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BIM Technology in Underground Transportation Engineering

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The purpose of this Bachelor thesis was to study the Building Information Modeling (BIM) technology used in underground transportation engineering. This thesis aimed at analyzing the significance and methods of the use of BIM in underground transportation construction.

The theoretical analysis covered the construction process from the design through construction to the maintenance phase of underground transportation engineering. Software related to the topic was listed and compared. Furthermore, specific software which supports tunnel design was studied. In addition, this thesis also studied pipeline clash detection, which is a common in the underground transportation station design phase. Finally, the use of BIM application in a Chinese metro station project was illustrated. The information and data for this thesis were collected from various articles and websites.

As a result of this thesis, the use of BIM in an underground transportation project was clarified. The advantages of using BIM for underground projects were presented. In addition, the development and challenges of BIM combined with underground transportation engineering were studied. Overall, this thesis can be further used as a guide to studies related to underground transportation engineering based on BIM technology.

Keywords	BIM, underground transportation engineering, 3D modeling, tunnel design, pipeline clash detection.

Contents

List of Abbreviations

BIM	Building Information Modelling
CAD	Computer-Aided Design
VR	Virtual Reality
3D	Three Dimension
4D	Four Dimension
HVAC	Heating, Ventilation, and Air Conditioning
MEP	Mechanical Electrical and Plumbing
IFC	Industry Foundation Class
FAS	Fire Alarm System
BAS	Building Automation System

1 Introduction

With the rapid growth in economy and population, urban transport has become one of the most important infrastructures in an urban area, and one which affects the area's development. Underground transportation relieves significantly the stress of urban traffic. Underground transportation is an urban railway transportation system that consists of tunnels, power, operating system and vehicles. An underground transportation system is mainly used in cities and metropolitan areas, transporting large numbers of people at a high frequency. Compared to other transportation methods, underground transportation has some obvious features, including large traffic volume, high capacity, less pollution, less noise, and no level crossings with the urban roads. However, the difficulties of underground transportation construction are non-ignorable. An underground transportation system has high fixed costs, a long construction period, massive data and information treatment. How to effectively promote the efficiency of the construction, operation, and maintenance of an underground transportation station while guaranteeing the progress, safety and quality of the project is an important issue for underground transport managers and engineers. [1.] In order to accelerate the comprehensive modernization of underground transportation construction, a scientific and efficient integrated construction method is desperately needed.

Building Information Modeling (BIM) is an intelligent tool known also as the second revolution in the construction industry. More specifically, BIM is a 3D modelling process that helps the architecture, construction, civil engineering, and other related engineering disciplines to design, construct and manage a building engineering project. The most important aim of BIM is to provide the project with an integrated and realistic engineering information database. With the help of these features and databases, the designer, constructor and operation department can conduct collaborative work, the efficiency of work can be improved effectively, resources can be saved, and the cost of the project can simultaneously be reduced. [2.]

The use of BIM technology in underground transportation engineering can establish a relationship between the designer, constructor, and owner of the project. By integrating models in different formats that come from different professionals into the BIM database, all data and documents from the design, construction, and maintenance stages can be saved. BIM can analyze all these data in a visual way so that a highly efficient intercommunication between data information and the building model can be realized. Furthermore, pipeline collision analyses, simulated analyses, and construction roaming related to underground transportation construction can be realized. In addition, utilizing BIM technology in underground site management can provide the project manager with comprehensive, immediate and accurate information of the schedule, safety, and risk of a project, improving the efficiency and precision of the information integration system for management decisions and lowering the risk of the underground transportation project. [3.]

2 BIM Technology in Underground Transportation Engineering

2.1 Difficulties Analysis

Underground transportation construction can be divided into two parts which are metro station construction and tunnel construction. The major difficulties of the underground transportation construction are discussed below.

The first difficulty in underground transportation construction is the fact that the surrounding working environment of the construction is complicated. Metro projects are often built under areas with a lot of high-rise buildings and through the complex underground pipeline systems of an urban area. All kinds of building materials and construction mechanical devices are accumulated in the working spaces both above ground and underground, causing uncertainties which involve numerous safety risks during the construction stage. Construction in a crowded urban environment can always cause ground deformation and surface subsidence. Furthermore, poor geological conditions, shallow buried structures and the stability of the surrounding rock can also be elements that influence the quality of underground transportation construction. [4].

The second difficulty in underground transportation construction is the complicated organizational structure of construction. As a part of a public transportation system constructed in an underground environment, the metro station construction usually involves multiple disciplines, which means that the management system, construction scheme, and working hours vary with each construction contractor. As various contractors with a diverse group of workers enter the construction site at the same time, the stability and coordination of the construction is difficult to guarantee. [4.]

The last difficulty in underground transportation construction is construction technical problems. Just like regular construction projects, the underground structure contains a variety of structural walls and HVAC components, there are many embedded parts and reserved holes in the design. Figure 1 shows a BIM model of the construction phase of an underground transportation project. Construction deficiencies such as omissions and embedding mistakes cannot be avoided when using the traditional construction method, mainly based on two-dimensional drawings. [4.]

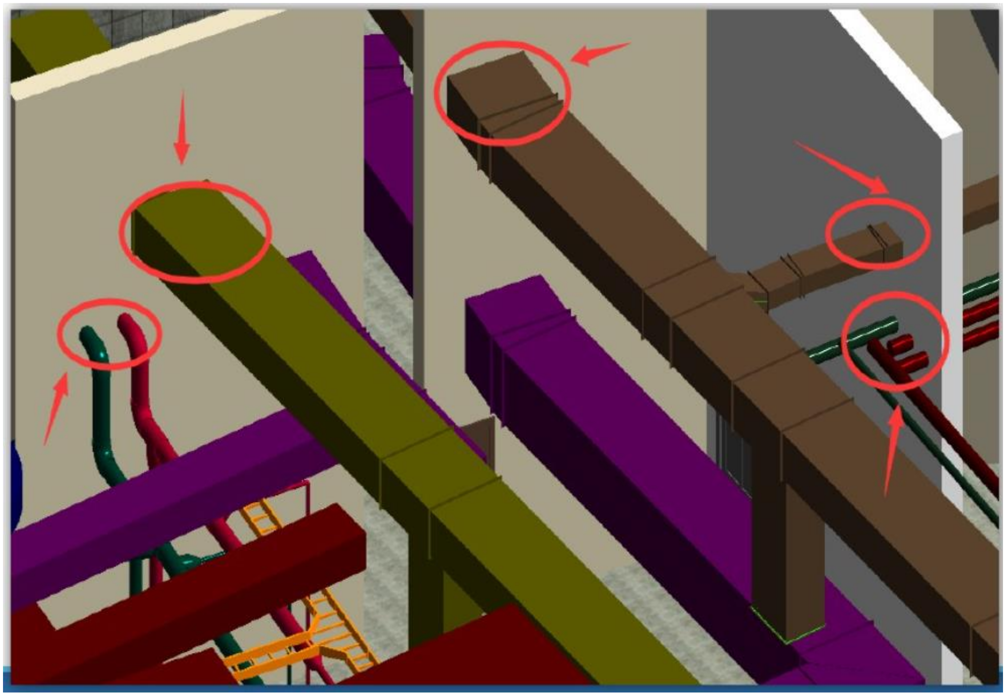

Figure 1. Reserved hole bases on a BIM model [5].

The potential difficulties discussed above can be avoided with the use of BIM technology in underground transportation engineering. The measurement images, calculation numbers, and construction information can be converted into 3D or 4D models for the designer and constructor. In addition, BIM can also provide a collaborative platform for each profession so that the management of the construction can be done easily. In addition, BIM technology can provide better solutions for the management of collision coordination with other buildings and pipelines, quantity control and performance analysis. In that way, the workload can be simplified, and the efficiency can be improved. Thus, the construction costs can be reduced. [3; 4.]

2.2 BIM Application Analysis

BIM technology has changed the traditional modeling concept, realized the technical evolution from a three-dimensional model to a multi-dimensional model, becoming a major auxiliary tool for decision making for an owner, as well as a necessary skill for design and construction units undertaking a large project. Nowadays, BIM technology is used in the planning, design, construction, and facility maintenance and operation phases of the underground transportation construction. The workflow of an underground transportation engineering project is shown in figure 2 below, including the use of BIM technology in each phase. [6.]

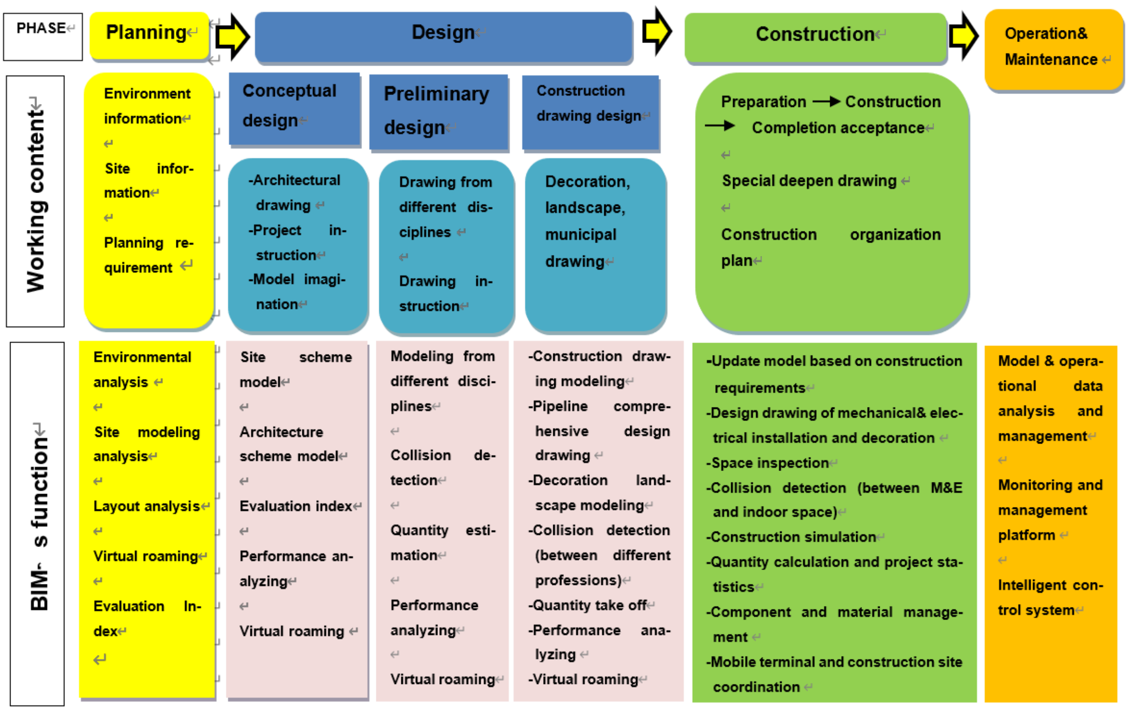

Figure 2. Workflow of an Underground transportation project with use of BIM.

The design phase of an underground metro station construction is very important. A metro station is the backbone of the underground transportation network. It not only collects and evacuates public but also operates the system and its devices. The design of a metro station always comprises more than 20 professions, not only the traditional construction professions like architects, structural engineers, and plumbers, also special disciplines like a vehicle and railway engineering are included. Unified decisions are hard to make when engineers from different fields are involved, which happens when using the traditional design method. If a project is lacks communication and coordination, the contradiction between the drawings of different units will appear, which may cause rework, thus decreasing the quality and efficiency of the project. [7.]

Unlike the traditional coordination design mode, in which the coordination is separated and restricted into two sectors, BIM technology provides a collaborative design stage for underground transportation construction. With the help of BIM technology, the coordination can be executed simultaneously by all sectors involved, as shown in figure 3 below.

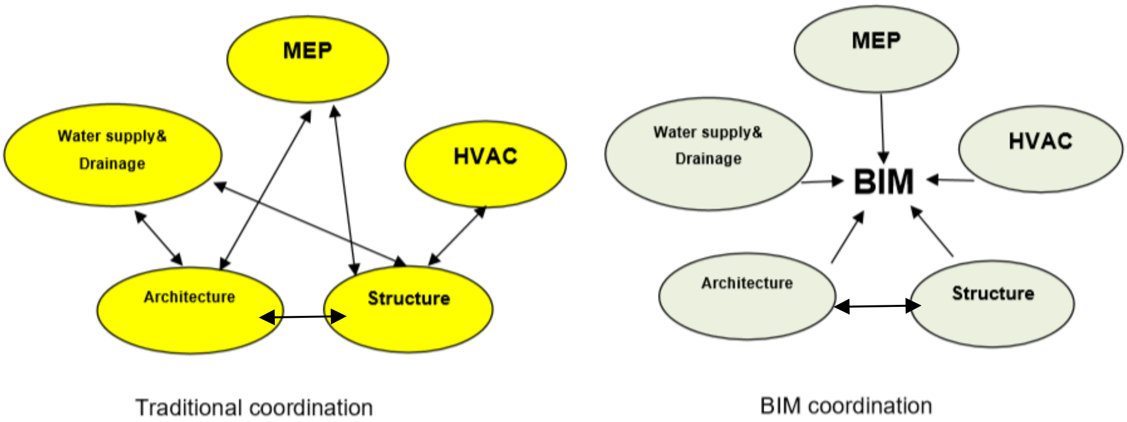

Figure 3. Integrated coordination comparison between traditional mode and BIM coordination mode.

BIM can collect and integrate all data and resources so that engineers from different sectors can get all the information they need through information sharing. In addition, the details of the structure can be observed directly during the design phase with the visualized characteristics of the BIM 3D model. Different construction options can be compared, the sequence of the construction order can be arranged at the design phase, and the best solution can be found. In addition, at the construction drawing design phase, the collision detection of BIM can find the problems in design drawings and construction scheme, effectively avoiding the design flaws and mistakes and any delays in the schedule. [6;7.]

Furthermore, the 5D management tool of BIM can provide core data like material consumption and cost accounting which can be used to control the investment of the project. The use of BIM technology during the design phase makes the communication more convenient, helps the designers adjust and improve the project easily, promoting the design quality. [7.]

By the means of virtual reality, BIM models can be used to create a metro station model, as well as the model colour rendering and animation producing, providing the constructor with a tentative result directly at the construction stage. [4.] Nowadays, a lot of construction failures are found when the construction is finished. [4.] In order to continue a project, the constructed part of a building with a failure must be removed and reconstructed. Sometimes, these failures are not only caused by the mistakes in the design phase but also by mistakes in the construction process by the constructor. For example, if construction site is too crowded, the method of excavation of the foundation pit may be done differently from the pre-defined method, and the purchased construction materials may not correspond to the construction progress. It may result in an excess of building materials and construction equipment stacking in the working area. The unmatched equipment may also influence the safety of the foundation pit.

By using the 4D simulated construction technology of BIM in underground construction, as figure 4 shows, a virtual construction scheme can be proposed. A 4D simulated construction means that a time dimension is added to a 3D model so that the construction process and period can be simulated in a dynamic way. Thus, situations in the construction period can be predicted and analysed with BIM. The construction site with variational placing of equipment and transport corridors can be controlled in advance. It is not only beneficial to the project time control and cost optimization, but also decrease the risk of mistakes during the construction, reducing rework and improving the construction quality. [8; 9.] In addition, the construction materials, for example the pipeline used in MEP and

HVAC systems of underground construction, can be determined and prefabricated before the construction starts. The constructor only needs to splice the pipeline on the construction site, without any field processing for pipeline installation. On one hand, the site noise, air pollution, and building debris can be reduced, and on the other hand, the construction labours can be minimized, and the construction efficiency can be improved. [9.]

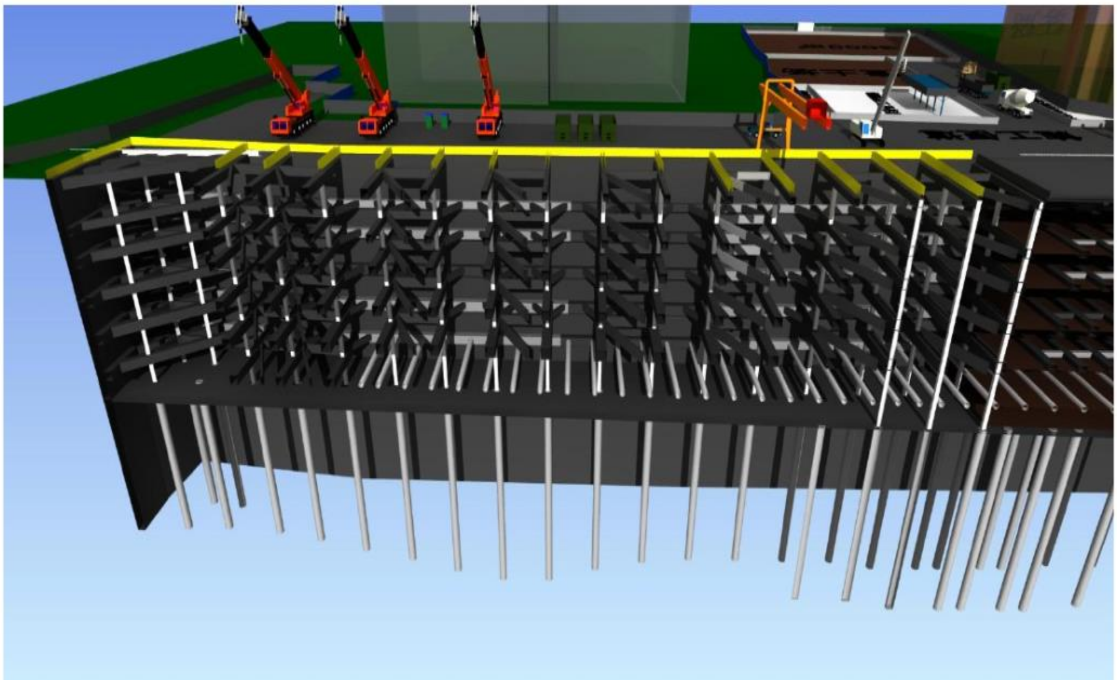

Figure 4. Construction Process Model view during the 4D simulation [10].

For the facility maintenance and operation phase, BIM technology can realize VR (virtual reality), assets statistics, spacing management, architecture system analysis and disaster simulation. An underground metro station usually involves a communication system, signalling system, ventilation and air conditioning system, water supply and drainage system, fire extinguishing system, and integrated supervisory control system. Various electronic equipment for the different systems make the daily maintenance and management more complicated and important. [11.] In addition, an accident like an underground structure damage or water leakage and seepage could also influence the maintenance and operation of underground transportation.

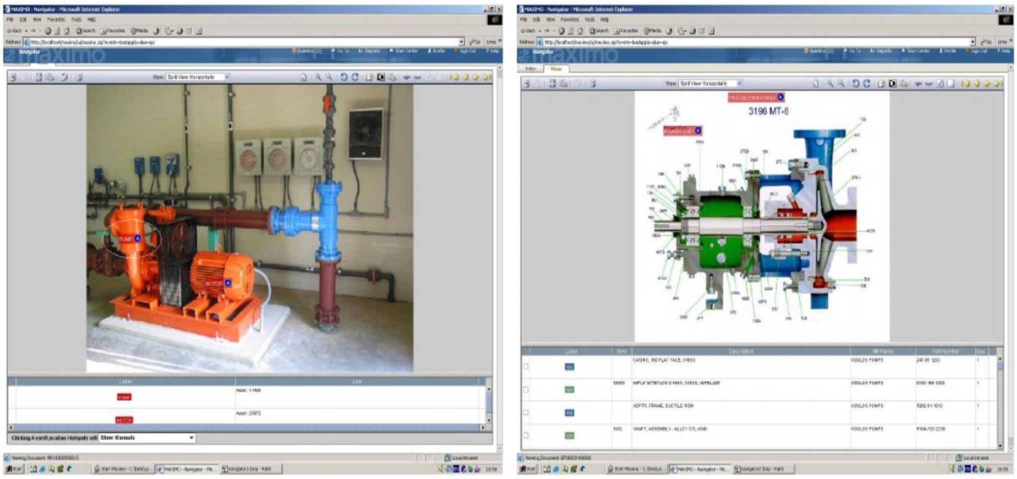

Figure 5. Visualized equipment management [12].

BIM can record specific information of all underground engineering devices. All data can be fixed and updated synchronously. The equipment operators can also use BIM to observe the condition of the equipment as is shown in figure 5 above so that the scheduled maintenance tasks can easily be finished. [11.] To illustrate, during a disaster prevention and rescue process, a maintenance engineer can access the real-time BIM database, the specific position of the failing equipment can be located accurately. Also, the best solutions for the repair of the equipment, based on all subsystem suggestions, can be provided before emergency personnel arrives.

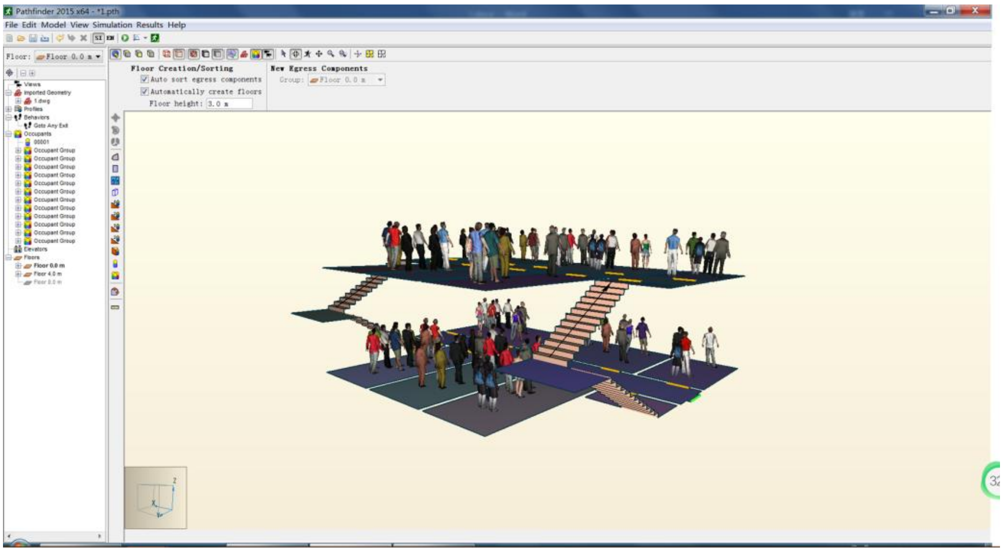

Figure 6. BIM model imported to Pathfinder for evacuation simulation [12].

In addition, exporting a BIM model to the Pathfinder software as shown in figure 6, can simulate the evacuation of accident scene, minimizing danger and the loss, which is necessary for public transportation with crowded population. To summarize, on one hand, BIM technology can improve the efficiency of facility operation and maintenance, lowering costs, extending the durability of a metro station, avoiding the risks of underground transportation engineering. On the other hand, BIM can assist the maintenance and operation, simulate emergencies and accidents, avoiding the risks of underground transportation construction. [7;11.]

2.3 BIM-Based 3D Modelling

2.3.1 3D Modelling Introduction

The most important feature of BIM application in underground transportation engineering is the fast and accurate model it produces. Compared with the traditional, two-dimensional drawing, three-dimensional model is more visualized. During the drawing examination and construction disclosures, a 3D model can help a constructor understand the intentions and the difficult points of a design drawing, ensuring the smooth run of construction work, avoiding mistakes. In addition, BIM technology allows the precise modelling of complex column, beam, joint, and the integrated pipeline construction, so that the complicated underground structures and pipeline systems can be described. [13.]

The basic requirement of underground transportation station modelling is that the model of a station should reflect the design intent and satisfy the accuracy requirement. It means that a BIM model can be consigned directly to the construction phase and support the construction management. The modelling principles in underground transportation engineering come from the designing party, the standard of the country, and the changing data of the project. The modelling work can be divided according to different professions into five parts, which are architectural engineering, structural engineering, mechanical and electrical engineering, environmental engineering and the railway area engineering. Examples of the tasks of the professions are listed below. [13.]

Architectural engineering:

- floor systems
- partition wall systems
- stairs and escalators
- windows and door systems
- accommodation rails

Structural engineering:

- foundations (that bear platforms, raft boards, foundation ditches, piles)
- shear walls
- frame column and constructional columns
- frame beams, secondary beams, lintels, ring beams
- reinforcing steel bars
- tunnel portals

Mechanical and electrical engineering:

- water supply and drainage system, pipelines
- HVAC systems, ductwork
- electrical system

Environmental engineering:

- surrounding buildings
- vegetations
- vehicles
- roads

Railway area engineering:

- rails
- sleepers

2.3.2 Modelling Software

Nowadays, there are more than 150 BIM tools in the software market. Some popular BIM software tools used in Chinese underground construction are Revit, Catia, Bentley, and Tekla. Each software has its distinct characteristics. The advantages and disadvantages of each software, as well as their scope of application, are summarized in table 1 below.

Table 1. BIM Software Comparison.

	Advantages	**Disadvantages**	**Scope of application**	**Supports underground construction**
Autodesk Revit	• Compatible multi-software platform • Wide application • Strong part family • Support secondary development • Strong platform integration ability • Easy to handle	• Poor 2D information processing ability • Running speed slow for big models • Design technology is undeveloped	• Civil architecture • Structure • MEP • HVAC	Yes
Bentley	• Support any complex surface • Record the process of compile • Strong collaborative design ability	• Not support the secondary development • Expensive • Hard to handle	• Industrial design (petrochemical industry, Pharmaceutical Engineering) • Infrastructure construction (road, bridge, hydraulic engineering)	Mainly in Electrical modelling
Catia	• Aim at a complex big project • Strong information management ability • Strong surface design • Fast processing speed • Support lightweight model	• Not apply to the construction industry project • Hard to handle	• Aerospace engineering • Automotive engineering • Complex shapes	Mainly in Vehicle modelling
Tekla	• Strong steel structure design ability • Structure analysis function included	• Weak in another profession modelling • Poor compatibility	• Steel structure	Mainly in Steel structure modelling

The comparison shows that the Revit can satisfy the requirements of structural, architectural, MEP and HVAC modelling for underground construction. It is versatile and can be used for various engineering needs. Hence, Revit can be recommended as the main BIM software for underground transportation engineering. [13.]

Table 2. Common software tools used in underground transportation engineering.

Software name	Function
Autodesk Revit	3D Modelling
Navisworks Manage	Collision detection, 3D data integration, roaming
3Ds MAX	Construction dynamic simulation
AutoCAD	Processing of 2D drawings
Lumion	Rendering
Hint SD	Underground tunnel design

In addition to Revit, other BIM-related software is also needed for different functions in underground transportation projects. Some of the common software tools can be found in table 2 above, with their function in an underground transportation project.

2.3.3 3D Modelling Process

A 3D modelling process of an underground transportation system can be broadly divided into two parts: the retaining structure modelling, and the station main body modelling. The retaining structure in underground transportation construction can balance the soil pressure, hindering the collapse of the foundation pit. It consists of a concrete top beam, retaining walls, steel supports, fender posts, and enclosing purlins. [14.] A comparison between 3D modelling and the actual work on a construction site is shown in figure 7 below.

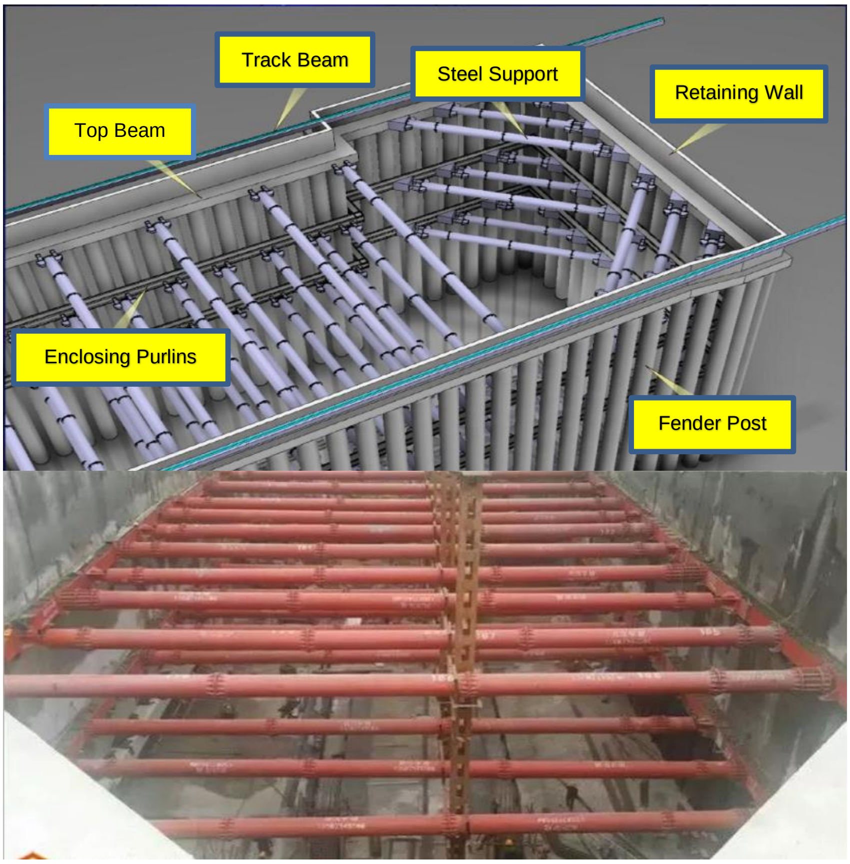

Figure 7. The retaining modelling and the actual construction [14].

Once the retaining structure modelling is completed, the station modelling can be begun. The station modelling consists of station hall modelling, station platform modelling, structure modelling, and the mechanic and electrical modelling. The modelling details of different systems are shown in figure 8 below.

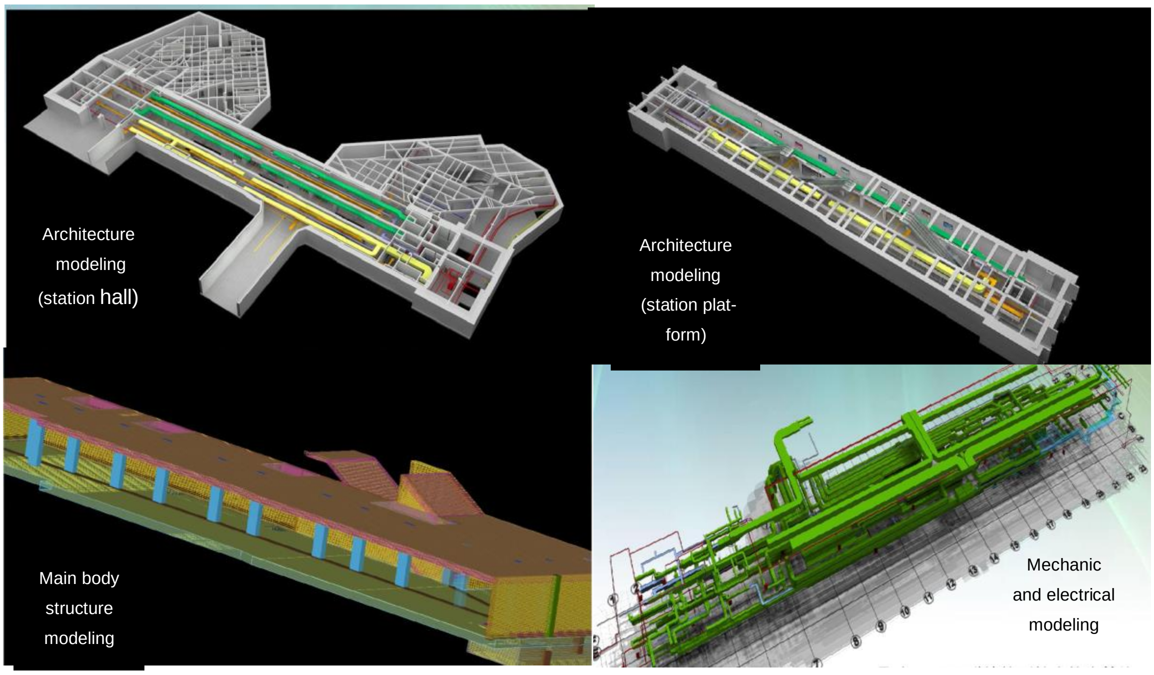

Figure 8. Modelling details from different sectors [15].

Except these models, models for, for example, water and supply drainage and HVAC systems should also be created. Figure 9 shows an IFC-based complete model interface which fully integrates all the models.

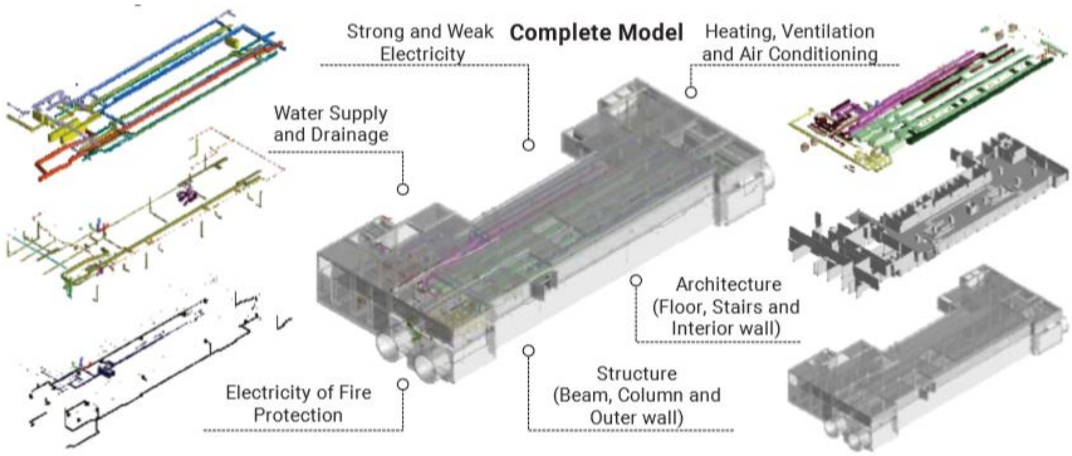

Figure 9. Integrated different models into a complete BIM model [16].

After the modelling process for different subsystems are done, a model interface based on industry foundation classes (IFC) is developed to import data from the sub models. [16.]

2.4 BIM with the Underground Transportation Project Management

BIM helps with the risk management of underground transportation construction. The safety risks for underground construction are always influenced by underground architectural forms, construction techniques, geological and hydro-geological conditions, and the surrounding environment. The construction technical risks are caused by the project's own characteristics, like the depth of pit excavation, and by the construction methods, like water gushing risk of tunnelling with the shield method. The geological risks indicate harmful geological conditions such as caves, water capsules, and harmful gases. The environmental risks caused by project activities also cannot be ignored either, for example, the tilt, crack or even collapse of surrounding structures caused by underground construction and underground pipeline leakage are some of them. Since there are several risks, a safety risk knowledge database can be established based on BIM-cloud. A BIM-cloud is a multi-user management platform and helps to sort out different types of safety risks. The standard specifications, regulations, manuals related to underground construction can be updated dynamically on the BIM-cloud. [17.] The process of building a risk knowledge database is illustrated in figure 10 below.

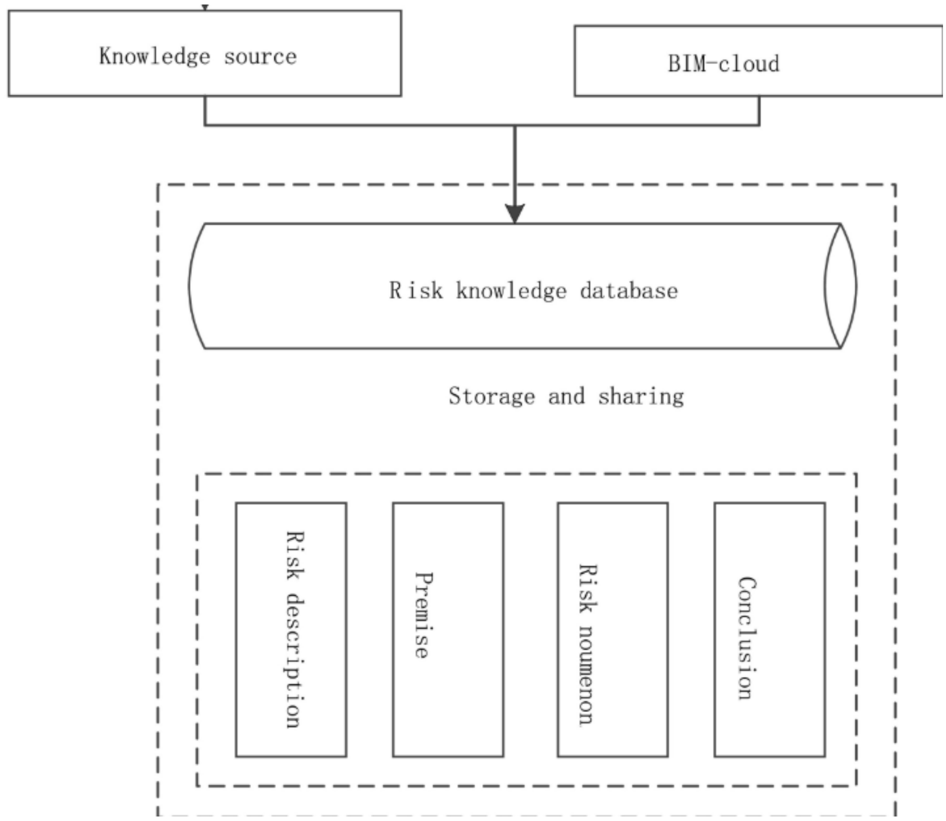

Figure 10. The process of building a risk knowledge database [17].

Once a risk knowledge database is set up, the next step is to analyse the risks on the basis of underground transportation project information provided by the BIM model. A BIM model can reflect the engineering information directly. Underground engineers and experts can recognize risks by reading BIM models. An underground BIM model always includes a general description, the retaining structure layout, strut layout and the general layout of tunnel. The model helps with the construction technical risk analysis of construction. In the underground tunnel construction, if a BIM model indicates that the vertical distance of central lines for two tunnels increases while the horizontal distance decreases, it is clear that the tunnel excavation may lead to soil disturbance near the tunnel, which may result in the displacement and deformation of the excavated tunnel. Geological risks can also be recognized by BIM because a BIM model also includes geological stratification information, hydrological information, and special geological distribution information. BIM also supports the environmental risks analysis, a BIM model can reflect the risks for tilt, crack and collapse of a structure, an underground pipeline leakage, as well as risks affecting the security of existing structures. [18.]

Except the safety risk management, BIM can also be used in underground transportation project statistics management. Comparing to the traditional statistics method, BIM technology can determine the amount of building materials thanks to its quantity take-off function, realizing the automatic retrieval and real-time statistic for underground transportation project quantities. In addition, with the time simulation function, the project quantities in future construction can be predicted precisely, so that the allocation of materials, staff, and machines can be optimized. [19.]

In the field of cost management, the traditional cost calculation method cannot satisfy the precision requirement of a big project like underground transportation construction due to the vast amount of calculations. With the help of BIM technology, things are getting easier. In the upfront cost prediction stage, BIM can be used to calculate the quantities of a project quickly and accurately by establishing a BIM database, promoting the accuracy of the project cost prediction. In the project construction phase, BIM can also control the investment effectively. For inner settlement and management of material acquisitions, BIM can control the procurement of the building materials. In the phase of completion settlement, the parametrization design function of BIM can include all models used in a project, so that the project assessor can log into the database and access all information about the project completion settlement. The efficiency of the calculation of final accounts can be enhanced greatly. [19; 20.]

3 HintSD: Underground Tunnel Design Based on BIM

3.1 HintSD System

A tunnel is one of the most important parts of any underground transportation project. The Hint SD systems is one of the most systematic professional-aided design software systems for tunnel projects in China. It is an independently researched and developed programme, integrated with the HintCAD 3D road CAD system, aiming to assist the design of tunnels and railways in underground transportation projects. The Hint SD system supports not only the design of a regular single cavern tunnel, but also the design of a multi-arched tunnel. By using the Hint SD system, a 3D solid BIM model of the main body of a tunnel, inner structure of a tunnel, as well as the steel structure of a tunnel can be automatically created. [21.]

3.2 Main Function of the HintSD system

As shown in figure 11 below, the HintSD system can automatically extract the data and sources of a project including the name, geometric design, relative position, and land surface line of a tunnel from CAD aided design database of an underground transportation project.

Figure 11. Tunnel design option field by HintSD [21].

There are some built-in functions, such as inner structure design and navigation tunnel structure gauge, as is shown in figure 12. When the inner structure type is selected, the system can automatically load a typical tunnel section layout with custom and modify functions. The arch height of the inner surface of a tunnel can be changed according to the design data. The geometrical parameters, such as drainage ditch and cable duct data, can be modified by the application. [21.]

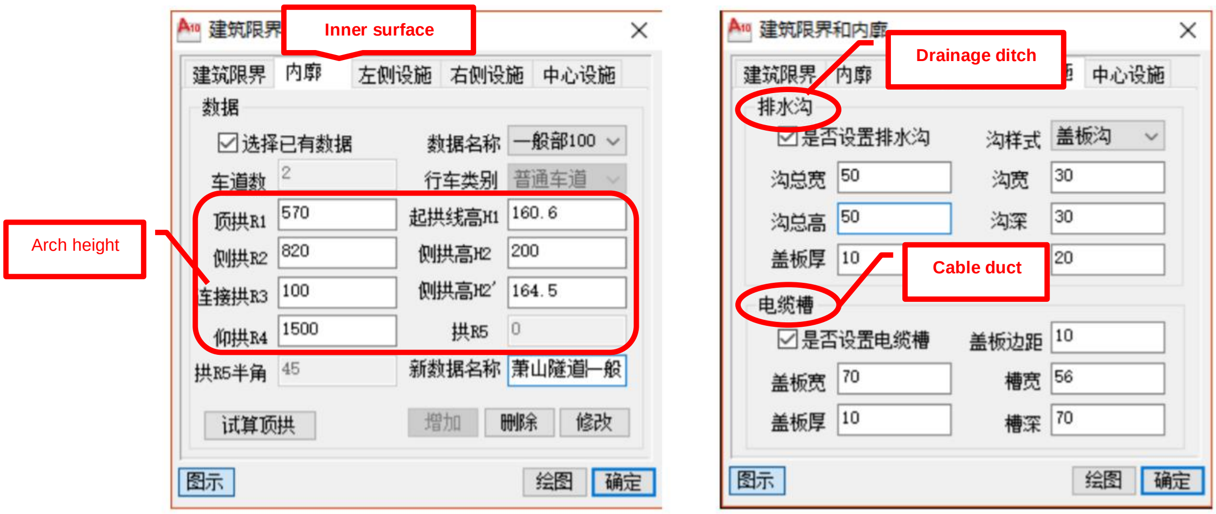

Figure 12. Tunnel inner structure settings by HintSD [21].

In addition, based on the surrounding rock segment data, segment lining can be achieved automatically and dynamically, as shown in figure 13.

Figure 13. Lining segment settings by HintSD [21].

A section drawing of surrounding rock and masonry structures can be also created, as shown in figure 14.

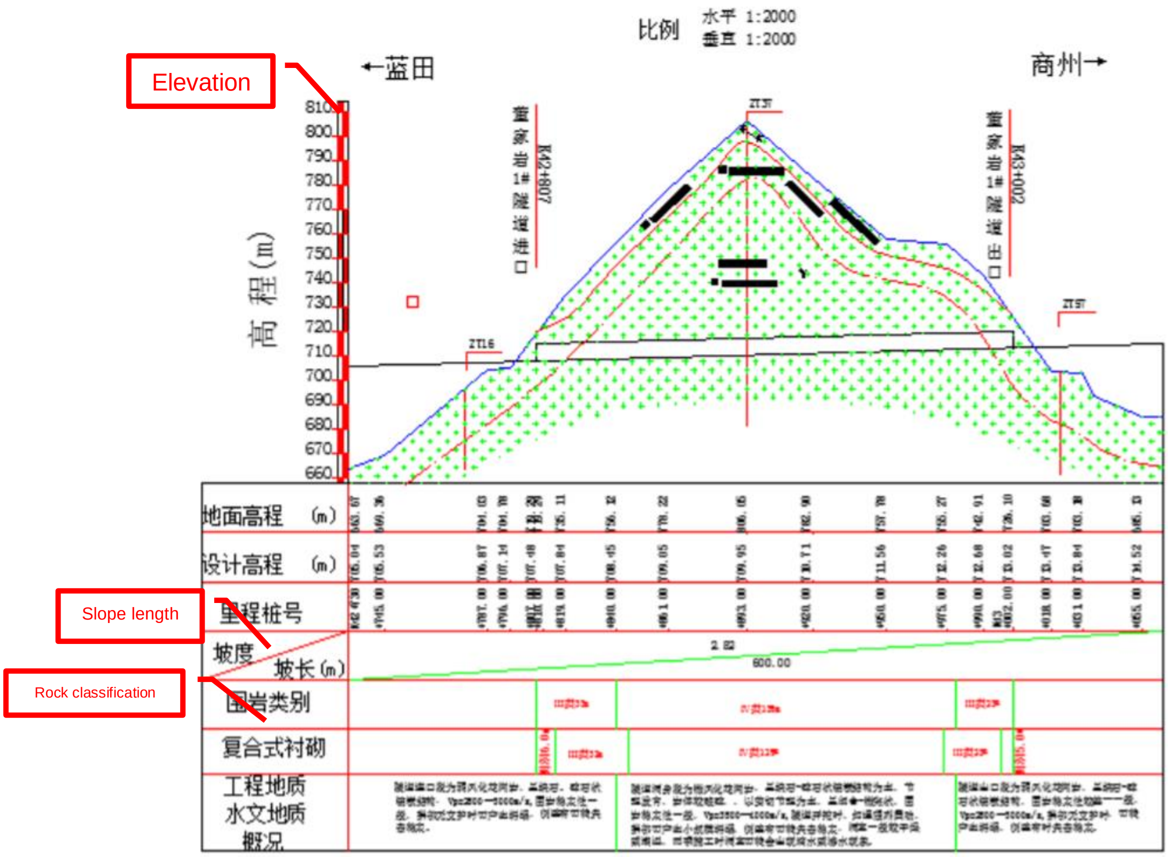

Figure 14. Section drawing of surrounding rock and masonry structures [21].

After the completion of the tunnel lining segment, the lining design, which includes lining structural design, advanced support design, steel arch design, and lining reinforcement design, can be accomplished swiftly, as shown figure 15.

Figure 15. The lining structure design interface with HintSD. [21.]

Then, the tunnel lining design drawings with all engineering components quantities related to tunnel projects can also be generated with the HintSD system, as shown figure 16. [21.]

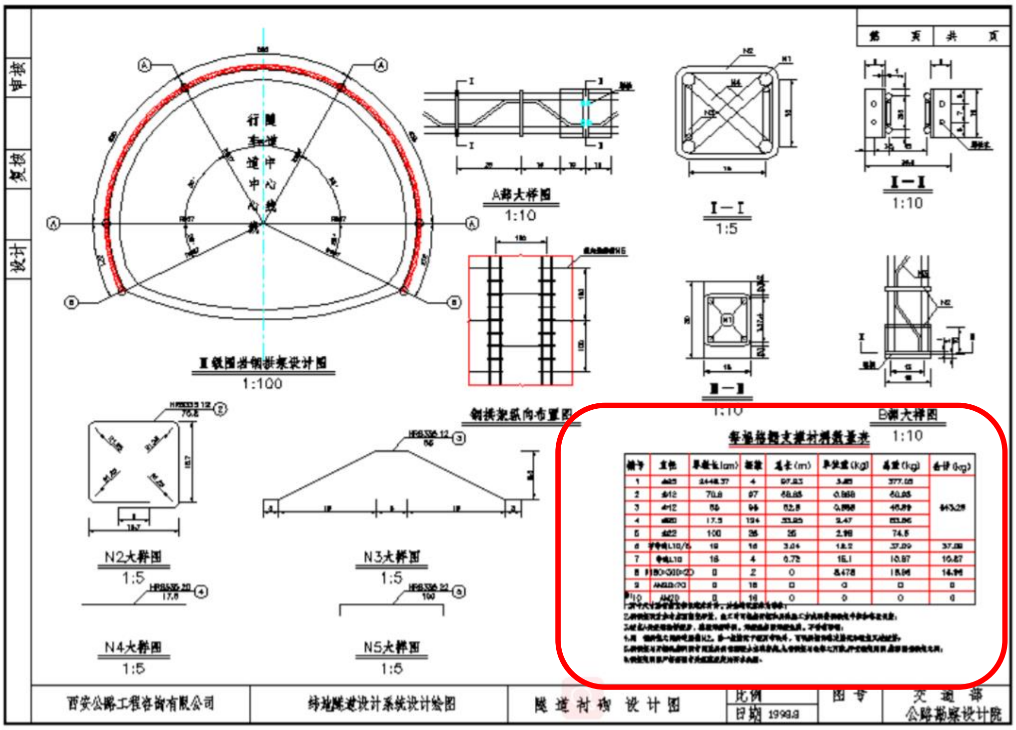

Figure 16. Tunnel lining design drawing generated with HintSD [21].

With the help of this drawing as well as the components quantities statistics, the central line of the tunnel can be defined. The design process of the lining can be accelerated, the necessary components and materials can be prefabricated and ordered from factory.

3.3 BIM-Based Tunnel Design with HintSD

A lot of Chinese construction projects need to start with the transfer of 2D drawings to a 3D model, whereas the HintSD system can integrated the of design and modeling processes. A model of the components of tunnel construction can be created automatically when the design is completed. [21.]

In tunnel design, according to the data of the lining segment and assembled lining, a solid 3D model of tunnel trunk lining can be created. The model includes the inner frame, exterior frame, rock bolt, and lining steel. The lining design, reinforcement layout, as well as the collision detection can be further evaluated on the basis of BIM model. [21.] A tunnel trunk lining model created by the HintSD system is shown in figure 17 below.

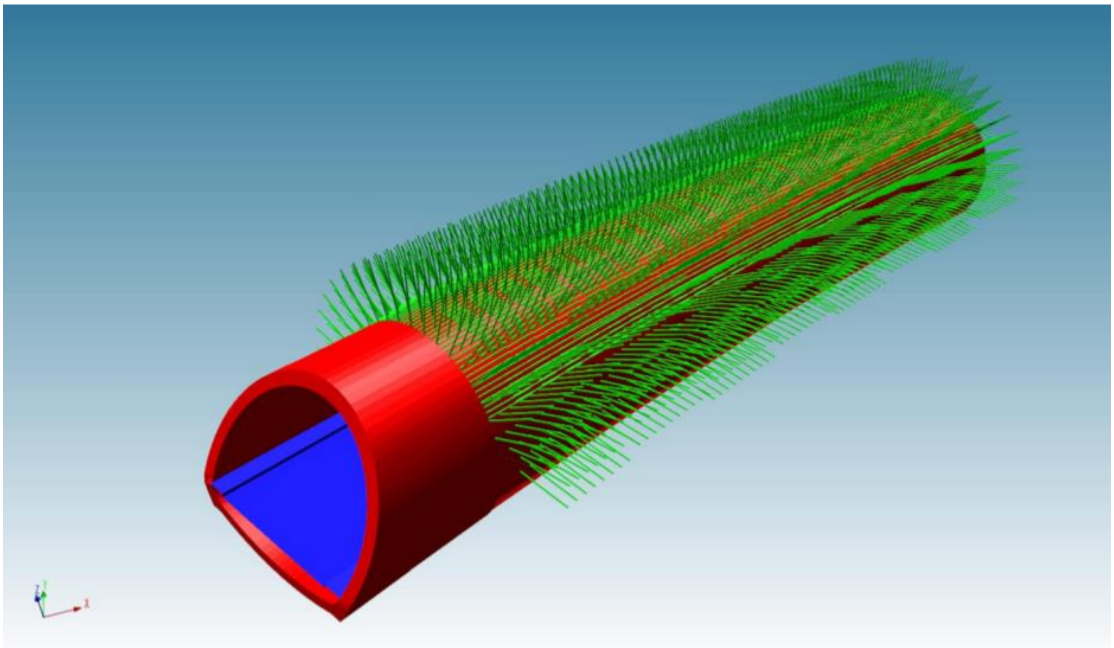

Figure 17. Tunnel lining BIM model by Hint SD [21].

In the design of tunnel construction, it is widely believed by tunnel engineers that the location selection and layout of the tunnel entrance are the most important factors that will influence the whole tunnel project. Tunnel design professionals are particularly concerned about the rational layout of the tunnel portal. The design should not only consider the condition and change of the surrounding geography and geomorphic conditions, but also the geology and the condition of the surrounding rock. Hence, the selection of portal location becomes one of the most difficult and significant issues. [21.]

Based on BIM technology, the HintSD system developed a three-dimensional interactive layout function, helping with the dynamically visualized design of a tunnel portal such as the layout, adjustment, and optimization of the portal as shown in figure 18.

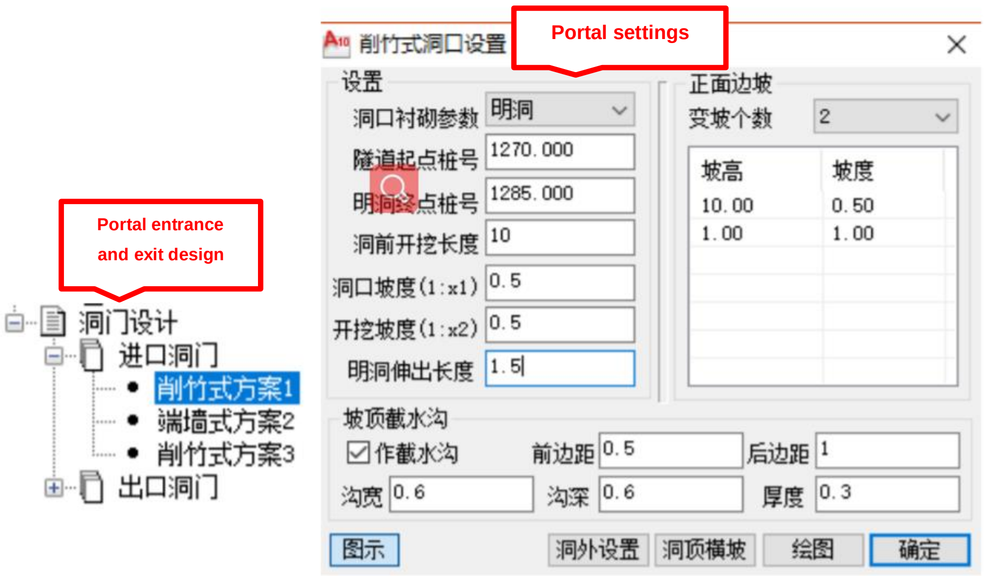

Figure 18. Tunnel portal settings interface by the HintSD system. [21.]

To be more specific, combined with a HintCAD digital terrain model and 3D modelling technology, the Hint SD system can establish a real-time 3D model of the surrounding terrain, a tunnel portal, and of a tunnel section, as shown in figure 19. Users can browse the real-time changes of the solid model of a tunnel portal by changing the stake number of the portal location and axis. It provides support for a reasonable selection of the tunnel portal location as well as coordination between the portal and surrounding topography, completely changing the tunnel portal design which has often been based on imagination. [21.]

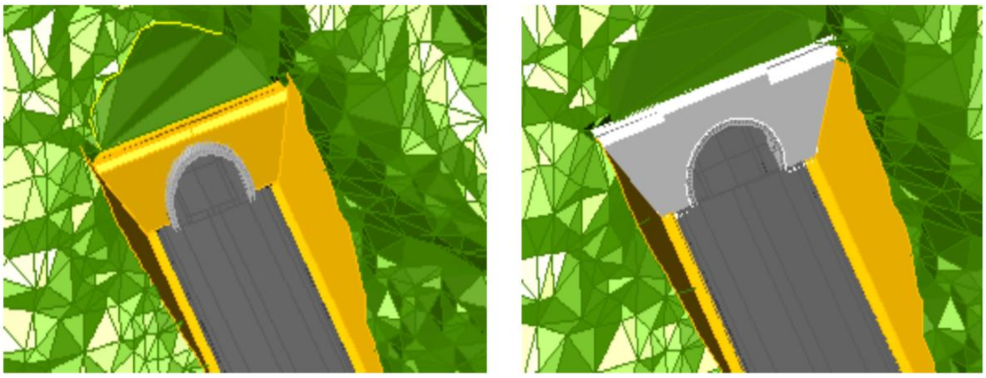

Figure 19. 3D model of the portal and surrounding terrain by HintSD [21].

After a model of the portal is created, the Hint system automatically generates a drawing of the vertical, plan-profile of the portal as well as an open-cut excavation, as shown in figure 20.

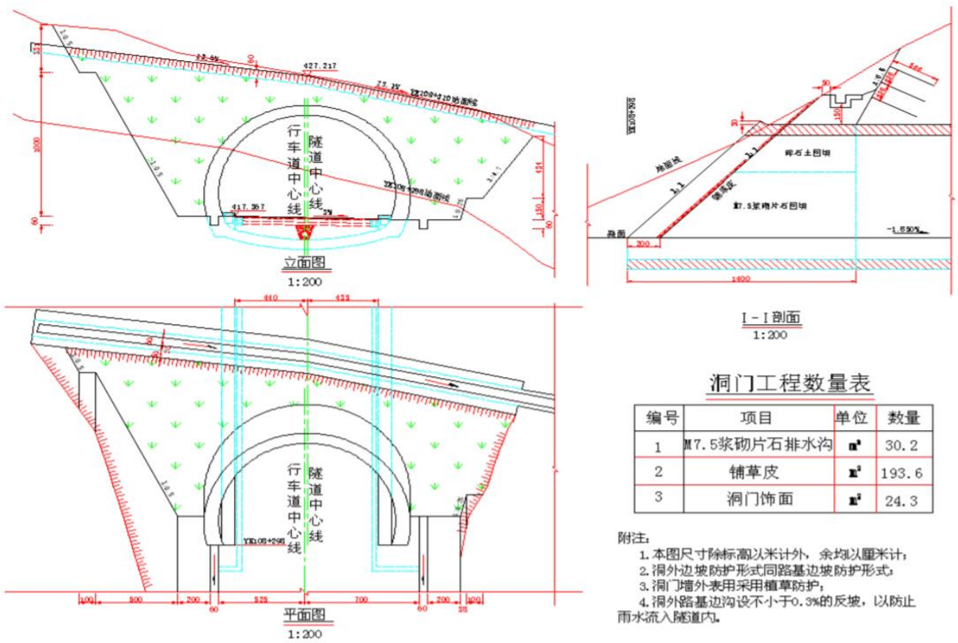

Figure 20. Detailed graphics of portal vertical and plan-profile drawings. [21.]

Based on the design data of lining segments, the lining length, and the design data of the portal, the HintSD system can calculate the quantities of the components for the whole tunnel or any part of the tunnel, generating a bill of quantities for the project components.

4 Underground Pipeline Clash Detection with BIM

4.1 Underground Pipeline System Characteristics

There are two main factors that cause difficulties in underground pipeline construction. The first factor is the limited space in an underground environment. The space between the equipment area corridor, the platform, and the platform stairs is limited, which results in difficulties in pipeline construction as shown in figure 21. Once the pipeline installation is unreasonable, there will be no installation space for an individual pipeline, which causes problems like redundant pipeline exposed to the public area. [22.]

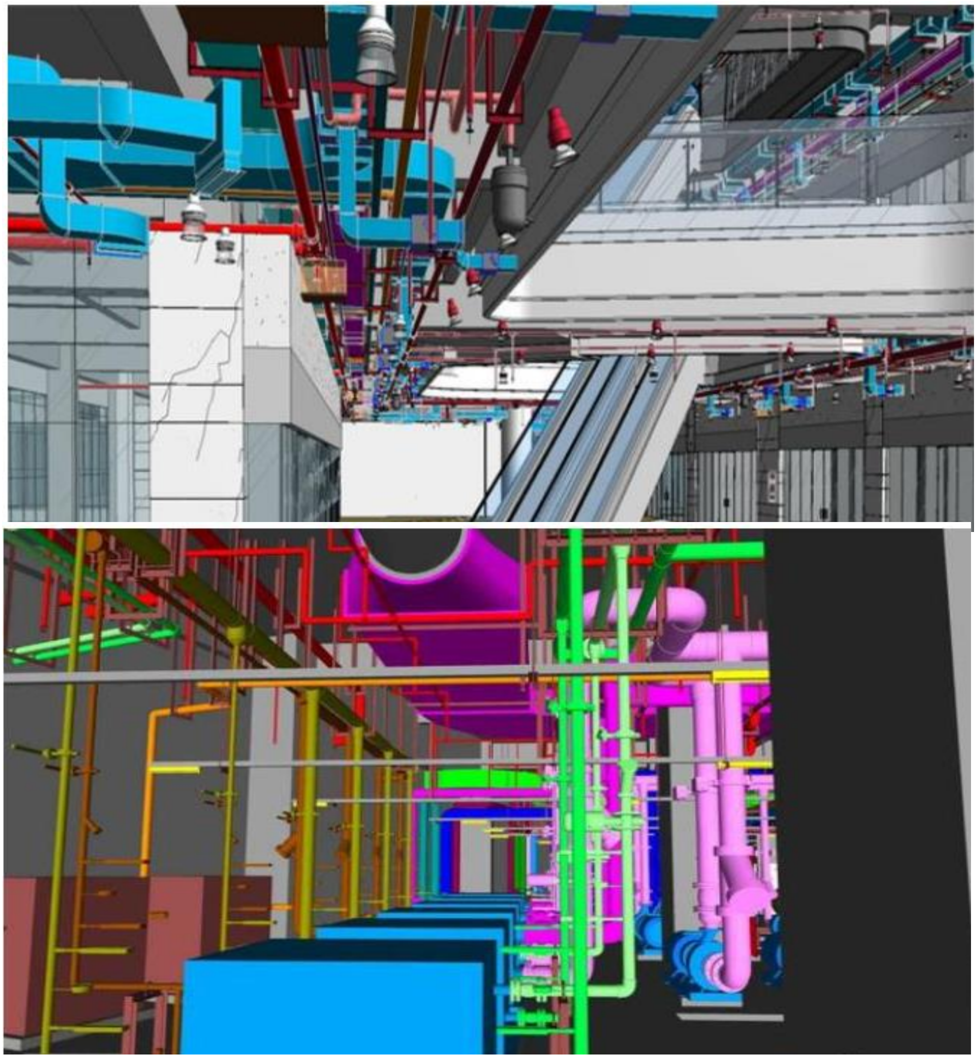

Figure 21. Complicated pipeline system in the metro station [22].

The second factor is that the pipeline systems of an underground transportation station always involves a great variety of professions, which can cause pipeline crossings so that collisions can appear. The ventilation ducts, electrical wires, supply water and drainage pipes, as well as the suspensions and support spare all involved in pipeline construction. Massive pipelines with different dimensions of the reserved holes makes pipeline system construction complicated. The pipelines for different systems all need to go through the corridors of the equipment area. If the optimization is faulty, there will be pipeline cross-interference and lack of pipeline installation space.

4.2 Collision Detection

Collision detection means that the intersections of different parts of the building are checked. It is the key to collaborative design. There are three main types of geometric collisions in underground transportation construction: hard collisions, soft collisions, and clearance collisions. A hard collision is a collision between two parts which cannot be allowed while a soft collision is a collision between two parts that can be allowed within a limit. A clearance collision means two parts do not actually physically collide, but the gap between them is less than an acceptable limit. Except the geometric collisions, semantic and rule-based detection algorithms can also be used for collision detection. [23; 24].

In the field of underground construction, BIM technology is mainly used for hard collision detection. The collision are pipeline collisions, collisions between mechanical and electrical equipment and structures, as well as collisions between mechanical equipment and architecture. BIM can be used to modify the collision problem in the early stage of design to reduce the design changes and rework in the later construction stages. In as 3D visualized BIM model, the collision positions can be located automatically. The steps of pipeline collision detection in underground transportation engineering are listed below. [24.]

- prior hole detection
- tubular well detection
- clear height detection

- fire-resisting shelter detection
- door height detection
- air shaft hanging plate detection
- waterpipe detection
- windpipe detection
- cable bridge detection

4.3 BIM-Based Pipeline Optimization

In the mechanical and electrical engineering of underground transportation construction, the optimization of pipelines affects the quality and schedule of the mechanical and electrical settlement. Hence, the requirement of electrical and mechanical construction management is higher than that of other professions. [25.] Traditional pipeline collision detection is usually based on 2D drawings and the experience and spatial imagination of the engineers. Some special collision cannot be detected due to the massive and complicated pipeline distribution. The characteristics of the visualization of the 3D model of BIM can assist the constructors to observe the layout of the pipeline system. Executing the clash detection and space optimization with BIM in the preliminary stages, the potential mistakes and rework can be avoided. In addition, the headroom clearance and the pipeline configuration scheme can also be optimized with BIM, so that the layout of the pipeline system can be constructed reasonably and in a well-organized manner. [26.] figure 22 shows the advantage of BIM in 3D clash detection compared with AutoCAD drawing.

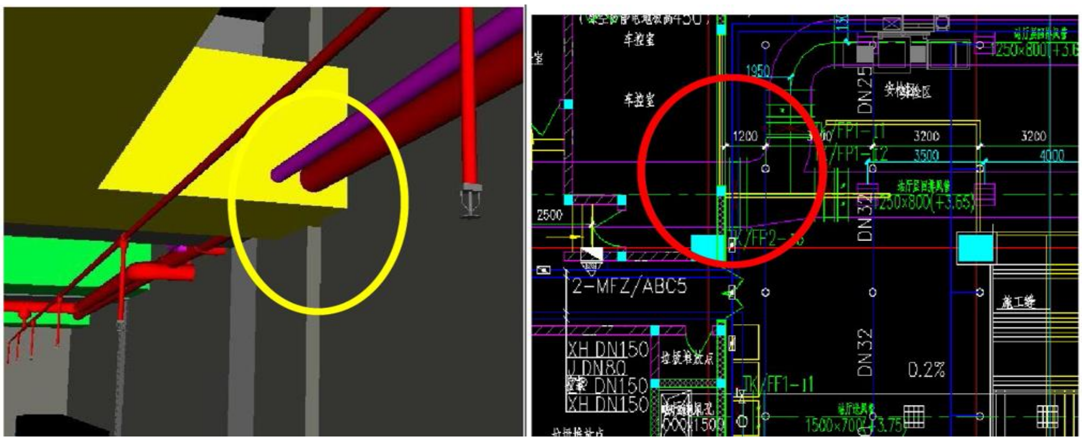

Figure 22. The comparison between 2D drawing and 3D model [15].

The main process of Aim-based pipeline distribution optimization is listed in figure 23 below.

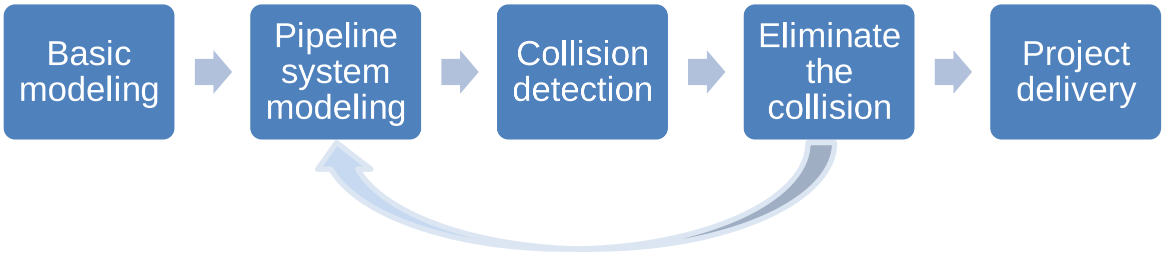

Figure 23. Pipeline optimization process [26].

In the pipeline system modelling process, a BIM engineer creates the pipeline model by Revit, adding the information of drawings into the model. The optimization of an intensive underground pipeline area is always based on the principle of wind duct at the top, cable bridge at the bottom. The relative positions between the pipeline systems and the equipment can be shown clearly, and the pipeline cross-sections drawn of each part can be exported easily, making the installation of integrated piping support and hanger convenient. BIM can also be used in cable bridge optimization. The sequence of the laying cable in the cable bridge can be arranged automatically with BIM on the basis of the principle of short cable at the top and long cable at the bottom. [26; 27.]

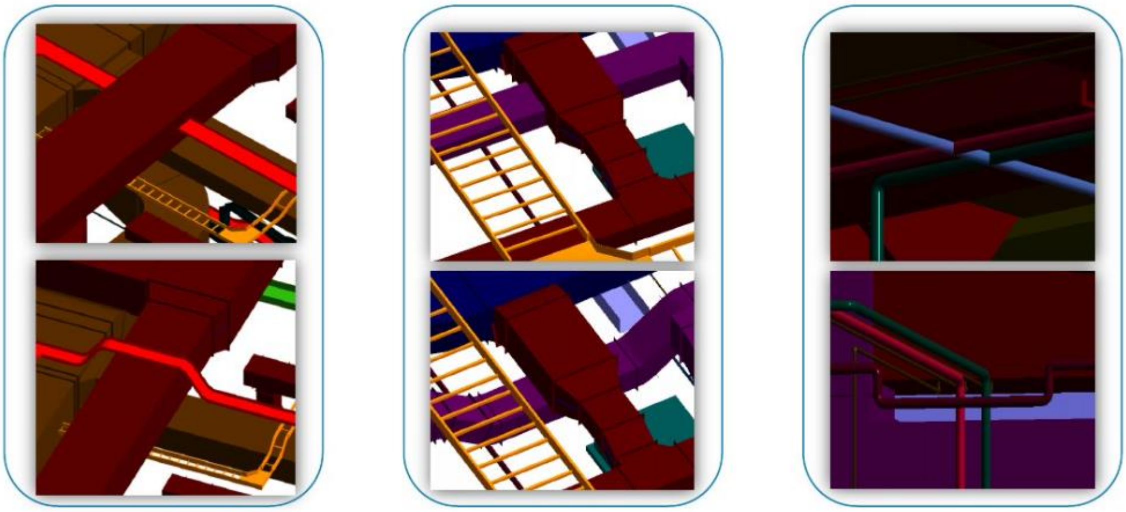

Figure 24. Pipeline distribution optimization based on BIM [28].

The optimized cable model as shown in figure 24 above is more reasonable and well-organized than the distribution before the optimization, eliminating mistakes in hole reservations for the pipeline system, saving the usage of cable conductors. In addition, the BIM-based pipeline optimization technology can decrease the space occupation of limited underground space, so that the metro station ceiling height can be raised. [27; 28.]

5 Use of BIM for LianBan Metro Station

Lianban station is a middle station in the Xiamen subway line number.1 metro project. The station is a two-layer underground station located at the intersection of Hubin South road and HuMing road. The main body of the station with total length 207.4 m and total area 12,516 m², contains four entrances, one urgent evacuation entrance, and two ventilation kiosks. The standard section of the station is 20.7 m in width and 12 m in burial depth, with a wall supported 1000mm diaphragm. One of the station entrances is directly linked to the Xiamen international trading building. [29.]

Figure 25. Lianban metro station hall [29].

The difficulties of the Lianban station project can be listed in several parts. Firstly, this project involves 42 different disciplines, nine in civil engineering, 20 in electrical and mechanical engineering, seven in collaborative design and six in other professions. The coordination of work between the different sectors is hard to implement. Secondly, the designer is hard to work collaboratively because the project involves different design organizations. The third difficulty is that the construction site is located in an underground environment, which means the working space is crowded, and the pipeline system is complex. In addition, due to the complicated surroundings, with the limited design period requirement, the difficulties of the project implementation have been increased. [30.]

To solve the difficulties and problems, a BIM design team of BIM engineers is formed. With BIM technology, projects can be constructed at a high level of accuracy with great communication between different specialties. To be more specific, BIM assists the project at the design phase, including civil engineering collaborative design, pipeline system collaborative design as well as integrated collaborative design. Furthermore, BIM technology is used in the construction phase of the project. [30.]

5.1 BIM in Civil Engineering Collaborative Design

The Lianban metro station project starts with the selection of scheme for the metro railway route. By combining the BIM model with the GIS (Geographic Information System), shown in the figure 26 below, the metro railway route design can be demonstrated in a real and stereoscopic way. This provides the route scheme selection with a direct and effective basis. [30.]

Figure 26. Combined BIM technology with GIS [30].

BIM engineers use Revit to accomplish the modelling process of the terrain and surrounding buildings and environment, shown like figure 27 below. Then, the model is imported to Autodesk Infraworks for roaming, and analysing the relationships between the surrounding environment and the metro station subsidiary facilities, such as entrances and wind pavilions. With the help of the BIM model and its roaming function, the design scheme can be directly shown to the owner, which brings great convenience to the coordination of the design work between the metro station and the ground environment. [30.]

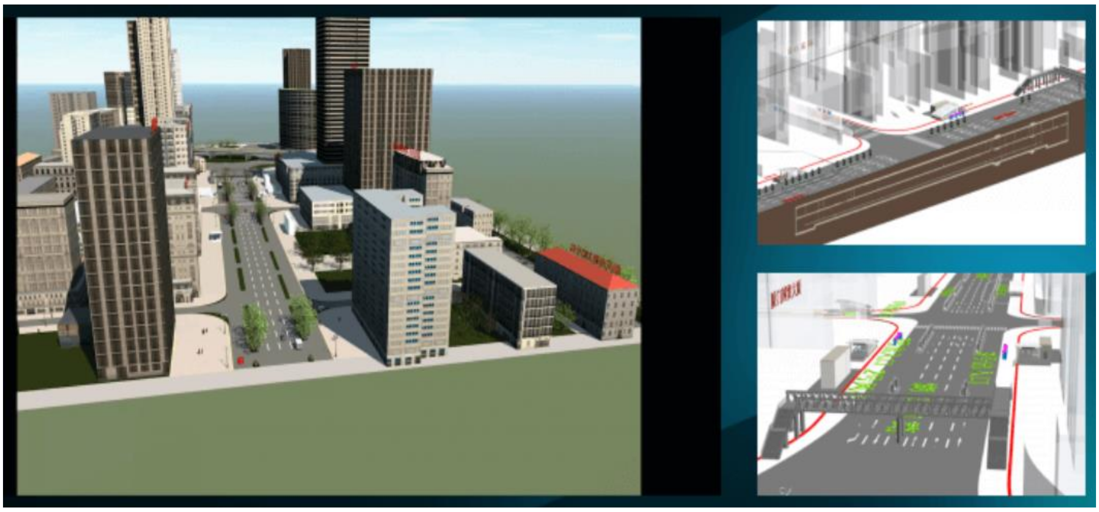

Figure 27. Lianban station terrain model based on BIM [30].

The modelling of Lianban metro station is based on 2D drawings. The architectural group generates a plane graph at the beginning of the design phase, then the civil engineering group generates a model of the station hall, and the platform, as well as the model of the terrain. The 2D drawings and the 3D model are shown in figure 28.

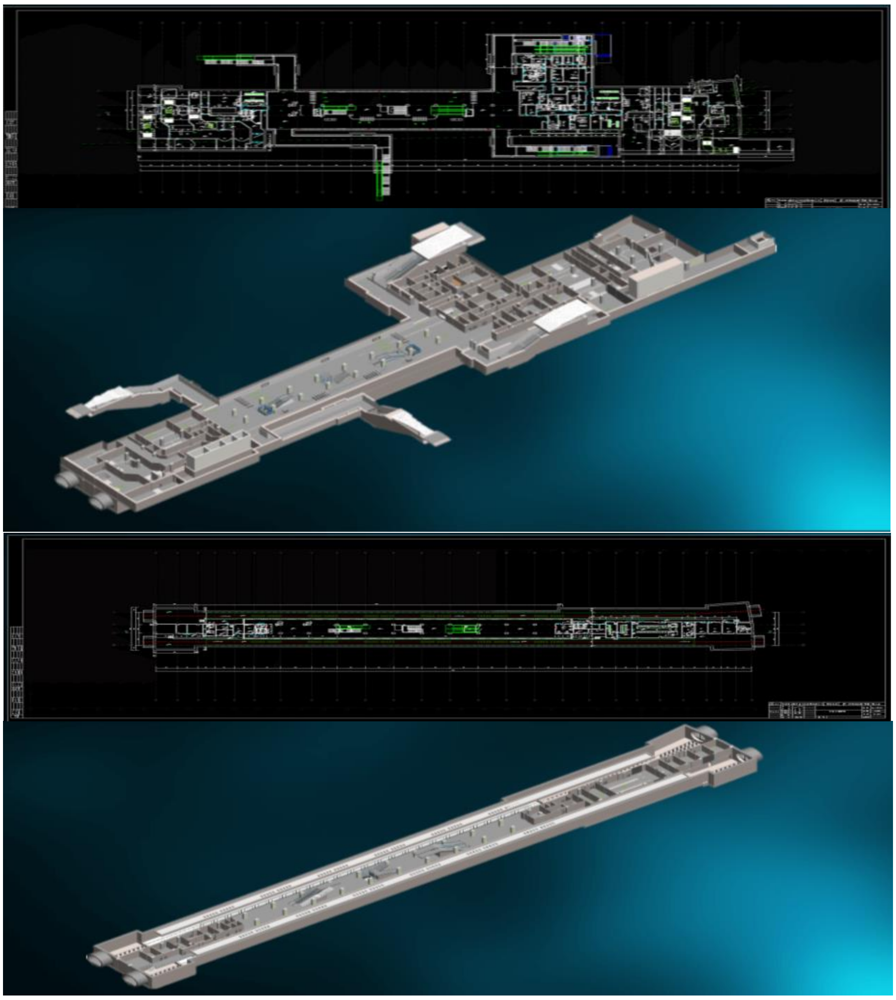

Figure 28. Model of Lianban station hall and Platform [30].

After the civil-related BIM model of the Lianban station is created, the designer inspects the rationality of components details in the model, for example, the opening hole reservation. Some significant data can be also checked from the 3D model like clear height detection. In addition, considering the Lianban station is one of the highest passenger flow volume underground metro stations, the designer also simulated the evacuation process within the BIM software, providing the solutions for an emergency in advance.

5.2 BIM in Comprehensive Design of Pipeline Systems

In the pipeline system's comprehensive design stage of the Lianban project, the BIM design team collaborates with the designer, creates the model for wind ducts, water pipes and electricity supply duct on the basis of the tender invitation and construction blueprint. The follow-up design work is also carried out in the BIM model. Based on the design progress and project quality, design problems such as pipeline collisions can be solved with the help of BIM technology. A flow chart of the comprehensive design of a pipeline system is shown in the figure 29 below. [30.]

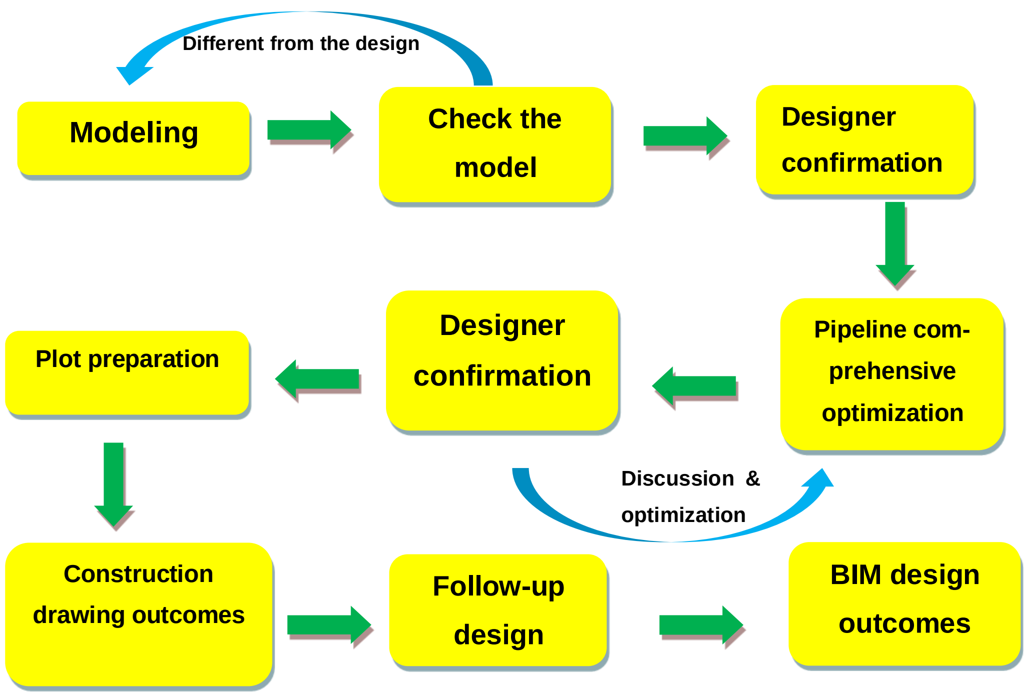

Figure 29. Pipeline system comprehensive design flow chart [30].

As the flow chart shows, the pipeline system model needs to be checked in detail after the modelling process in order to eliminate mistakes and leakage. Then the designer of the pipeline system needs to confirm the consistency of the model and drawings by comparing the 2D drawing generated with AutoCAD with the 3D drawing generated with Revit, as shown in figure 30 below.

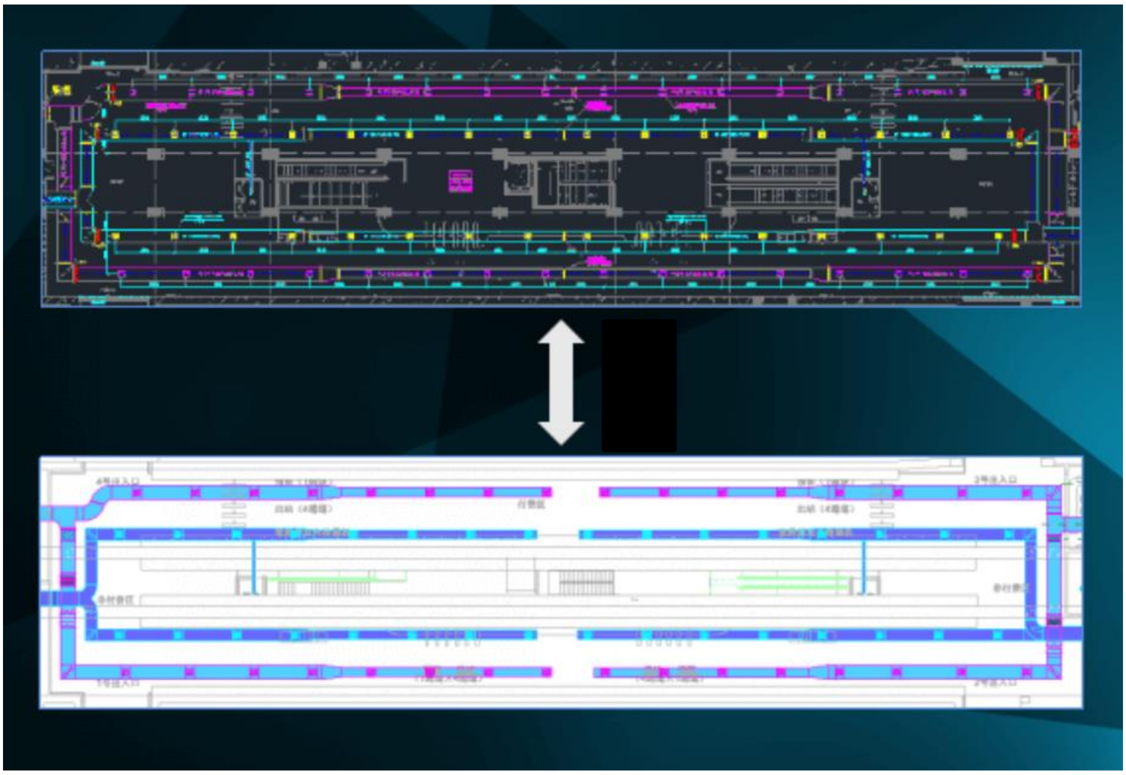

Figure 30. Drawing comparison for designer confirmation. [30.]

After the designer has confirmed the drawing, the next step is the pipeline optimization. In the Lianban station project, the optimization process should always consider three requirements: the space requirements for pipeline layout, the pipeline equipment position requirements, and the requirements set by the maintenance and inspections to the pipeline installation. Furthermore, the optimization process should always obey the optimization order, from the component parties to the integrated system. In the Lianban station project, the pipeline system optimization starts from the air ducts and structural detection, followed by the aisles, private rooms, public spaces, and mechanical rooms, finally connecting the whole pipeline system. [30.]

The pipeline clash detection of the Lianban project is executed with the Clash Detection function of Navisworks. First, input the integrated model is loaded into Navisworks, the type of collision is set as Hard Collision and the location tolerance as 0.001 m, and then the clash detection can be executed automatically. Second, the repeated collision points are deleted and rechecked. Finally, the result of the collision detection is exported into a graphic result report. [30.]

There are 363 collisions reported in the Lianban project. Each report listed the specific clashing point location, description of the collision, the relative location in the 2D drawing, as well as the adjustment method. The clash report reflects the mistakes of the pipeline system model, the structural model and the architectural model visually. Some of the collisions detected in the project are discussed below. [30.]

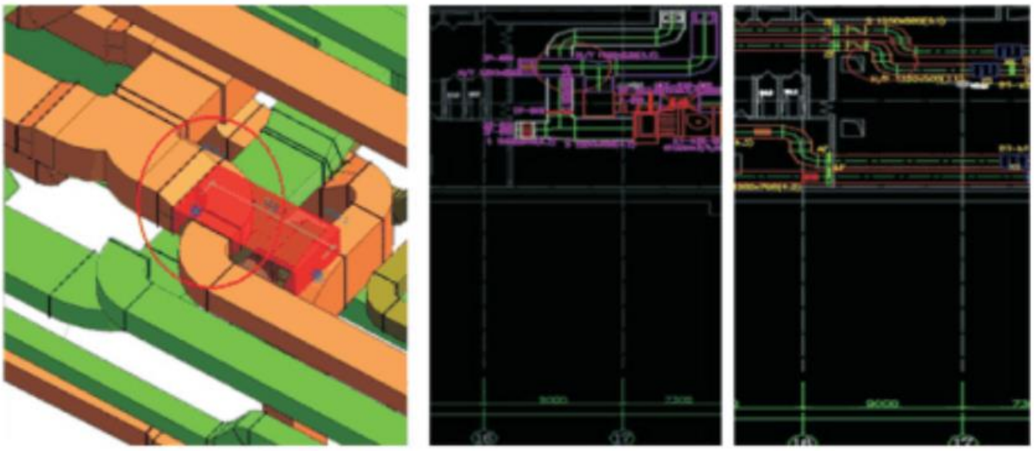

Figure 31. HVAC clash point and the relative drawing [30].

The collision in an independent system can be easily detected with the Clash Detection function of Navisworks by choosing MEP for both detection objects. Figure 31 above shows a collision between the small air return pipe 1000*500+4500 mm and a large air return pipe 1600*630+4400mm in the middle plate. [30.]

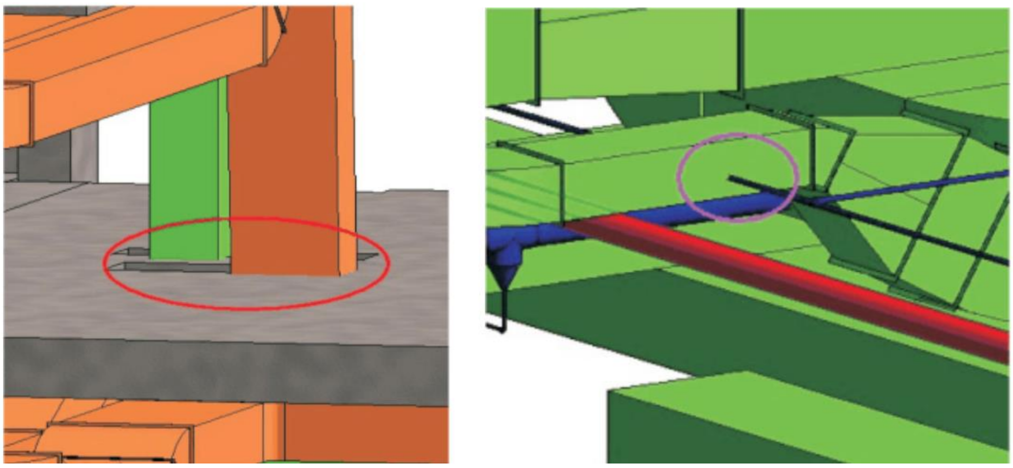

Figure 32. Pipeline Collision of multiple system detection [30].

The Lianban station involves multiple pipeline systems, the execution of one detection may cause clutter at the collision point display. In order to reduce the number of checks, a multiple system detection should be made, so that a partial collision of pipelines in the different systems can be detected. Figure 32 shows the collision between a supply water pipe and ventilation pipe, as well as the collision between HVAC systems and the structures. With BIM-based pipeline optimization, the clearance height of Lianban is raised by 60 cm, saving about 2,000,000 yuan for this single station. [30.]

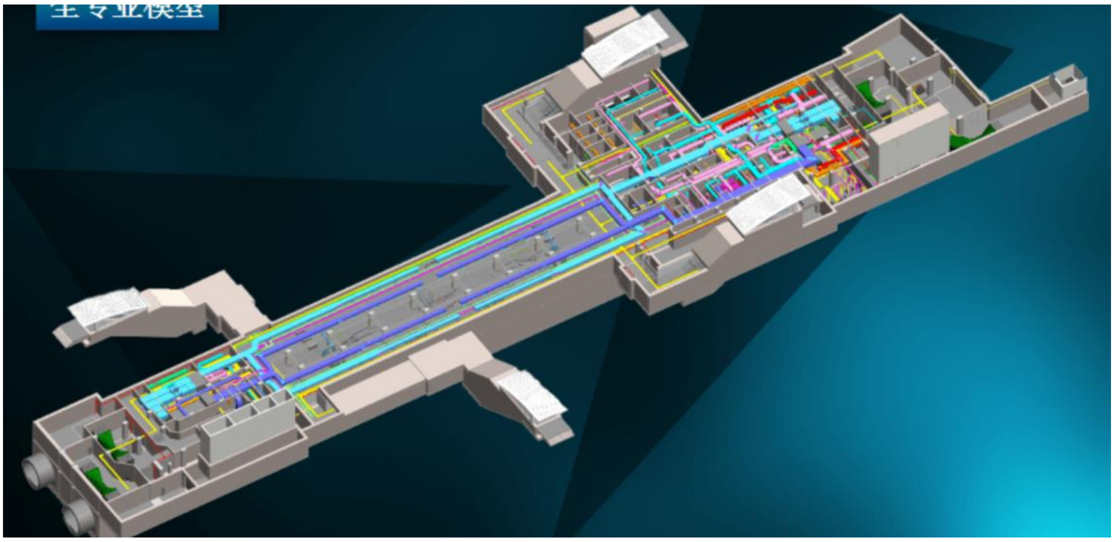

Figure 33. Integrated BIM model of Lianban station [30].

After the optimization is re- confirmed by the designer, the construction drawings for the HVAC, supply water and drainage, and MEP pipeline systems for the Lianban station can be created on the basis of the modified BIM model, shown in appendix 1. An impeccable integrated BIM model of the Lianban metro station with both civil engineering and pipeline system models can be combined, as shown in figure 33 above.

5.3 BIM in Construction Phase

In addition to the design phase, BIM technology also helps with the construction phase of the Lianban station project especially for the M&E (mechanical and electrical) detailed construction. With the support of the BIM model created in the design phase, the collision between the M&E components and the has been eliminated. Figure 34 shows illustrates how some collisions between the pipeline and suspended ceiling are caused because the designer did not consider the thickness of the suspended ceiling in the design phase of Lianban project. The problem has been deleted and solved in time before the construction. [30.]

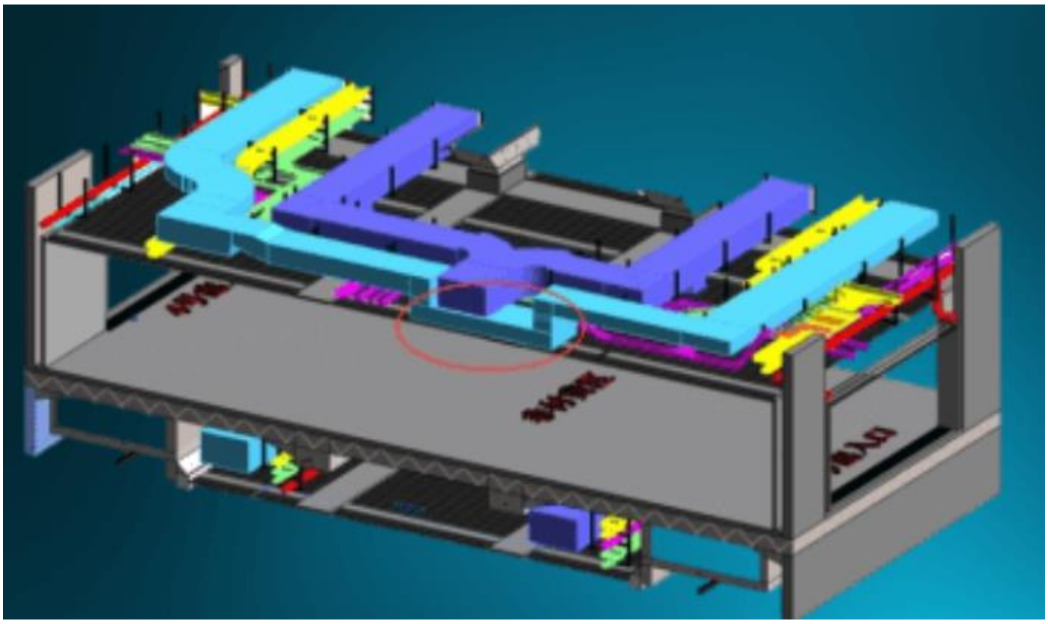

Figure 34. M&E deepen design based on BIM [30].

In the construction phase, the installation of pipe support hangers is also a challenge for the Lianban station project. With the help of BIM technology, an integrated model for hangers is created, then accurate drawings for local supports and hangers are generated from the BIM model. The drawings can be submitted to the manufacture directly, and the manufacture of the support hangers can be based on the picture shown in the picture 35 below. With the detailed support drawings, the support hanger prefabrication is done before the start of the construction, accelerating the construction schedule. [30.]

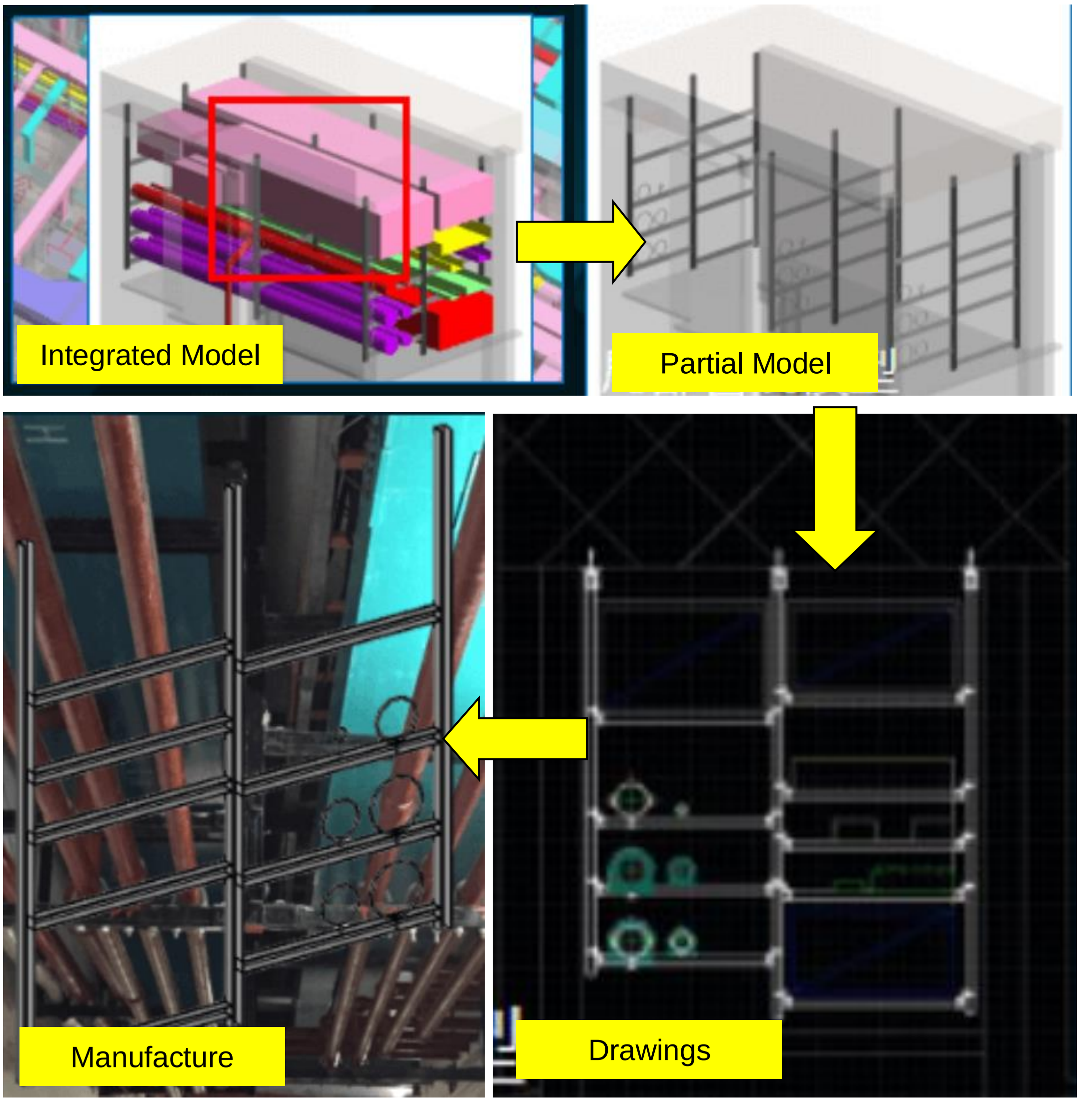

Figure 35. the support hangers manufacture process base on BIM. [30.]

Before the start of the construction, the construction process of the Lianban project is simulated with the help of BIM technology, as shown in figure 36, On one hand, the simulation can test the feasibility of the construction schedule, which is helpful for the project construction management of the project, on the other hand, the number of components used in the project is calculated with the Quantity Take-off function of Revit, providing a reference for budget estimate. [30.]

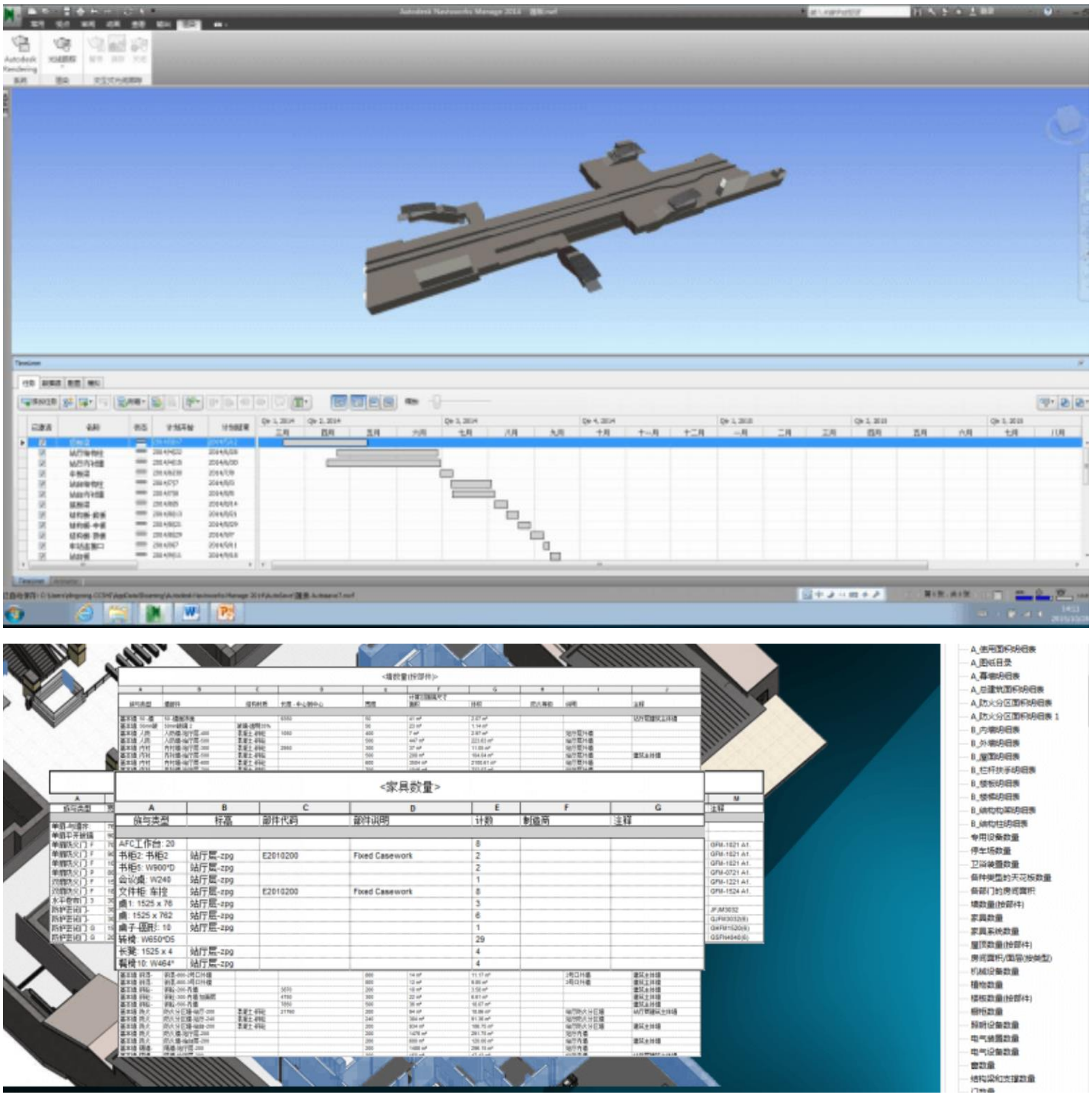

Figure 36. Construction simulation and quantity take-off with BIM [30].

In the actual construction site of Lianban station, the constructor used the BIM 360 Glue to compare the model with the real-time construction situation on the actual site. [30.] The software and model can be downloaded to the mobile devices which is easy to be carried to the construction site, shown in figure 37 below,

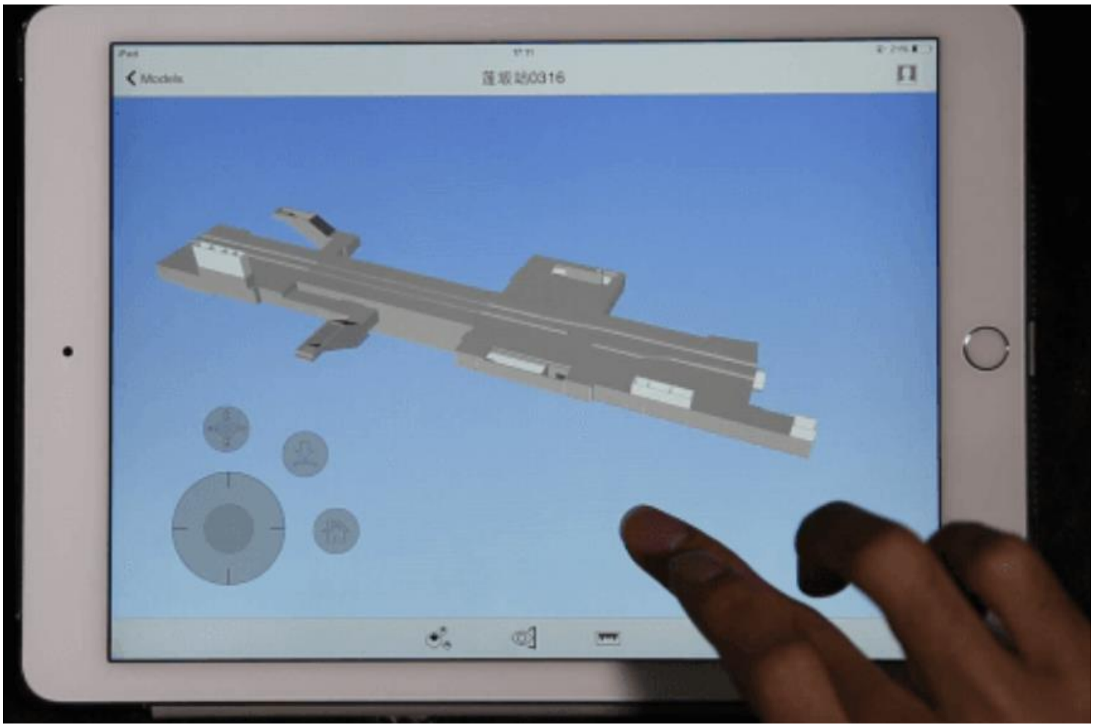

Figure 37. Browsing the station model in the mobile device by BIM 360 Glue [30].

In the LianBan metro station project, BIM technology is necessary for both design and construction phases. In the infrastructure design phase, BIM can help with the terrain analysis and site planning, the station infrastructural 3D model can be created to inspect the design details and find design mistakes. In the pipeline design phase, BIM provides different sectors with an integrated platform so that the coordination between different sectors can be easily executed. The integrated pipeline system model can be generated and optimized with BIM technology, eliminating collisions before construction.

In the construction phase, the installation of machines and components such as pipe hangers can be more accurate with the help of the M&E BIM model. The construction process can be simulated with the station BIM model, the number of components and construction budgets can be calculated automatically. The construction site work becomes clearer with the BIM application on mobile devices. The difficulties of the project are raised and solved before the project starts.

6 Development and Challenges

BIM has been increasingly mandated by government and public clients around the world. The US General Services Administration pioneered the adoption of BIM for public projects. In the UK, BIM has been used on major new-build projects, but in refurbishment and infrastructure the use of BIM has not been as widespread. Nordic countries like Finland, Norway, and Denmark are the earliest BIM adopters, and BIM tools are widely used in 70% of their construction projects. The adoption of BIM is increasing in Asian countries like South Korea, Japan, and China, while the biggest challenge is the lack of skilled BIM engineers. Although BIM is not compulsory in Australia, BIM is a promoter of the technology with the implementation of the first 5D BIM pilot project. In Latin America, BIM is mainly used for cost control of the construction phase, the use in the design phase is still limited. [31; 32.]

Nowadays, green building is involved in the deeper level of sustainable development architecture. BIM technology can assist green building engineers to compare sustainable alternatives in the design phase, reduce the energy requirement of green buildings, minimize waste, and lower costs. With the assist of BIM, the energy consumption of a building can be analysed with BIM-based conceptual energy models. In addition to this, a topography model can be built with BIM for the solar and shadow analysis. After all, the solar energy and daylight are key factors in green building design. [33.]

With the rapid development of underground transportation engineering, the use of BIM has a wide prospect which brings convenience for the construction of underground transportation. However, there are still some obstacles on the road to general use of BIM. First and foremost, there are no standards or criterion for BIM technology in underground transportation construction. There is no regulation system or standard specification for the use of BIM in the construction of underground transportation. Some components are still missing especially in the field of underground transportation engineering. BIM engineers need to create a library for the missing components, which makes the modelling process of underground projects much more difficult than that in other fields of engineering. [34; 35.]

Another challenge is that the software lacks compatibility. Some of the software can not satisfied with the user-defined requirement for multiple metro station construction types. In addition, some models and data transfer inside the software, as well as the secondary development of the software is difficult to execute. [34.]

A further challenge is about investment. Although BIM can bring tremendous economic benefits to a project, the investment in software purchasing and training of personnel can be severe in the beginning. [34.]

The last challenge is a lack of technical BIM engineers because the most experienced engineers are accustomed to the traditional 2D drawing design method. In addition, the adoption of BIM technology is limited in China as the procurement for the design and construction elements of projects must be tendered separately. All these challenges slow down the development of BIM in the field of underground transportation engineering to some degree. [34.]

7 Conclusion

It is shown in this thesis that the use of BIM technology in underground transportation engineering offers several benefits in each phase of construction. In the design phase, BIM can provide a collaborative platform for the designers of the various sub-systems, help the designers realize the model visualization, promoting the efficiency of design. In the construction phase, a BIM-based 4D-simulated construction function can simulate the construction process and determine the best construction plan, reducing rework and improving project quality. In the facility maintenance and operation phase, BIM can also assist the management of equipment and response to emergencies promptly by its dynamic monitoring function. Furthermore, BIM can also manage the construction space, the project statistics and project cost of underground transportation engineering.

The BIM-based modelling process of underground transportation engineering can be divided by different sub-systems into architecture modelling, structural modelling, mechanical and electrical modelling, modelling of surrounding environment and railway modelling. The most important function of BIM in underground transportation modelling is pipeline clash detection. With the help of BIM-based pipeline modelling, the collision position of the pipelines of the various sub-systems can be located precisely, and the distribution of pipelines can be optimized. Thus, omissions and rework can be avoided underground pipeline construction.

Underground tunnel design is also an important process in the construction of underground transportation. With the help of BIM technology associated with HintSD software, the data and resources from the geometric design of a project and complete horizontal and longitudinal tunnel layouts can be shared directly. For the lining design, the lining process of a segment can be automatically executed according to the surrounding rock conditions. All engineering quantities of tunnel projects can be generated automatically. In addition, the design and selection of the tunnel portal can be easily done with the digital terrain model of HintSD and 3D modelling technology.

Based on the case of the Lianban station, the use of BIM in a metro station project can be divided into four phases: the planning phase, the architectural design phase, the pipeline system design phase, and the construction phase. In the planning phase, BIM together with GIS is used to generate a model of the surrounding environment and terrain for the project which helps the designer to plan the station location and coordinate the station with the ground in the beginning of the project. In the architectural design phase, a 3D model of the main body of the station can be created, and 2D drawings can also be generated accurately. In the pipeline system design phase, all pipeline models, which are for HVAC, supply water and drainage, and MEP can be integrated in BIM. The collision detection of different sectors can easily be executed. Based on the number of collisions in the Lianban project, it is obvious that in order to decrease the amount of rework and material waste, collision detection is necessary before construction. In the construction phase, some important components such as pipeline support hangers can be prefabricated by the manufacturer with the help of a BIM model, which accelerates the construction schedule to some degree. A construction process simulation with BIM and a BIM model in mobile devices also help the project to be executed as planned.

In summary, BIM technology is beneficial throughout the whole lifecycle of any part of an underground transportation engineering system. From the planning, design, and construction, to the operation and maintenance, all phases benefit from BIM technology. BIM can connect all parties involved in a project including the owner, designer, constructor, manager, supplier, and operator, improving the efficiency of integrated cooperation. As the quality requirements of underground transportation projects become stricter, the use of BIM technology will become an essential part of future underground transportation projects.

Over the past decade, BIM has become one of the most significant tools in construction. However, the use of BIM is still at the beginning stages in most countries. In order to develop the construction of underground transportation and realize the modernization of urban infrastructure, it is essential to develop and promote BIM technology. Governments should formulate policies and establish BIM standards according to the conditions of the country. The owners of a project should provide BIM with financial support. Enterprises should increase the research and development of BIM software as well as the secondary developments of existing software. Educational organizations should cultivate more highly skilled personnel. Only that way can BIM technology play an active role in the development of future construction.

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Drawings of Lianban Station

Figure 1. HVAC drawing of Lianban station

Figure 2. Supply water and drainage drawing of Lianban station

Drawings of Lianban Station

Figure 3. MEP Drawing of Lianban station