model Element Coloring

In addition to visualizing the field progress by coloring it in Navisworks, progress on site can also be examined from numerical data contained in the parameters of these elements (Figure 5.9).

Property	Value
Progress "Y/N"	No
Completed Amount "m"	0.600
Completed Percentage "%"	60.000
Project Amount "m"	48.000
Cumulative Completed Amount "m"	19.200
Cumulative Completed Percentage "%"	40.000
Progress Status	I/P

Figure 5.9 Sample Image for the Parameters

CHAPTER 6

EXPERT ASSESSMENT

In this chapter, results regarding the assessment of the framework by experts via the conducted interview questionnaire are presented.

6.1 Demographic Information

According to the answers given to the questions in the first three sections of the questionnaire, the demographic information of the five respondents who participated in the interview is summarized in Table 6.1.

Table 6.1 General Information of the Respondents

Respondent	Profession	Company Position	Education Level	Experience
R1	Mechanical engineer	Consultant	Master's Degree	15-30
R2	Civil engineer	Design Engineer	Bachelor's Degree	1-5
R3	Civil engineer	Design Engineer	Master's Degree	1-5
R4	Civil engineer	Project Manager	Master's Degree	8-15
R5	Civil engineer	Design Engineer	Master's Degree	1-5

The respondents consist of one mechanical engineer and four civil engineers with varying educational level and experience in their professions. Respondents have distinct roles in the company they work for such as consultant, design engineer and project manager with varying perspectives.

6.2 Experience Details

Each respondent claimed to have decent knowledge and skills in BIM. The respondents' experience in BIM is shown in Figure 6.1

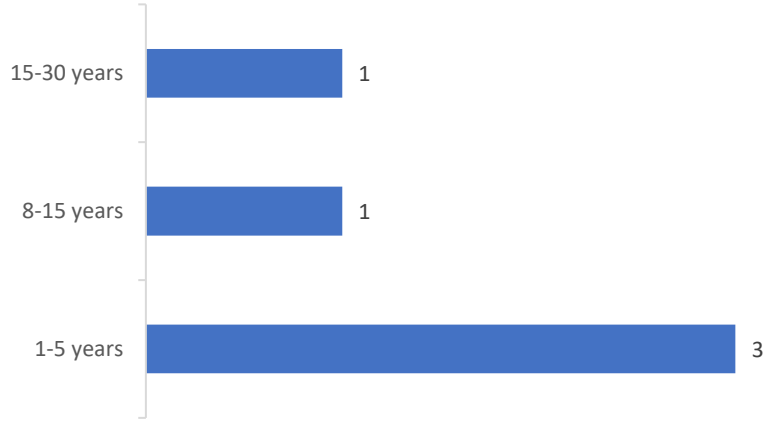


Figure 6.1 Respondents Experience in BIM

In addition to being experienced in BIM and its applications, each respondent is also familiar with at least Level 4 BIM applications in metro projects. Figure 6.2 shows how many people have experience with different software packages.

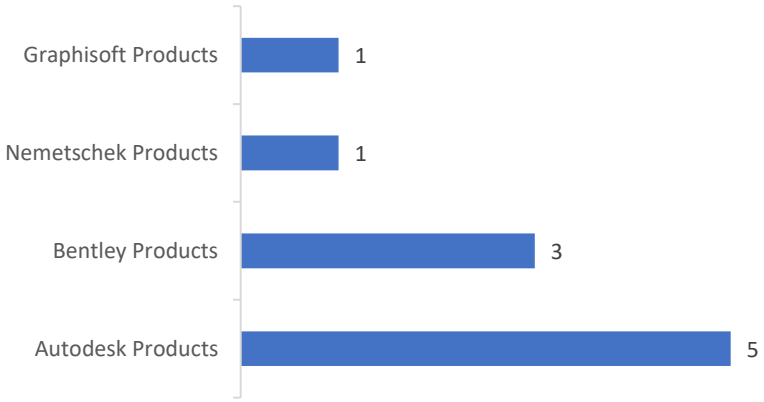


Figure 6.2 Respondents Experience in BIM Software Packages

As intended, companies that the respondents work for operate in distinct fields that are consultancy, construction and design (Figure 6.3). By this way, the goal of obtaining opinions of experts with different perspectives was achieved.

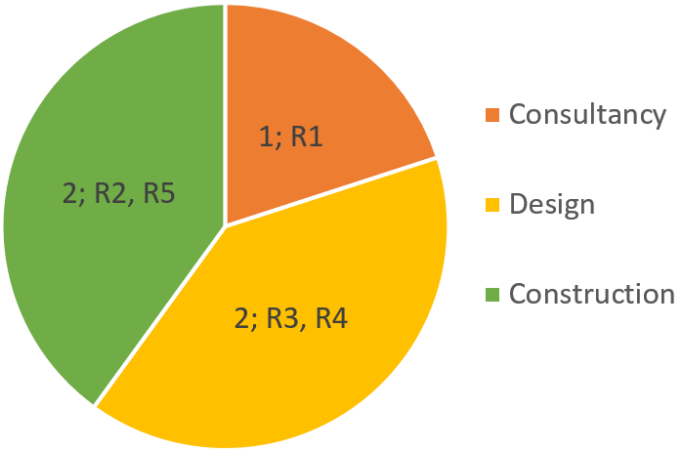


Figure 6.3 Distribution of Company Fields

Furthermore, the companies that the respondents work for are private and have a fair history and background with BIM in metro projects, each having quite number of professionals directly utilizing BIM. Three of the respondents have indicated that their company creates and uses Building Information Models at 5D level, while the other two respondents utilize BIM at 4D level. Moreover, all of the respondents indicated that Autodesk and Bentley products are mostly used in their companies.

6.3 Framework Evaluation Results

In this section, assessment results of the experts regarding the framework for BIM-based construction planning and simulation in underground metro projects is presented. Since there are only five respondents, the method of analyzing data regarding the rating of the listed items is not suitable for statistical analysis. For this reason, the rating of the listed items is presented on a respondent basis and the analysis was based on the respondents. In Table 6.2 and 6.3, respondents' ratings of the challenges and identified problems are given.

Table 6.2 Respondent Evaluation for Section 4

ID	Challenge Items (Section 4)	R1	R2	R3	R4	R5	Mean
C1	Lack of standardizations and guidelines for the detail level of BIM models (LOD)	2	4	5	5	4	4
C2	Lack of standardizations and guidelines for modeling technique of BIM objects to be compatible with construction logic	4	3	4	5	5	4,2
C3	Insufficient detail level of the project schedule (lack of activities in a schedule)	2	5	4	3	4	3,6
C4	Human errors in establishing the project schedule	2	4	1	1	3	2,2
C5	Inconsistency between data gathered on site and BIM models	4	4	4	3	3	3,6
C6	Lack of predefined procedure for control mechanism of BIM-based progress tracking and scheduling	3	5	3	5	4	4

Table 6.3 Respondent Evaluation for Section 5

ID	Identified Problems (Section 5)	R1	R2	R3	R4	R5	Mean
P1	Geotechnical tunnel elements can be modeled as a single model object in compliance with LOD300 due to continuous nature of geotechnical construction. However, this results in imprecise visualization of progress tracking.	4	4	4	5	4	4,2
P2	When the excavation elements are not modeled according to planned construction sequence, it results in inconsistencies in the phase planning simulations.	4	4	5	5	4	4,4
P3	When some activities are not included in the project schedule, the related activity information (WBS codes) cannot be entered into the model elements, and these activities cannot be shown in the phase planning simulations. Assigning a general activity to these elements causes inaccurate simulation.	2	5	5	4	4	4
P4	Due to errors in project schedule, activity relations are not compatible with the design of the project which leads to unconstructable sequences in the simulation.	2	4	3	1	4	2,8
P5	Progress on site cannot be properly visualized with BIM models due to progress data gathered on site not being compatible with the BIM model elements.	4	4	4	4	3	3,8

The analysis will be done with reference to the ID of the listed items. When the ratings given to items C1 and C2 were examined, it was observed that the respondents agreed that the lack of a standard and guideline for the level of detail and modeling techniques of BIM models, specifically 4D modeling in metro projects, is important. Although respondent R1 rate the importance of item C1 as two, when R1, which is given as an example for the detail level of model was explained in the next section of the questionnaire, R1 rated P1 in terms of its importance as four. Similarly, the respondents rated the P2 problem regarding the modeling technique, which was given as an example for the C2 problem, as important. Respondent R1 stated that the C3 problem and the example given for this problem, P3, are of less importance and these problems can be compensated. However, other respondents working in the field of design and construction found this problem important. For item C4, three out of five respondents rated the importance of this problem as low, stating that this is one of the main purposes of creating a project schedule simulation. On the other hand, they agreed that a proper control mechanism was required to detect the problems mentioned in item C4, which was lacking, therefore they rate the item C6 as quite important. Respondents working in the construction field think C4 problem is more important unlike other respondents. Considering that they work in different fields, it can be inferred that this problem affects people working in the construction more. Lastly, the respondents stated that the problem of the data obtained in the field not being compatible with BIM models is important by giving high scores to items C5 and P5.

As a result of the evaluations made by experts, it was determined that the lack of a standard and guidelines for the level of detail of BIM models and modeling techniques, and the lack of procedures for the control mechanism of BIM-based progress tracking and scheduling are the most important problems in 4D application in metro projects. What follows is the incompatibility of the data obtained from the field and BIM models, and the insufficient level of detail of the project schedule.

After evaluating the problems in terms of importance, the respondents evaluated the proposed solutions listed for these mentioned problems in terms of their suitability. The results are given in Table 6.4.

As seen in the table, the respondents gave high scores to all solution items proposed for the identified problems. Respondents found the solution proposed within the framework to be quite appropriate.

Table 6.4 Respondent Evaluation for Section 6

ID	Proposed Solutions (Section 6)	R1	R2	R3	R4	R5	Mean
S1	Although the detail level (LOD) of model elements is specified in documents such as BIM Execution Plan (BEP), further standardizations are necessary for 4D applications. For example, the length of geotechnical model elements should be standardized as 1 meter in order to have precise progress information and visualization of progress.	4	5	4	5	5	4,6
S2	For BIM-based progress tracking and construction sequencing, BIM model's references must definitely include project schedule plan in addition to design documents, and this should be stated in the BEP documents. By this way, BIM models become compatible with the actual site conditions.	4	4	5	4	4	4,2
S3	Detail level of the project schedule should be mature enough to create a proper phase planning simulation. For the missing activities which are not yet included due to uncertainties in the design or other reasons, different activities should be assigned to BIM elements under certain assumptions with the approval of the project planner.	4	4	5	4	5	4,4
S4	Checking project schedule via phase planning simulation have great benefits. These controls should be performed based on certain rules which are defined before starting the control of 4D model. Detected errors should be reported to project planner as feedback on the errors.	4	5	4	3	5	4,2

S5	While gathering progress information on site, BIM models should be taken into consideration. In other words, BIM model-based acquisition of progress information methods should be used.	4	4	4	5	5	4,4

In addition to the problems identified and the proposed solutions, the respondents were asked about the issues they identified and necessitates attention to during the process of 4D modeling in metro projects. The answers are listed below with the explanations made by the respondents.

- Existing structure models should also be included in the 4D simulation, and these models should be taken into consideration when performing relevant checks. Metro projects interact with many existing structures such as infrastructure lines and superstructure buildings. In order for this interaction to be examined more accurately, the project schedule should also be considered.
- Human errors encountered in manual data processing processes are important. Data processing is still done manually to a certain level. This may cause incorrect data when processing data. This process can be automated by using different technologies to obtain progress data, but considering the size of metro projects, it is difficult to predict whether its implementation will be effective or not.
- Temporary construction stages are necessary to be modeled and demonstrated. Geotechnical construction mostly consists of temporary staged construction, and this is important part of the project schedule because staged construction activity relations should also be examined. Therefore, if BIM models are to be used in simulations, staged constructions must be modeled.
- Regardless of the progress information collected for progress payment in the field, separate information gathering should be done dedicated to BIM-based

progress tracking and this data should be forwarded to the BIM department in order to accurately process progress data into BIM models.

To conclude, the proposed framework was found to be meaningful and appropriate. Making evaluations with people at diverse levels working in different fields has produced effective feedback. The respondents were able to make more valid evaluation of the 4D application in metro projects with specific examples given on these issues. The questionnaire was limited to five people due to method of interview. In a longer period of time, conducting a questionnaire with more stakeholders in the future will be beneficial in detecting an overlooked problem and more suitable for statistical analysis.

CHAPTER 7

CONCLUSION

Infrastructure projects, especially metro systems, requires efficient management system due to their complex nature. This necessity resulted in BIM utilization in infrastructure project, which BIM tools are not generally convenient for. In recent years, implementation rate of BIM in infrastructure sector has been increasing as the benefits of BIM have been realized. However, infrastructure sector, especially metro projects, lags behind the BIM implementations such as BIM-based progress tracking and scheduling, compared to building sector, because the transition from traditional methods to BIM is rather complicated. This study aimed to develop a framework to standardize BIM-based construction planning and simulation as there is still a need for a workflow on how to properly utilize BIM for progress tracking and scheduling in metro projects.

In this study, literature review was conducted to gain a perspective on the current status of 4D implementations in metro project. Then, an on-going construction metro project has been investigated, and the implementation of BIM in an infrastructure project has been observed. Several project documents that include 4D models, phase planning reports, project schedule and BIM models have been analyzed in depth. Both strengths and flaws of the process of creating 4D models within the scope of the investigated project were identified and categorized in a systematic way. Causes of the identified problems were explained by giving examples from the examined project, and potential solutions were discussed. Based on the findings from the investigation of the project, a framework for BIM-based construction planning and simulation in underground metro projects was developed. The expected benefits of the framework are reducing errors in the scheduling and planning, increasing the efficiency of decision making, improving the optimization of construction schedule, increasing efficiency of the collaboration between the parties involved, enabling

comprehension of tunnel construction activities. Lastly, the proposed framework was assessed by industry experts. An interview questionnaire was conducted with BIM professionals who have experience in using BIM in metro projects. In one-on-one interviews, identified challenges in the case study project and proposed solution strategies were explained to the experts, and they are asked to evaluate the challenges in terms of their importance and solutions in terms of their applicability. The data obtained from the questionnaire was used to validate the suitability of the proposed framework.

In the literature view, it was observed that the interest towards the implementation of BIM in infrastructure projects has increased although it still lags behind the building sector. 4D modeling related studies mainly focuses on the data gathering and updating of 4D models. Modeling standards to have the desired 4D simulations are rather unexplored in infrastructure sector. A study where the main focus is defining workflow and modeling standards regarding BIM-based progress tracking and scheduling of underground metro projects have not been found. Thus, the purpose of this study is to fill these gaps regarding the 4D implementation of BIM in metro projects.

Firstly, the case study project was investigated. Identified problems that causes inaccuracies in the BIM-based progress tracking and scheduling have been categorized under three categories which are BIM models, project schedule, and progress report. Before starting to create BIM models, if detail of model elements and modeling technique are not properly defined, these BIM models fail to meet the 4D model requirements. In the investigated project, it was observed that the geotechnical model elements for tunnels were divided into 1-meter pieces. Although, creating single geotechnical model objects for each tunnel does not violate LOD300 requirements, it is not adequate to have precise information regarding the progress. The method applied in the project was correct, but such a requirement was not specified in the BIM-related documents. In addition, design documents and progress reports were examined in order to establish a systematic relationship for the length of geotechnical tunnel elements. As for the modeling technique, it was noticed that

not taking the project schedule into consideration when creating the models causes inaccuracies in the simulation. The project schedule is an important part of 4D modelling. When the phase planning report was checked, the errors in the phase planning simulation consisted of two main reasons: insufficient detail level of the project schedule and errors in the project schedule. Since some activities were not in the work program yet, relevant activity data could not be processed for some model elements. In the investigated project, more general activities or different activity data was processed into these elements, which caused errors in the simulation. These errors can be prevented with a proper procedure for the creating 4D models and control mechanism of the simulation. Lastly, it was observed that the inconsistencies between the data in progress reports and BIM models was the main problem in creating progress tracking models. Tunnel lengths in the progress report did not match the BIM model elements due to unclear references of the tunnel lengths.

Based on the findings of the investigated project, BIM-based construction planning and simulation framework was proposed. The first step is to determine the suitable detail level of BIM model elements. LOD300 is sufficient to have a precise model for 4D modeling and progress tracking models. Furthermore, the length of the geotechnical tunnel elements should be standardized before creating BIM models. To do so, design documents and approximate progress expectations should be taken into account. From the case study, 1-meter length pieces are observed to be proper in order to have precise information visualization regarding the progress. These standardizations are necessary to be stated in BIM-related documents to be systematically implemented in BIM models. BIM models being in compliance with the construction sequence is an essential for phase planning simulations. To do so, reference documents in creating BIM models should include project schedule plan in addition to design documents, and this should also be stated in BEP documents.

Detail level of project schedule is another crucial factor. In the case of missing activities due to uncertainties in the design or other reasons, different construction activities can be assigned under certain assumptions with the approval of the project planner. Checking project schedule via phase planning simulation have great

benefits. These controls should be performed based on certain rules which are defined before starting the control of 4D model. An expert planner must guide while defining these check rules. Detected errors should be reported to project planner as feedback on the errors.

The data gathered on site and BIM model elements should be compatible to create progress tracking models. To achieve this, BIM-based progress information gathering methods should be adopted. Furthermore, global parameters featured in Autodesk Revit can be used to improve the processing of progress data in a timely and efficient manner. Editing thousands of model elements at one time through a global parameter instead of selecting all elements one by one and editing the parameter values has been observed to be quite useful. After entering all the necessary progress information into BIM model elements, the progress onsite can be visualized in a combined model that contains all the produced BIM models. Then, model elements are colorized based on the values of progress related parameters. Project review software such as Navisworks can be used for this purpose. Navisworks has the “appearance profiler” tool that can perform rule-based coloring by matching the data in parameters.

In one-on-one interviews with industry professionals, the most important problems were determined to be the level of model detail and the lack of instructions for the modeling technique, and the lack of a control mechanism procedure for 4D models which is followed by the incompatibility of the data obtained in the field with the BIM models and the insufficient level of detail of the work program. Respondents made a deeper evaluation on the 4D application of metro projects with specific examples given on these topics. Afterwards, the respondents found the solutions proposed within the framework to be logical and suitable. When the respondents were asked if they had any other suggestions on the subject, they answered that the items listed below should be taken into consideration.

- Including existing structures in the 4D simulations
- Making efforts to automate manual data processing

- Modeling temporary construction stages and including them in 4D simulations
- Dedicated progress information gathering for BIM model

Based on the case project examined, a framework is proposed to improve the process of creating phase planning and progress tracking models in metro projects. The characteristics of construction projects vary from project to project, and it should be noted that some benefits to be obtained from the proposed framework may not be certain depending on the project conditions. Despite this, the proposed framework has been created not only on the basis of the project examined but also in a comprehensive manner for other metro projects which has been confirmed in expert evaluations. Conducted interview indicated that the respondents agree on the benefits that the proposed framework provides. However, conducting a questionnaire with more stakeholders in the future will be beneficial in identifying all the challenges on this topic. Moreover, applying this framework in other metro projects is necessary to effectively verify the benefits it provides. As a result, the framework proposed in this study has the potential to significantly improve the process of creating project schedule simulation and progress tracking models in metro projects.

REFERENCES

Abdelwahab, H. T. (2018). Intelligent design (4D, 5D and beyond) for road design and construction projects: Two case studies. International Road Federation (IRF) Examiner, 12, 21-25. Retrieved from https://www.irf.global/ebooks/IRF-Examiner-17Vol12.pdf#page=28

Amberg Engineering. (n.d.). [Bözberg Tunnel]. Retrieved March 15 2023, from https://ambergengineering.com/references/projects/boezberg-tunnel

Autodesk. (2021). Accelerating Digital Transformation Through BIM. Retrieved 4 April 2023, from https://damassets.autodesk.net/content/dam/autodesk/www/industry/aec/bim/aec-smart-market-insight-2021-bim-digital-transformation-japan-en.pdf

Baraibar, J. M., De-Paz, J., & Rico, J. (2022). Challenges for the Implementation of BIM Methodology in the Execution of Underground Works. *Buildings*, *12*(3). https://doi.org/10.3390/buildings12030309

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. *Automation in Construction*, *71*, 139–152. https://doi.org/10.1016/J.AUTCON.2016.08.019

Borrmann, A., Kolbe, T. H., Donaubauer, A., Steuer, H., Jubierre, J. R., & Flurl, M. (2015). Multi-Scale Geometric-Semantic Modeling of Shield Tunnels for GIS and BIM Applications. *Computer-Aided Civil and Infrastructure Engineering*, *30*(4). https://doi.org/10.1111/mice.12090

Civilverse. (2021). *Calgary Light Rail Tunnel is a Cut & Cover Tunnel*. Retrieved March 24 2023, from https://www.civilverse.org/tunnel-construction-methods/

Chen, S. M., Griffis, F. H., Chen, P. H., & Chang, L. M. (2013). A framework for an automated and integrated project scheduling and management system. *Automation in Construction*, *35*. https://doi.org/10.1016/j.autcon.2013.04.002

Cheng, J. C. P., Lu, Q., & Deng, Y. (2016). Analytical review and evaluation of civil information modeling. *Automation in Construction*, *67*, 31–47. https://doi.org/10.1016/J.AUTCON.2016.02.006

Costin, A., Adibfar, A., Hu, H., & Chen, S. S. (2018). Building Information Modeling (BIM) for transportation infrastructure – Literature review, applications, challenges, and recommendations. *Automation in Construction*, *94*. https://doi.org/10.1016/j.autcon.2018.07.001

Dibernardo, S. (2012). Integrated modeling systems for bridge asset management - Case study. *Structures Congress 2012 - Proceedings of the 2012 Structures Congress*. https://doi.org/10.1061/9780784412367.043

Ding, L. Y., Zhou, Y., Luo, H. B., & Wu, X. G. (2012). Using nD technology to develop an integrated construction management system for city rail transit construction. *Automation in Construction*, *21*(1). https://doi.org/10.1016/j.autcon.2011.05.013

Fanning, B., Clevenger, C. M., Ozbek, M. E., & Mahmoud, H. (2015). Implementing BIM on Infrastructure: Comparison of Two Bridge Construction Projects. *Practice Periodical on Structural Design and Construction*, *20*(4). https://doi.org/10.1061/(asce)sc.1943-5576.0000239

Fouracre, P., Dunkerley, C., & Gardner, G. (2003). Mass rapid transit systems for cities in the developing world. *Transport Reviews*, *23*(3). https://doi.org/10.1080/0144164032000083095

Guo, F., Turkan, Y., Jahren, C. T., & David Jeong, H. (2014). Civil information modeling adoption by Iowa and Missouri DOT. *Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering*. https://doi.org/10.1061/9780784413616.058

Guo, H. (2019). A Review of Metro Tunnel Construction Methods. *IOP Conference Series: Earth and Environmental Science*, *218*(1). https://doi.org/10.1088/1755-1315/218/1/012110

Hamledari, H., McCabe, B., Davari, S., & Shahi, A. (2017). Automated Schedule and Progress Updating of IFC-Based 4D BIMs. *Journal of Computing in Civil Engineering*, *31*(4). https://doi.org/10.1061/(asce)cp.1943-5487.0000660

Han, K., Degol, J., & Golparvar-Fard, M. (2018). Geometry- and Appearance-Based Reasoning of Construction Progress Monitoring. *Journal of Construction Engineering and Management*, *144*(2). https://doi.org/10.1061/(asce)co.1943-7862.0001428

Han, K. K., & Golparvar-Fard, M. (2017). Potential of big visual data and building information modeling for construction performance analytics: An exploratory study. *Automation in Construction*, *73*. https://doi.org/10.1016/j.autcon.2016.11.004

Hartmann, T., Gao, J., & Fischer, M. (2008). Areas of Application for 3D and 4D Models on Construction Projects. *Journal of Construction Engineering and Management*, *134*(10). https://doi.org/10.1061/(asce)0733-9364(2008)134:10(776)

Ingram, J. (2020). Understanding BIM: The past, present and future. Routledge.

International Association of Public Transport. (2018). World Metro Figures 2018. Retrieved from https://cms.uitp.org/wp/wp-content/uploads/2020/06/Statistics-Brief-World-metro-figures-2018V3_WEB.pdf

International Association of Public Transport. (2021). World Metro Figures 2021. Retrieved from https://cms.uitp.org/wp/wp-content/uploads/2022/05/Statistics-Brief-Metro-Figures-2021-web.pdf

Kandregula, S.H., & Le, T. (2020). Investigating the Human Errors in 4D BIM Construction Scheduling. Construction Research Congress 2020. http://dx.doi.org/10.1061/9780784482889.079

Karakuş, M., & Fowell, R. J. (2004). An insight into the new Austrian tunnelling method (NATM). In 7th Regional Rock Mechanics Symposium, Sivas, Türkiye.

Kastor, A., & Sirakoulis, K. (2009). The effectiveness of resource levelling tools for resource constraint project scheduling problem. International Journal of Project Management, 27(5), 493-500. https://doi.org/10.1016/j.ijproman.2008.08.006

Kim, H., Orr, K., Shen, Z., Moon, H., Ju, K., & Choi, W. (2014). Highway Alignment Construction Comparison Using Object-Oriented 3D Visualization Modeling. *Journal of Construction Engineering and Management*, *140*(10). https://doi.org/10.1061/(asce)co.1943-7862.0000898

Kim, J. U., Kim, Y. J., Ok, H., & Yang, S. H. (2016). A study on the status of infrastructure BIM and BIM library development. *Proceedings - 2015 International Conference on Computational Science and Computational Intelligence, CSCI 2015*. https://doi.org/10.1109/CSCI.2015.52

Koch, C., Vonthron, A., & König, M. (2017). A tunnel information modeling framework to support management, simulations and visualizations in mechanized tunnelling projects. *Automation in Construction*, *83*. https://doi.org/10.1016/j.autcon.2017.07.006

Koo, B., & Fischer, M. (2000). Feasibility Study of 4D CAD in Commercial Construction. *Journal of Construction Engineering and Management*, *126*(4). https://doi.org/10.1061/(asce)0733-9364(2000)126:4(251)

Kopsida, M., & Brilakis, I. (2020). Real-Time Volume-to-Plane Comparison for Mixed Reality–Based Progress Monitoring. *Journal of Computing in Civil Engineering*, *34*(4). https://doi.org/10.1061/(asce)cp.1943-5487.0000896

Kumar, B., Cai, H., & Hastak, M. (2017). An assessment of benefits of using BIM on an infrastructure project. *International Conference on Sustainable Infrastructure 2017: Technology - Proceedings of the International Conference on Sustainable Infrastructure 2017*. https://doi.org/10.1061/9780784481219.008

Lee, P. C., Wang, Y., Lo, T. P., & Long, D. (2018). An integrated system framework of building information modeling and geographical information system for utility tunnel maintenance management. *Tunnelling and Underground Space Technology*, *79*. https://doi.org/10.1016/j.tust.2018.05.010

Li, H., Chan, N. K. Y., Huang, T., Skitmore, M., & Yang, J. (2012). Virtual prototyping for planning bridge construction. *Automation in Construction*, *27*. https://doi.org/10.1016/j.autcon.2012.04.009

Mawlana, M., Vahdatikhaki, F., Doriani, A., & Hammad, A. (2015). Integrating 4D modeling and discrete event simulation for phasing evaluation of elevated urban highway reconstruction projects. *Automation in Construction*, *60*. https://doi.org/10.1016/j.autcon.2015.09.005

Minagawa, M., & Kusayanagi, S. (2015). Study on BIM utilization for design improvement of infrastructure project. *Procedia Engineering*, *125*. https://doi.org/10.1016/j.proeng.2015.11.113

Osello, A., Rapetti, N., & Semeraro, F. (2017). BIM Methodology Approach to Infrastructure Design: Case Study of Paniga Tunnel. *IOP Conference Series: Materials Science and Engineering*, *245*(6). https://doi.org/10.1088/1757-899X/245/6/062052

Park, J., & Cai, H. (2017). Framework of dynamic Daily 4D BIM for tracking construction progress through a web environment. *Congress on Computing in Civil Engineering, Proceedings*. https://doi.org/10.1061/9780784480823.024

Providakis, S., Rogers, C. D. F., & Chapman, D. N. (2019). Predictions of settlement risk induced by tunnelling using BIM and 3D visualization tools. *Tunnelling and Underground Space Technology, 92*. https://doi.org/10.1016/j.tust.2019.103049

Jones, S.A., & Laquidara-Carr, D. (2017). The Business Value of BIM for Infrastructure, Smartmarket Report. Retrieved May 13 2023 from https://www2.deloitte.com/content/dam/Deloitte/us/Documents/finance/us-fas-bim-infrastructure.pdf

Sankaran, B., France-Mensah, J., & O'Brien, W. J. (2016, July). Data integration challenges for CIM in large infrastructure: a case study of Dallas Horseshoe Project. In Proceedings of the 16th International Conference on Computing in Civil and Building Engineering, Osaka, Japan (pp. 6-8).

Sharafat, A., Khan, M. S., Latif, K., & Seo, J. (2021). BIM-Based Tunnel Information Modeling Framework for Visualization, Management, and Simulation of Drill-and-Blast Tunneling Projects. *Journal of Computing in Civil Engineering*, *35*(2). https://doi.org/10.1061/(asce)cp.1943-5487.0000955

Shi, K., & Ouyang, Y. (2017). Implementation Method of Construction Schedule Management for Metro Engineering Based on BIM Modeling. *International Conference on Construction and Real Estate Management (ICCREM 2016)* https://doi.org/10.1061/9780784480274.008

Shim, C. S., Yun, N. R., & Song, H. H. (2011). Application of 3D bridge information modeling to design and construction of bridges. *Procedia Engineering*, *14*. https://doi.org/10.1016/j.proeng.2011.07.010

Structurae. (2016). *Excavation in accordance with the New Austrian Tunnelling Method (NATM)*. Retrieved April, from https://structurae.net/en/media/255016-excavation-in-accordance-with-the-new-austrian-tunnelling-method-natm

Teizer, J. (2015). Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites. *Advanced Engineering Informatics*, *29*(2). https://doi.org/10.1016/j.aei.2015.03.006

Tompagenet. (2006). *1992 stock Tube train at Lancaster Gate station, London*. Flickr. https://www.flickr.com/photos/tompagenet/303824827/

Wikipedia. (2013). *A schematic view of a station box.* Wikipedia. Retrieved 26 April 2023 from https://en.wikipedia.org/wiki/Station_box

Wang, G., & Zhang, Z. (2021). BIM implementation in handover management for underground rail transit project: A case study approach. *Tunnelling and Underground Space Technology*, *108*. https://doi.org/10.1016/j.tust.2020.103684

Wang, J., Hou, X., Deng, X., Han, H., & Zhang, L. (2022). Application of BIM in Tunnel Design with Compaction Pile Reinforced Foundation Carrying Carbon Assessment Based on Advanced Dynamo Visual Programming: A Case Study in China. *Sustainability (Switzerland)*, *14*(23). https://doi.org/10.3390/su142316222

Wang, S., Fu, J., Zhang, C., & Yang, J. (2021). *Shield Tunnel Engineering: From Theory to Practice*. https://doi.org/10.1016/B978-0-12-823992-6.00007-2

Yin, X., Liu, H., Chen, Y., Wang, Y., & Al-Hussein, M. (2020). A BIM-based framework for operation and maintenance of utility tunnels. *Tunnelling and Underground Space Technology*, *97*. https://doi.org/10.1016/j.tust.2019.103252

Zhang, Y., Zhang, J., Wang, C., & Ren, X. (2023). An integrated framework for improving the efficiency and safety of hydraulic tunnel construction. *Tunnelling and Underground Space Technology*, *131*. https://doi.org/10.1016/j.tust.2022.104836

Zhou, C., & Wang, W. (2009). *Highway Bridge Construction Process Simulation Base on 4D Visualization*. 138–145. https://doi.org/10.1061/41042(349)18

Zhou, Y., Ding, L. Y., & Chen, L. J. (2013). Application of 4D visualization technology for safety management in metro construction. *Automation in Construction*, *34*. https://doi.org/10.1016/j.autcon.2012.10.011

APPENDICES

A. Interview Questionnaire

1. General Information

1.1. What is your profession?

- Architect
- Civil engineer
- Electrical engineer
- Geotechnical engineer
- Mechanical engineer
- Other (Please specify)

1.2. What is your position in the project you are working on or in your last project?

- Academician / Teaching assistant
- Consultant
- Control or Chief engineer / Architect (for public authority employees)
- Design engineer / Architect
- Design chief
- Project manager / Vice manager
- Director or superior (for public authority employees)
- Other (Please specify)

1.3. What is your education level?

- Associate degree
- Bachelor’s degree
- Master’s degree
- PhD degree

1.4. How many years of experience do you have in your profession?

- 1-5 years
- 5-8
- 8-15
- 15-30
- 30+

2. Experience Details

2.1. How do you rate your knowledge and skills in BIM? (0 - no experience / 5 - highly skilled)

0 1 2 3 4 5

2.2. How many years of experience do you have in BIM?

- 1-5 years
- 5-8
- 8-15
- 15-30
- 30+

2.3. Do you have experience in 4D modeling?

- Yes
- No

2.4. Have you ever worked on a transportation infrastructure related project?

- Yes
- No

2.5. If yes, have you used BIM on a transportation infrastructure related project on which you have worked?

- Yes
- No

2.6. Have you ever worked on a metro project?

- Yes
- No

2.7. If yes, have you used BIM on a metro project on which you have worked?

- Yes
- No

2.8. Which of the following BIM software packages do you have experience working with? (Please rate each option: 0-no experience / 5-highly skilled)

- Autodesk products
- Bentley products
- Nemetschek products
- Graphisoft products
- Other (Please specify)

3. Company Details

3.1. Which sector are you currently working in?

- Public
- Private
- Academy

3.2. If you currently working in the private sector, which field does your company operate in?

- Design
- Consultancy
- Construction
- Other

3.3. Does your company have any experience in using BIM?

- Yes
- No

3.4. How many professionals who are directly utilizing BIM and related software are employed by your company?

- 1-10
- 10-20
- 20-35
- 35-50
- 50-100
- More than 100

3.5. How many years has it been since your company first implemented BIM?

- Less than 3
- 3-5
- 6-10
- 11-15
- 16-20
- More than 20

3.6. Does your company have any experience with using BIM in metro projects?

- Yes
- No

3.7. If yes, how is your company related to BIM utilization in metro projects?

- Using BIM tools to analyze BIM models but not creating BIM models
- Creating and Using Building Information Models at 3D level
- Creating and Using Building Information Models at 4D level
- Creating and Using Building Information Models at 5D level
- Creating and Using Building Information Models at 6D level
- Creating and Using Building Information Models at 7D level
- BIM Education
- Academic Research
- Other (Please specify)

3.8. Which of the following BIM software packages does your company utilize? (Multiple options can be selected)

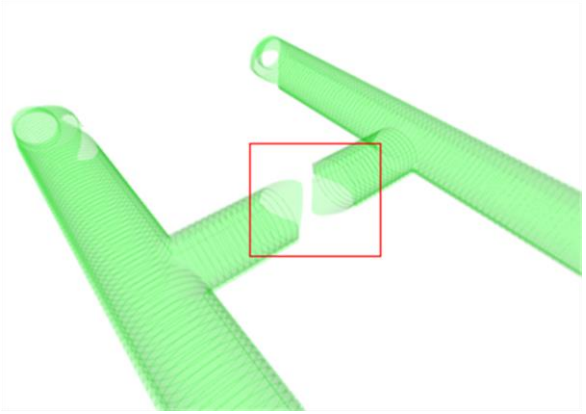
- Autodesk products
- Bentley products
- Nemetschek products
- Graphisoft products
- Other (Please specify)

4. Please rate the following listed challenges in BIM implementation at 4D level in metro projects.

ID	Challenge Items	Not at all Important (1)	Slightly Important (2)	Important (3)	Fairly Important (4)	Very Important (5)
C1	Lack of standardizations and guidelines for the detail level of BIM models (LoD)					
C2	Lack of standardizations and guidelines for modeling technique of BIM objects to be compatible with construction logic					
C3	Insufficient detail level of the project schedule (lack of activities in a schedule)					
C4	Human errors in establishing the project schedule					
C5	Inconsistency between data gathered on site and BIM models					
C6	Lack of predefined procedure for control mechanism of BIM-based progress tracking and scheduling					

5. Please rate the following identified problems in the case study project in terms of their importance.

ID	Identified Problems	Not at all Important (1)	Slightly Important (2)	Important (3)	Fairly Important (4)	Very Important (5)
P1	Geotechnical tunnel elements can be modeled as a single model object in compliance with LOD300 due to continuous nature of geotechnical construction. However, this results in imprecise visualization of progress tracking. (Upper part of the indicated tunnel) Yellow: In progress, Green: Completed, Red: Not started Coloring of Progress with Single Model Elements Coloring of Progress with Multiple Model Elements					

P2	When the excavation elements are not modeled according to planned construction sequence, it results in inconsistencies in the phase planning simulations.  Disconnection Between Tunnel Elements					

P3	When some activities are not included in the project schedule, the related activity information (WBS codes) cannot be entered into the model elements, and these activities cannot be shown in the phase planning simulations. Assigning a general activity to these elements causes inaccurate simulation.				
P4	Due to errors in project schedule, activity relations are not compatible with the design of the project which leads to unconstructable sequences in the simulation.				
P5	Progress on site cannot be properly visualized with BIM models due to progress data gathered on site not being compatible with the BIM model elements.				

Please specify if you have identified problems regarding the 4D applications other than the ones mentioned above.

6. Please rate the suitability of the following solutions for the problems mentioned in the previous section.

ID	Proposed Solutions	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
S1	Although the detail level (LOD) of model elements is specified in documents such as BIM Execution Plan (BEP), further standardizations are necessary for 4D applications. For example, the length of geotechnical model elements should be standardized as 1 meter in order to have precise progress information and visualization of progress. Sample Image for Standardized Geotechnical Elements (Shotcrete, Excavation)					

S2	For BIM-based progress tracking and construction sequencing, BIM model's references must definitely include project schedule plan in addition to design documents, and this should be stated in the BEP documents. By this way, BIM models become compatible with the actual site conditions.				
S3	Detail level of the project schedule should be mature enough to create a proper phase planning simulation. For the missing activities which are not yet included due to uncertainties in the design or other reasons, different activities should be assigned to BIM elements under certain assumptions with the approval of the project planner.				
S4	Checking project schedule via phase planning simulation have great benefits. These controls should be performed based on certain rules which are defined before starting the control of 4D model. Detected errors should be reported to project planner as feedback on the errors.				
S5	While gathering progress information on site, BIM models should be taken into consideration. In other words, BIM model-based acquisition of progress information methods should be used.				

Please specify if you have any solutions other than the ones mentioned above for the identified problems and the ones you have mentioned.

B. Human Subjects Ethics Committee Approval



UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

29 KASIM 2023

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Aslı Akçamete Güngör

Danışmanlığını yürüttüğünüz Sami Batuhan Kalpakçı'nın ***"YER ALTI METRO PROJELERİNDE BIM TABANLI İNŞAAT PLANLAMASI VE SİMULASYON ÇERÇEVESİ"*** başlıklı araştırmanız İnsan Araştırmaları Etik Kurulu tarafından uygun görülerek 0515-ODTUİAEK-2023 protokol numarası ile onaylanmıştır

Bilgilerinize saygılarımla sunarım.