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Article

Research on BIM Technology Standardization and Information Management of Tunnel Engineering Based on the Maturity and Standardity Theory Framework

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Abstract: Information management is an important development direction in the field of tunnel engineering, and BIM technology provides an important approach for the realization of it. However, standardization is the first step of the implementation of BIM technology. Only through a set of unified BIM standards for tunnel engineering can the late platform development with information sharing and exchange be carried out normally and orderly. In view of the current lack of unified BIM technology standards and related theoretical research in the field of tunnel engineering, this paper proposes a theoretical framework for the study of a BIM technology standard in the field of tunnel engineering on the basis of the existing standardization research work and establishes a new maturity model in the field of tunnel engineering for the first time. On this basis, this paper classifies and codes the information in the field of tunnel engineering and carries out a series of preliminary studies and discussions on the standardization of BIM technology in the field of tunnel engineering, initially establishing a relatively complete system of BIM technology standards. With the Daliangshan Tunnel under construction in Sichuan Province of China as a pilot application case, the feasibility of the proposed standards is preliminarily verified. In addition, this paper puts forward the new concept of "standard degree" for the first time and tentatively discusses the relationship between the standard degree and four influencing factors, the standard unity degree, the recognition degree of project participants, the applicable degree of software and the perfection degree of platform construction, which provides a reference for subsequent related research and promotes the development of BIM technology standardization and the management process of information in the field of tunnel engineering.

Keywords: tunnel engineering; information management; BIM technology; maturity; standard degree

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1. Introduction

BIM (building information modeling) is the digital expression of the physical and functional characteristics of architectural projects and can realize the sharing of data and information in the whole lifecycle of architectural engineering and promote the collaborative work of all stakeholders in architectural engineering [1,2]. BIM technology has five advantages: visualization, coordination, simulation, optimization and mapping capability, and has been widely applied in the field of architectural engineering [3–6]. Many scholars have carried out a series of related studies from different perspectives by varied methods that have embodied quality control [7], risk assessment [8], carbon emission and thermal comfort [9], environmental protection [10–12], safety, etc., [13–16]. In addition, some scholars have also conducted research on the combination of BIM technology and other technologies such as wireless real-time sensing technology [17–19], 3D laser scanning technology and point cloud technology [20,21].

With the gradual improvement of economic levels, infrastructure construction in countries around the world has developed rapidly and an increasing number of tunnels have appeared in the fields of railway, highway, water conservancy and urban underground space development [22–24]. Especially in China, large and long tunnels and large tunnel groups have emerged in recent years. However, engineering project management has become a major problem, restricting the development of tunnel engineering [25–29]. The unique advantages of BIM technology provide technical means and approaches to solve this problem, which makes it possible to integrate, informatize and coordinate the management of tunnel engineering. Therefore, some scholars have tried to introduce BIM technology into the field of tunnel engineering. For instance, Zhou and others [15] systematically analyzed the application status of BIM in tunnel engineering in China by summarizing such problems as the lack of standards, software incompatibility and management chaos, and evaluated the application prospect of BIM technology in tunnel engineering. Zheng et al. [30] designed a 3D tunnel modeling method that not only enabled workers to better understand the real-time situation inside the tunnel but also made it easier for tunnel project managers to supervise and modify the tunnel construction schedule. Sharafat et al. [31] proposed a new BIM-based multi-model tunnel information modeling (TIM) framework that improved project management, construction, and delivery by integrating five interrelated data models and project performance data for drilling and blasting tunnel construction. Fabozzi et al. [32] utilized the interoperability from BIM to FEM to BIM to validate the maturity of BIM methods in the field of geotechnical infrastructure applications. Hussain et al. [33] developed a parametric lifecycle carbon assessment (PLCCA) model for automated data integration, dynamic calculation, and online visualization of carbon emissions, and calculated carbon emissions through specific tunnel engineering. Guo et al. [34] proposed a hybrid method combining building information modeling (BIM) and Dempster–Shafer (D-S) evidence theory to support the systemic risk assessment and visualization of underground tunnels. Yin et al. [35] proposed a new framework based on the BIM model, an operation and maintenance database and a monitoring system for the sustainable operation and maintenance of public engineering tunnels.

Although BIM technology has begun to be applied in the field of tunnel engineering, it originated in the field of construction engineering and the standard system is established based on the characteristics of the field. The relevant implementation software is also targeted for the development of construction engineering [36,37]. Therefore, the universality of the original standard system in the field of tunnel engineering and the applicability of the existing software in this field need to be further explored.

The essence and ultimate goal of BIM technology is to achieve information sharing and efficient data docking [38]; therefore, the application of BIM technology needs to be carried out and completed on the premise of standardization. The 21st century is an information age, and the realization of informatization in the field of engineering is a development trend. The emergence of BIM technology provides basic technical means for the informatization in the engineering field. However, in order to realize collaborative work and information sharing among all project participants, unified standards are required so as to better promote the exchange of information and data. Badens et al. adopted the ERP information system and successfully applied it in practical cases, providing new methods for information sharing and management in the construction industry [39]. At present, the application of BIM technology in tunnel engineering is still superficial and cannot be further deepened, which is specifically reflected in the single project participants, single-stage application, information discretization, lack of integrated information management and so on. Through detailed analysis, it can be found that the most fundamental reason for the above application status is that the existing standard system cannot meet the professional requirements of tunnel engineering in terms of applicability. Additionally, there is a lack of a set of professional BIM standards that are fully applicable to the field of tunnel engineering.

Since BIM technology originated from the field of architectural engineering, the formulation and implementation of relevant standards also began in this field and are relatively mature. For example, the United States, the United Kingdom, Finland, Sweden, Norway, Australia, Japan, South Korea and China have all issued BIM standards in the field of architectural engineering [40]. By contrast, there are few BIM standards in the field of tunnel engineering at present. According to the general plan of railway engineering construction informatization by the China Railway Corporation, through extensive investigation and in accordance with the framework of the ISO 12006-2 system, the Railway BIM Alliance has formulated guidelines on the decomposition of the solid structure of railway engineering (version 1.0) and the classification and coding standards of railway engineering information model (version 1.0). However, both standards were compiled with tunnel engineering as a sub-item of railway engineering, and they were only a relatively rough framework in terms of content and far from perfect concerning fineness and completeness. In fact, tunnel engineering, as an independent project, should have a set of independent and complete professional BIM standards.

In view of the application status of the abovementioned BIM technology in the field of tunnel engineering and according to the characteristics of tunnel engineering, this paper systematically studies the BIM standards in the field of tunnel engineering from several aspects such as research basis and theoretical framework, stage information and maturity model, information classification and coding, standardized modeling and application, information achievement delivery and standard degree based on the existing international BIM standards, which will provide a relevant reference for the subsequent research of BIM standards in the tunnel engineering field.

2. Materials and Methods

Tunnel engineering, which is different from architectural engineering, occurs in a zonal distribution and has large spatial spans. The topographical variation along the tunnel line and the geological structure of rock strata are the main factors affecting tunnel construction [41]. Therefore, in addition to the main structure of the tunnel, the topographical and geological conditions across the region are also crucial for tunnel engineering. For urban tunnels, settlements due to loss of effective tensions due to infiltration and drainage must be evaluated [42]. Tunnel engineering deals with a considerable amount of engineering data and information, including topographic data, geological data, unfavorable geological information, main structure design data, information of tunnel excavation and construction, advanced geological prediction information, monitoring measurement information, etc. Vibrations during excavation must be evaluated [43]. At present, these data and this information are relatively discrete and cannot achieve integrated information management. The development of standardization is conducive to the exchange and transmission of information and is of great significance to the realization of the integrated management of engineering data information. Standardization research is closely related to the application of BIM technology in practical engineering. The application of BIM technology in tunnel engineering is mainly embodied in the following aspects:

(1) Topographic and geological informatization: based on the original topographic and geological data and drainage conditions the information that is beneficial to tunnel engineering planning is extracted and analyzed.

(2) Tunnel entrance location and route planning: on the basis of topographic and geological informatization, tunnel entrance location and route planning schemes are formed.

(3) Main structure design optimization: three-dimensional design models of topography, geology, civil engineering, structure, electromechanical, track and other specialties are established, collision conflicts between models within and among specialties are checked and secondary optimizations in case of problems are made.

(4) Construction progress and process simulation: based on the three-dimensional design model, the construction progress and key construction technology are simulated. The construction scheme is optimized by means of virtual construction, which can minimize the construction cost, reduce the construction period and achieve fine and efficient construction on the premise of ensuring construction safety, quality and environmental protection.

(5) Information and intelligent advanced geological prediction: based on the screening, filtering and analysis of the data measured by various advanced geological prediction means, the geological situation in front of the excavation face is predicted and the information that can guide the excavation of the tunnel is formed; the intellectualization of the analysis work is gradually realized in the later stage.

(6) Dynamic information feedback of monitoring measurement: informatization of original monitoring and measurement data and real-time information feedback to guide the actual construction; if there is excessive deformation, stress surge or other situations, the construction plan can be adjusted and changed in a timely manner.

(7) Tunnel health monitoring and intelligent maintenance: real-time monitoring of carbon emissions, structural deformation, structural stress and other indicators in tunnels is carried out. Then, based on these original health monitoring data and on-site monitoring, related analysis are carried out and tunnel health status information and real-time feedback are formed; finally, the appropriate maintenance and reinforcement plan are given in a timely manner.

(8) Real-time fire monitoring and intelligent positioning: real-time monitoring of tunnel fire status through fire sensors is provided; if a fire occurs, it can alarm in a timely manner and feedback the fire size, specific location and other information, so that firefighters can quickly obtain effective information and take the relevant fire control measures.

The above application points are the key application nodes of BIM technology in the whole lifecycle of tunnel engineering, which involves four stages: planning, design, construction and operation and maintenance. These application points are also the basis of this study, and the ideas and systems of this study are established on this basis. Figure 1 offers a schematic diagram of BIM technology research basis and a theoretical framework in the field of tunnel engineering.

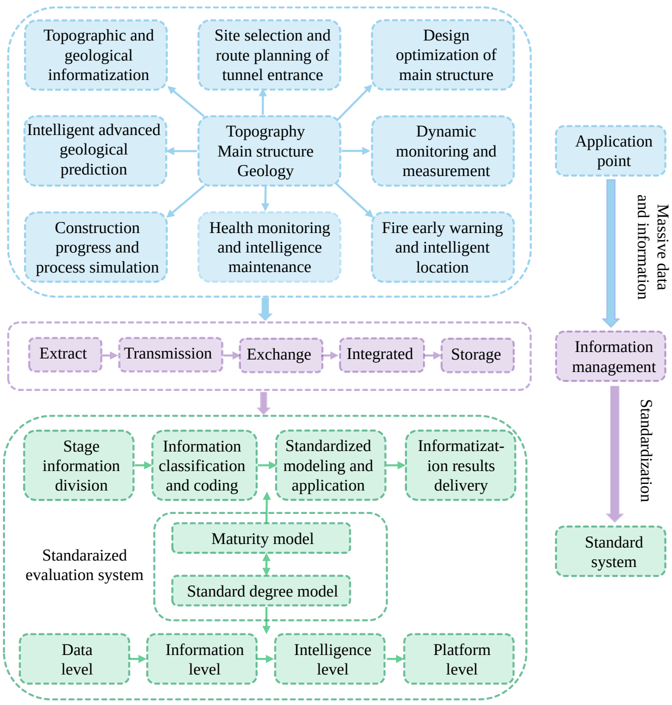

Figure 1. Schematic diagram of BIM technology research basis and theoretical framework in the field of tunnel engineering.

3. Stage Information and Maturity Model

The whole lifecycle of tunnel engineering involves four stages: planning, design, construction and operation and maintenance. Each of these four stages contains a large amount of engineering data and information. The forms of these data and information are complex, diverse and relatively discrete. Therefore, in order to realize the integrated management of tunnel engineering information, it is necessary to systematically manage the data and information involved in the whole field of tunnel engineering, which is the first and most critical step in the information management of tunnel engineering. According to the characteristics of tunnel engineering, the information of each stage in the field of tunnel engineering is divided as follows:

(1) Planning stage: This stage includes topographic data, geological data, location information of tunnel entrance, route planning information, single planning scheme optimization analysis information and multi-planning scheme evaluation and optimization information.
(2) Design stage: This stage includes geometric data, non-geometric information, single design optimization information and multi-design optimization information of the tunnel's main structure design.
(3) Construction stage: This stage includes monitoring and measurement data, advanced geological prediction data, excavation parameters, support parameters and other construction data, progress, quality, safety, environmental protection and other construction process information, single construction scheme optimization and risk prediction information, multi-construction scheme intelligent evaluation and optimization information.
(4) Operation and maintenance stage: This stage includes tunnel engineering operation data, tunnel health monitoring information, tunnel disease intelligent analysis and single maintenance scheme optimization information, multi-maintenance scheme evaluation and optimization information.

As mentioned above, a great deal of data and information will be generated in tunnel engineering, and there are essential differences between data and information. Data is the most primitive digital resource and will not produce any effective and useful value, information is a valuable resource obtained from the analysis and processing of raw data by manual or informationization tools. Paulk et al. defined maturity as the degree to which a specific process is clearly defined, managed, measured, controlled and effective [44]. The maturity of BIM technology in tunnel engineering applications from low to high is the conversion process from data to information, from information discretization to information integration and from manual analysis to intelligent platform. Because the application of BIM technology in tunnel engineering is in the primary stage and all aspects are immature compared with the field of construction engineering, in order to better measure the maturity of BIM technology in the field of tunnel engineering, this paper specially divides the maturity of BIM technology application in the field of tunnel engineering into nine grades. Maturity 1 and 2 are data integration stages; Maturity 3 and 4 are information transformation stages; Maturity 5 and 6 are intelligent analysis stages; Maturity 7, 8 and 9 are platform integration stages. Figure 2 gives a schematic diagram of the maturity of BIM technology application in tunnel engineering.

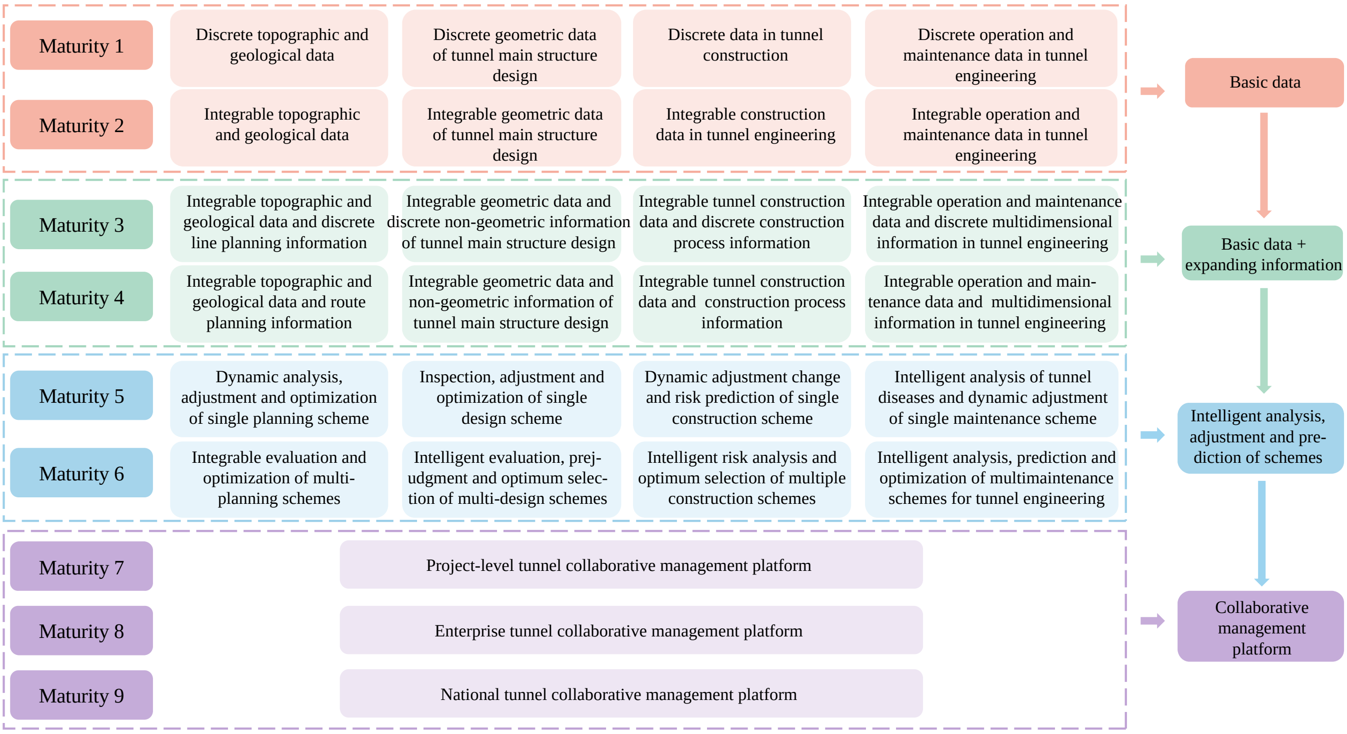

Figure 2. Schematic diagram of the maturity of BIM technology application in tunnel engineering.

4. Information Classification and Coding

For the moment, errors and omissions often occur in the process of information transmission in the application of BIM technology [45,46]. In the field of tunnel engineering, where the application of BIM technology is more immature, these problems will be more prominent; the standardization of information classification and coding is of great significance for solving the above problems. The significance of information classification standardization lies in the systematization of all kinds of information in the application process of BIM technology, which lays a solid foundation for the integrated management of information in the later stage. The value of information coding standardization lies in the unification of the basic units of secondary development of each software platform, so that each software platform can seamlessly dock into the process of information transformation and transmission. Therefore, in order to maximize the value of BIM technology in tunnel engineering and eliminate “information island” and “information fault”, it is necessary to standardize information classification and coding [47]. Based on this, this paper explores the standardization of information classification and coding.

The geological environment and the main structure of the tunnel are two key parts in tunnel engineering, whereas component-based modeling is one of the characteristics of BIM technology. Therefore, the object of information coding is divided into four parts: the file part, the geological part, the component part and the model part. Among them, the file part includes the planning stage file, the design stage file, the construction stage file and the operation and maintenance stage file. The geological part mainly includes the rock and soil body, geological structure and bad geology. The model includes mountain tunnels, submarine tunnels and urban tunnels. The component part includes advanced support, initial support, temporary support, secondary lining, waterproofing and drainage, inverted arch filling, grooves, auxiliary caverns, openings and prefabricated components. Figure 3 is a schematic diagram of information classification and coding objects in the field of tunnel engineering.

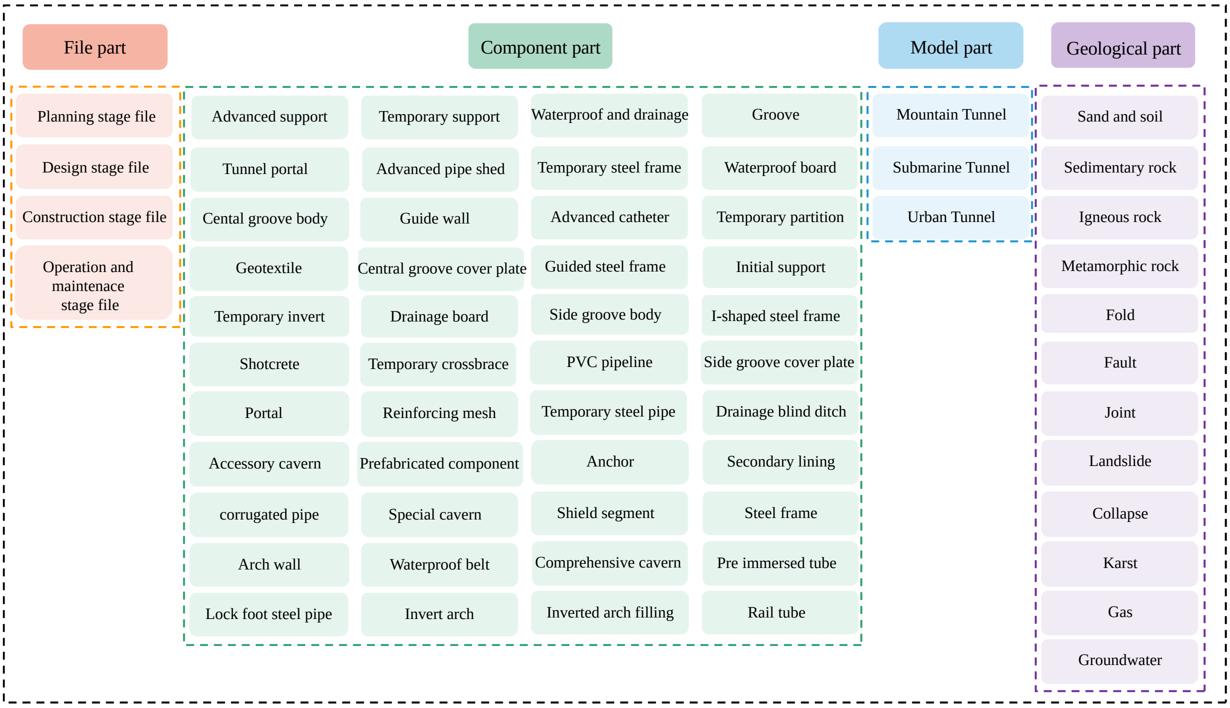

Figure 3. Schematic diagram of information classification and coding objects in the field of tunnel engineering.

Based on the above classification, this paper proposes a preliminary coding rule that encodes the above parts accordingly and provides a reference for the related follow-up research. The details are as follows: In line with alphabetically and numerically combined hierarchical coding rules, all parts of the objects were classified and the corresponding classified coding was carried out. For example, the advanced pipe shed code was A-01-001. To be specific, "A" was the first-level code, which represented the first-level classification of the pipe shed component library, "01" was the second-level code, which represented the second-level classification of pipe shed advanced support and "001" was the third-level code and represented the advanced pipe shed component. Figure 4 offers a schematic diagram of coding rules in the field of tunnel engineering.

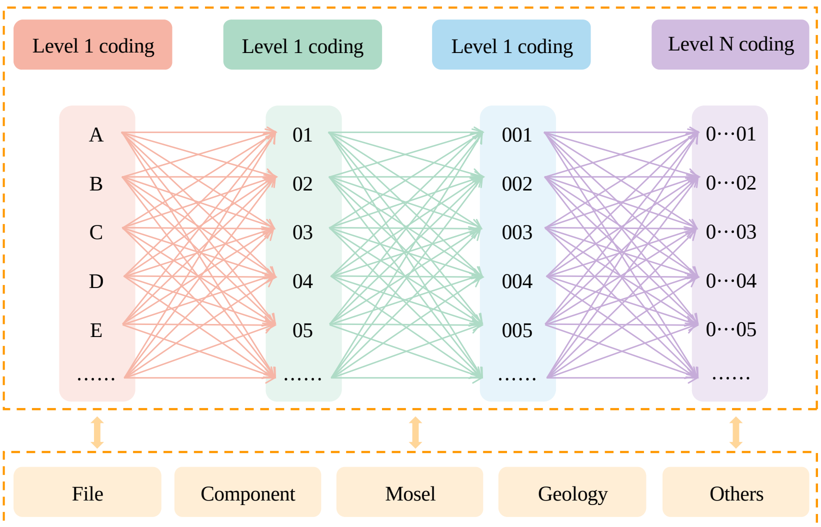

Figure 4. Schematic diagram of coding rules in the field of tunnel engineering.

5. Standardized Modeling and Application

The model is the foundation of BIM technology application. Apart from the information gradually added to the model in the later stage of the project, the model itself contains a large amount of geometric information steadily generated during the modeling process. For tunnel engineering, details such as tunnel length, tunnel net height, tunnel buried depth, secondary lining thickness, bolt length and inclination angle are generated and gradually increased in the process of model establishment. Therefore, it is necessary to standardize the process of model building, which can lay a foundation for later information extraction and integrated management.

5.1. Standardized Naming

Naming is a key part of the process of model standardization, so it is necessary to standardize the naming process. In this paper, a preliminary naming rule is proposed for future research. Now the mixed alphabetical and name hierarchical naming rules for naming are used. The detailed naming rules are as follows:

(1) File part naming rules: files included project files, drawing files, family files and model files. The first-level naming and the second-level naming are both designated alphabetical naming rules, whereas the third-level naming distinguished itself from the first two levels of naming by using the project names for naming. Example: "F-PR-Daliangshan Tunnel". Specifically, "F" was the first-level classification and represented the file, "PR" was the second classification, which represented the project file and "Daliangshan Tunnel" was the third-level classification, indicating the project name.

(2) Component part naming rules: the first-level naming and second-level naming take alphabetic naming rules, whereas the third-level naming differed from the first two levels of naming by adopting the component name for naming. Example: "C-CQ-Advance pipe shed". Specifically, "C" was the first-level classification and represented the component, "CQ" was the second-level classification, indicating the advanced support and "Advance pipe shed" was the third-level classification, which represented the component name.

(3) Model part naming rules: the first-level naming and the second-level naming take alphabetic naming rules; the third-level naming distinguished itself from the first two levels of naming by adopting the tunnel function name for naming according to the tunnel function classification, whereas the fourth-level naming adopted the tunnel name for naming. Example: "M-MO-Highway-Daliangshan Tunnel". Specifically, "M" was the first-level classification and represented the model, "MO" was the second-level classification, representing the mountain tunnel, "Highway" was the third-level classification, indicating the tunnel function and "Daliangshan Tunnel" was the fourth-level classification, indicating the tunnel name.

(4) Geological part naming rules: the first-level naming and second-level naming take alphabetic naming rules, the third-level naming is distinguished from the first two levels of naming and takes the rock and soil mass name for naming. Example: "L-CJ-limestone". Specifically, "L" was the first-level classification and represented the strata, "CJ" was the second-level classification and represented sedimentary rock and "Limestone" was the third-level classification, indicating the name of rock and soil mass.

5.2. Standardized Labeling

For tunnel engineering, all plane views of the model need to be annotated during the modeling process, which is conducive to the later model inspection and for the output of design drawings based on the 3D model. During the outputting of design drawings, the drawings must be standardized, so the contents of these labels should also be standardized, including the full length of the tunnel, the length of the surrounding rock sections at all levels, the elevation of the vault, the basic size of the section, the grade of surrounding rock, etc.

5.3. Standardized Color Matching of Surrounding Rock

For tunnel engineering, the grade of surrounding rock directly determines the selection and implementation of the tunnel construction scheme. In the process of 3D modeling, color matching should be carried out to better distinguish surrounding rock grades. In order to avoid color confusion caused by multiple color schemes for surrounding rocks, a set of unified standards should be built to standardize the color matching of surrounding rocks in the BIM modeling process.

5.4. Model Fineness—T-LOD

According to the NBIMS standard system proposed by the building SMART Alliance and the characteristics of tunnel engineering, and on the basis of LOD model, this paper presents a T-LOD accuracy model suitable for the field of tunnel engineering. Similar to the field of construction engineering, the different application stages of BIM technology in tunnel engineering have different requirements for model accuracy. Now the following regulations are made for the model accuracy level.

T-LOD100: Geographical planning stage of GIS. The preliminary plan for a tunnel is formed at this stage, the stage model should be able to show the spatial distribution and planning of the whole project. The model specifically contains the surrounding geographical environment of the tunnel, tunnel location, tunnel line and length, tunnel site selection scheme, cost per kilometer and other information.

T-LOD200: Geological and exploration stage. Geological data and information are the core part of this stage model; the stage model should be able to express the complex geological conditions of the region that the tunnel passes through in detail. The model specifically includes more detailed geological information, survey data, the general direction of the tunnel, the location of the opening, the number of working faces, drainage conditions, the excavation scheme of each working face and so on.

T-LOD300: The main structure design stage. The preliminary design scheme and later optimization of tunnel engineering are completed at this stage. The stage model should be able to fully express the design parameters and civil engineering information, structure, electromechanical engineering, track engineering and other related specialties. The model includes the attribute and parameter information of basic components of tunnel engineering, such as initial support, secondary lining, advanced large pipe shed, advanced small conduit, anchor, steel arch and other components, as well as non-geometric information such as basic materials and equipment.

T-LOD400: Construction simulation and optimization stage. The preliminary construction plan and later optimization of tunnel engineering are completed at this stage. The stage model should be able to represent the actual construction progress and various construction parameters of the project, including construction progress information, monitoring data and information such as surrounding rock deformation and surrounding rock stress, advanced geological prediction data and information and numerical simulation optimization information.

T-LOD500: Component factory manufacturing stage. The factory processing and installation of some prefabricated components are completed at this stage. The stage model should be able to describe the detailed structure and size of the real components. Specifically, such information as the basic size of the shield segment, the basic size of the tunnel steel arch screw nut and the basic structure of the tunnel waterproof layer hot-melt gasket should be included in this stage model.

T-LOD600: Operation and maintenance stage. This stage belongs to the final stage of the whole-tunnel engineering. The stage model should be able to reflect the information on the whole lifecycle of the tunnel. It includes all the data and information from the T-LOD100 to T-LOD500 models. On this basis, new data and information generated during the later operation and maintenance of the tunnel are appended to the model. In other words, the model data and information at this stage are constantly updated dynamically with the operation of the tunnel project until the end of the service life of the tunnel.

The abovementioned T-LOD accuracy model is proposed on the basis of the international NBIMS standard system. It adds one grade to the original five grades. In terms of content, it adds the special geographic environment, geology and exploration module in the field of tunnel engineering, which have the characteristics of tunnel engineering, and its professionalism is stronger, so it is suitable for the field of tunnel engineering. Table 1 presents the standardization scheme for the T-LOD model in tunnel engineering.

Table 1. Standardization scheme for T-LOD model in tunnel engineering.

	Model Accuracy	Information Characteristics	Formation Stage
Geographic planning Model	T-LOD100	Geographical environment, route planning, location of tunnel entrance	Geographical planning stage of GIS
Geological exploration model	T-LOD200	Survey data, geological information and working face information	Geological and exploration stage
Structural design model	T-LOD300	Basic information and design parameters of components	Main structure design stage
Construction optimization model	T-LOD400	Construction progress information, monitoring and measurement information, advanced geological prediction information	Construction simulation and optimization phase
Processing and installation model	T-LOD500	Prefabricated component processing and installation information	Component factory manufacturing stage
Operation and maintenance model	T-LOD600	Full lifecycle information of tunnel engineering	Operation and maintenance stage

6. Informatization Results Delivery

The implementation of BIM technology in tunnel engineering is not only a simple application issue in different stages (design stage, construction stage, operation and maintenance stage, etc.) but also involves the delivery of the total results after completing the project (the total results are delivered to the management unit). Therefore, it is necessary to formulate unified standards to determine the content and form of deliverables and achieve delivery standardization.

(1) Deliverables

The deliverables mainly included the BIM model, design drawings based on the BIM model, bill of quantities, animation video and other BIM application results. To be specific, the delivery forms of drawings covered printed version drawings based on the BIM model (PDF format) and exported CAD electronic versions (DWG format).

As regards the geographical planning stage of GIS, the geological and exploration stage and the main structure design stage, topography, geology, civil engineering, structure, mechanical and electrical and ventilation and other professional models were set up according to the design objectives of each stage. The phased BIM application results mainly include the design model of each stage, the two-dimensional drawing based on the BIM model, the three-dimensional auxiliary drawing and the analysis report, the statistical analysis report and the bill of quantities for each stage and the design change model.

For the construction simulation and optimization phase, the model was based on the model at the design stage. The phased application results of BIM mainly included the deepening model of each major part (the optimized model according to the problems that occurred in the construction process), deepening the design node model, application point model for the construction process, site layout model and two-dimensional drawings of the above models.

For the component factory manufacturing stage, the phased BIM application results mainly included prefabricated component processing models and drawings, electromechanical pipeline comprehensive models and documents, quantity statistics and cost analysis documents, construction process (including changes) models and associated lightweight 4D/5D management models.

For the operation and maintenance phase, the BIM application results mainly included the deliverables of all the above stages, the completion model and drawings based on the completion model and all relevant completion acceptance materials.

(2) Delivery formats

The formats of BIM deliverables for tunnel engineering were mainly divided into four types: model file, review file, media file and image file. The model was created by software such as Revit, which was project based; the project file format was .rvt. Review files were created by Navisworks and other software in the formats .nwc/.nmd. Media files were animated videos created by Lumion and other software in the formats .avi/.wmv/.mp4; image files were created by Photoshop and other software in the formats .jpeg/.png.

7. Standard Degree and Its Influencing Factors

In order to preliminarily measure the standardization degree of tunnel engineering, the concept of "standard degree" is proposed for the first time to describe the standardization degree of BIM technology in tunnel engineering. According to the application status of BIM technology in tunnel engineering and the characteristics of information expansion and interaction in the application process of BIM technology, this paper divides the standard degree from low to high into four levels, which are the data level, information level, intelligence level and platform level. Among them, the first level is the data level, which is mainly the integration process of discrete basic data sources. The second level is the information level. This standard level is mainly the transformation process from integrated basic data sources to effective information sources. The third level is the intelligence level, which is mainly based on the intelligent analysis and intelligent feedback process of effective information sources. The fourth level is the platform level. Under this standard level, the final integration process of the collaborative management platform is the main one. At present, the field of tunnel engineering is in the stage level 1 standard degree and the main structure data, geological data and all process data sources of the tunnel are in the discrete state. Level 4 is the final stage, with the highest degree of standardization. Information and integrated management in the field of tunnel engineering is realized in this stage. Figure 5 shows the schematic diagram of the standard degree model grading.

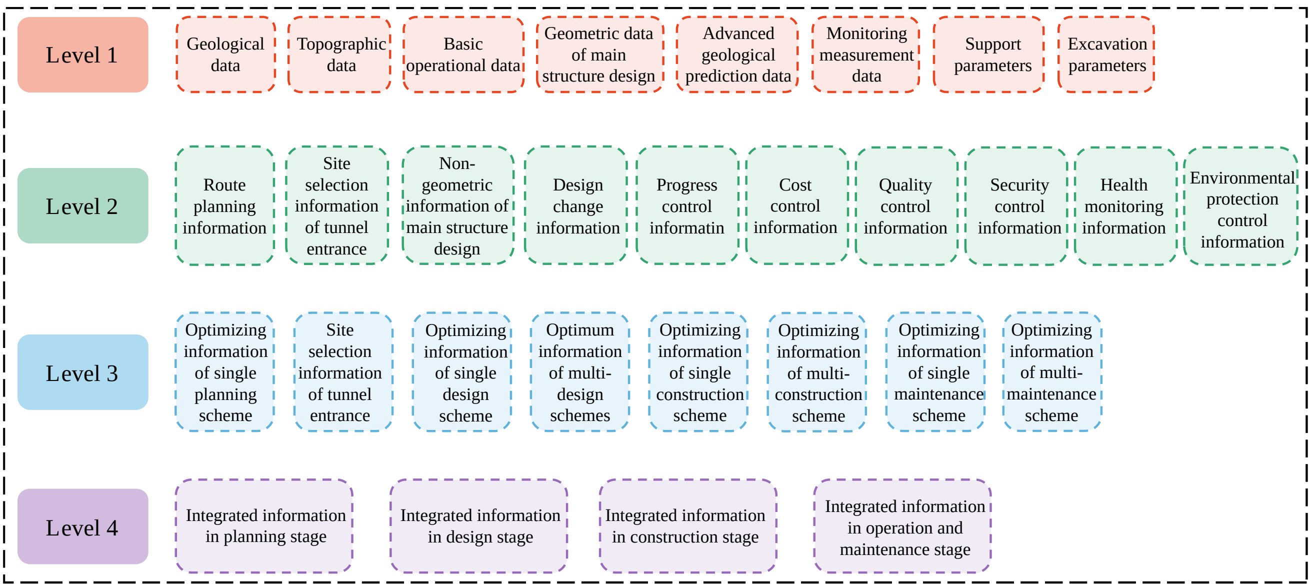

Figure 5. Schematic diagram of the standard degree grading.

At present, there are still many factors restricting the development of BIM technology standardization. After analysis, this paper summarizes the following four factors, the degree of standardization and the degree of unification of standards, the acceptance by project participants, the applicability of software and the perfection of platform construction. The more unified the standards are, the higher recognition the project participants show and the higher the applicability of the software is. At the same time, the more perfect the platform construction is, the higher the degree of the BIM standardization of tunnel engineering.

(1) Standard uniformity

At present, various countries and departments have issued BIM technical standards in different fields. Table 2 gives some BIM technical standards that have been published by some countries (international organizations) and different departments in China. As can be seen from Table 2, the existing BIM technical standards are mainly applicable to the field of construction engineering, whereas the standards applicable to the field of tunnel engineering are scarce. Whether in the field of construction engineering or tunnel engineering, there is a universal problem: the unification of standards. When different standards are in use, information sharing and exchange will inevitably create obstacles and form new information islands and information faults, failing to realize the application goals of BIM technology.

Table 2. List of published BIM technical standards.

	Domestic and Foreign BIM Standards	Country/Unit	Issue Time
Foreign standards	IFC (Industry Foundation Classes)	IAI (Industry Alliance for Interoperability)	1995
	Building Information Modeling—Information Delivery manual	ISO (International Standard Organization)	2010
	NBIMS (National Building Information Model Standard)	The United States	2004
	BIM Requirements	Finland	2007
	AEC (UK)BIM Standard for Autodesk Revit	The British	2010
	AEC (UK)BIM Standard	The British	2010
	CALS/EC (Continuous Acquisition and Lifecycle Support/Electronic Commerce)	Japan	2010
	SN/TS 3489: 2010 Implementation of support for IFD Library in an IFC model	Norway	2010
	BIM project implementation plan guide—first edition	The United States	2009.08
	BIM project implementation plan guide—second edition	The United States	2010.04
	National digital analog guide	Australia	2009
	Revit User Group Japan Modeling Guideline	Japan	2010
	Application guide of BIM in building field	Korea	2010.01
National standards	JG/T198—2007 standard	China	2007
	GB/T25507—2010 Industry foundation classes platform	China	2008
	CBIMS (China Building Information Model Standards)	China	2010
	GBT/51212-2016 Unified standard for building information modeling	Ministry of Housing and Urban–Rural Development of the People's Republic of China (MOHURD)	2017.07
	GB/T51235-2017 Standard for building information modeling in construction	MOHURD	2018.01
	Standard for classification and coding of building constructions design information model (draft for public comment)	MOHURD	2012
	Storage standard for building information modeling (draft for public comment)	MOHURD	2012
	Deliver standard of building design-information modeling (draft for public comment)	MOHURD	2012
	Application standard for manufacturing industrial engineering design information model (draft for public comment)	MOHURD	2012

Table 2. *Cont.*

	Domestic and Foreign BIM Standards	Country/Unit	Issue Time
Hong Kong standards	Guidelines for the use of architectural information simulation (1.0)	Hong Kong Housing Authority	2009.09
	Standard manual for building information simulation (1.0)	Hong Kong Housing Authority	2009.09
	Building information simulation component library reference (1.0)	Hong Kong Housing Authority	2010.01
	Architectural information simulation module library design guide (1.0)	Hong Kong Housing Authority	2009.07
Local standards	DBII/T 1069-2014 Design standard for civil building information model	Beijing Municipal Commission of Housing and Urban-Rural Development	2013.02
	DG/TJ082201-2016 Application standard for building information modeling	Shanghai Municipal Commission of Housing and Urban–Rural Development	2015.12
	Shanghai construction information modeling technology application guide	Shanghai Municipal Commission of Housing and Urban–Rural Development	2015.05
	DBJSI/T047-2015 Sichuan construction engineering design information model delivery standard	Sichuan Department of Housing and Urban–Rural Development	2015.12
	DBI3J/T213-2016 Unified standard for building information modeling	Hebei Department of Housing and Urban–Rural Development	2016.07
	DGJ32/TJ210-2016 Jiangsu civil building information model design application standard	Jiangsu Housing and Urban–Rural Construction Department	2016.09
	Standard for building information modeling in construction	Guangxi Department of Housing and Urban–Rural Development	2016
Industry standards	Structural decomposition guidelines for railway engineering (1.0)	China Railway BIM Alliance	2014.12
	Railway engineering information model classification and coding standard (1.0)	China Railway BIM Alliance	2014.12
	Railway engineering information model data storage standard (1.0)	China Railway BIM Alliance	2015.12
	Construction decoration and fitment engineering BIM implementation standard T/CBDA-3-2016	China Building Decoration Association	2014.06
	Guidelines for BIM implementation in China's municipal industry	China Exploration & Design Association	2015.08
	Guidance on building information model of urban rail transit project	Shanghai ShenTong Group Co. Ltd.	2014.09
	CIASII001-2015 Technical standard of BIM component library in construction electromechanical engineering	China Safety Production Association	2015.09
Enterprise standards	Guidelines for BIM application implementation in China Railway Engineering Corporation (2.0)	China Railway Engineering Corporation	2016.01
	BIM design standard in China Northwest Architecture Design and Research Institute Co. Ltd. (1.0)	China Northwest Architecture Design and Research Institute Co. Ltd.	2015.02
	BIM modeling standard for engineering construction	China Construction First Division Group	2016.05
	Wanda light asset design stage BIM technical standard (C)	Wanda Group	2015.07

In order to achieve the application goals of BIM technology and further improve the maturity of BIM technology application, it is necessary to solve the unification of BIM standards. Therefore, different countries and different departments in the same country need to reach an agreement, formulate an international unified BIM standard framework applicable to different fields such as construction engineering and tunnel engineering, and stipulate that local and enterprise BIM technical standards should be based on this standard framework. This can not only ensure accessible information sharing and exchange but also ensures the universality of standards in different countries and departments.

(2) Standard acceptance

The implementation of BIM technical standards requires the active participation and cooperation of all participants in the project. In order to fully realize BIM technology standardization in tunnel engineering, the standards must be well recognized by all participants and professionals in the field of tunnel engineering. Therefore, whether the standardization can be truly realized depends upon the content and quality of the compiled standards on the one hand and on the recognition from engineers in the field of tunnel engineering on the other.

To improve the acceptance of BIM technical standards by engineers in the field of tunnel engineering, the country needs to promulgate relevant policies, implement new standards in the state form, set up a pilot project for BIM standards, test and improve the originally proposed standards when they are implemented in pilot projects and amend the unreasonable parts of the original standards so as to better serve the actual projects. On the other hand, the project construction units need to gradually standardize the implementation process of the BIM technical standards and set up an implementation team for BIM technical standardization.

(3) Software applicability

There are many available kinds of BIM software currently available; however, all kinds of software have their advantages and disadvantages. The tunnel itself belongs to the belt project, and its length varies from tens of meters to tens of kilometers. As a result, the volume of BIM three-dimensional visualization model is particularly large, which is not conducive to later model merging and browsing. Worse still, the commonly used software for BIM 3D visualization modeling (Revit software, etc.) does not have the function of model lightweight, meaning that ordinary hardware devices fall short of the requirements.

As for software applicability, there are two solutions. The first solution is directional development based on a certain software platform, during which new modules suitable for tunnel engineering are developed on the basis of the original software. The second solution is to redevelop the BIM application software series in the field of tunnel engineering without basing it on any software platform. The development cycle of solution 1 is shorter than that of solution 2, but the development space of solution 1 is far smaller than that of solution 2 because of the limitation of the original software platform; the development direction of solution 2 shows more diversity and freedom. Therefore, each solution has its pros and cons and should be adopted according to the specific situation.

(4) Platform construction perfection

The ultimate goal of BIM technology is to form a unified collaborative management platform to realize the sharing and exchange of engineering data and information and to integrate information management. Classification and coding standards in the BIM technical standard of tunnel engineering are the basis of the later development of a co-operative management platform. The development of management platform imporves the secondary optimization and adjustment of BIM technical standards. Therefore, the development and construction of the platform is of great significance to the standardization of BIM technology.

To improve the construction of the BIM technology platform, the country needs to count the projects that have been built or are under construction in recent years, summarize the data and information from all participants and various professional fields involved in the project, use modern computer technologies such as cloud storage and big data to develop a national tunnel project collaborative management platform and integrate all data and information to realize the integrated management of data and information in tunnel engineering. Local governments, enterprises and project construction units should gradually develop collaborative management platforms at the local, enterprise and project levels based on the national platforms, eventually forming a top-down integrated management system for tunnel engineering information.

8. Case Study

The Daliangshan Tunnel passes through a region with a changeable geographical environment and complex geological conditions. The data and information contained in the tunnel are considerable in quantity and form. The disadvantages of the traditional management mode are increasingly exposed, which cannot meet the new requirements of tunnel construction in the current information age. Based on this, BIM technology is introduced into the engineering project. In this paper, the standardization and information integration management mode of BIM technology in the field of tunnel engineering are studied and discussed based on the pilot project of Daliangshan Tunnel.

8.1. Engineering General Situation

The Daliangshan Tunnel is located in the Mabian–Zhaojue section of the Lexi expressway. The tunnel entrance is located in Leshan City and the exit is located in Zhaojue County. The Xichang–Zhaotong expressway is connected to the south of Zhaojue County. The geographic location satellite map is shown in Figure 6.

Figure 6. The line map of Lexi expressway.

The altitude of the Daliangshan Tunnel is between 1680 and 2300 m, which is between the Sichuan Basin and the Yunnan–Guizhou Plateau. Overall, it is low in the east and high in the west and low in the north and high in the south. The tunnel site is located in the high mountain area of structural erosion and the terrain is very steep. The landform is mainly controlled by the geological structure, and the tunnel site passes through the core of the anticline. Figure 7 shows the geological profile of Daliangshan Tunnel.

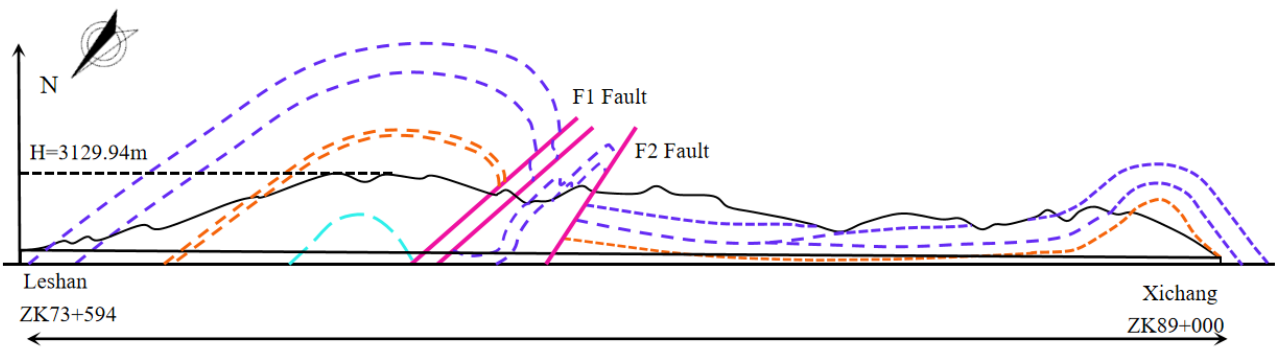

Figure 7. Geological profile of Daliangshan Tunnel.

8.2. Standardization in Modeling Phase

In order to standardize the components and models in tunnel engineering and the management of achievement documents and to lay a good foundation for subsequent application and final product delivery, the BIM technical standards proposed in this paper were applied to the BIM modeling stage of Daliangshan Tunnel. Figure 8 displays the diagram of standardization of file naming, component naming, surrounding rock color matching and material naming for Daliangshan Tunnel.

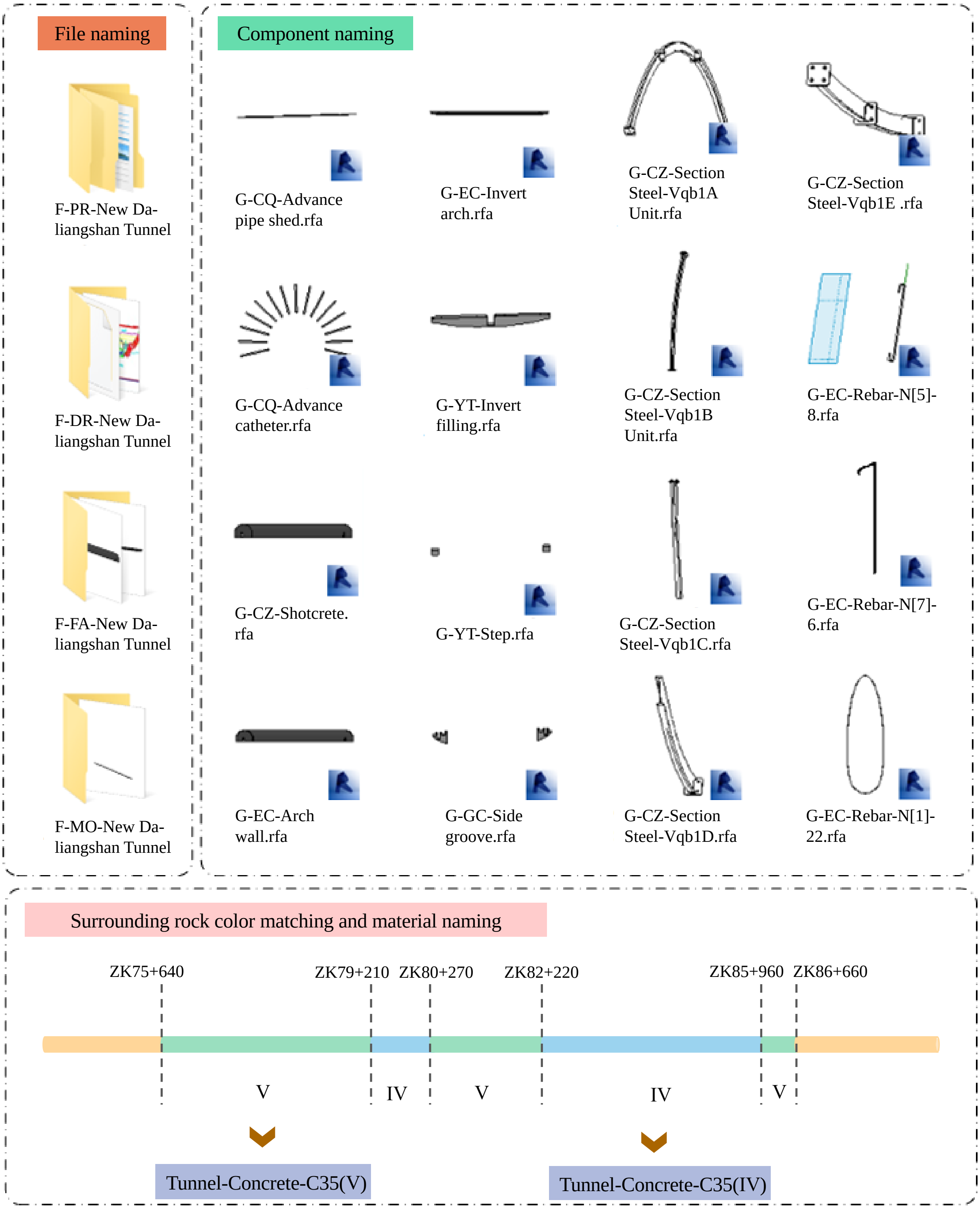

Figure 8. Diagram of standardization of file naming, component naming, surrounding rock color matching and material naming for Daliangshan Tunnel.

8.3. Standardization in Delivery Phase

After the collection of previous information, the deepening of modelling in the medium term and the later practical application, a set of standardized delivery system BIM results for Daliangshan Tunnel was finally formed. The system consisted of two modules: a basic module and an application module. Specifically speaking, the basic module included the basic components in tunnel engineering and professional models. The professional models included the architectural design model, structural deepening model, three-dimensional terrain model and three-dimensional geological model (.rvt). The application module included the tunnel construction process model (.nwc), construction simulation animation (.avi), numerical simulation calculation model (.gts), virtual roaming video (.mp4) and BIM5D engineering quantity calculation results (.xls). Figure 9 is a diagram of the standardized delivery of BIM results in Daliangshan Tunnel.

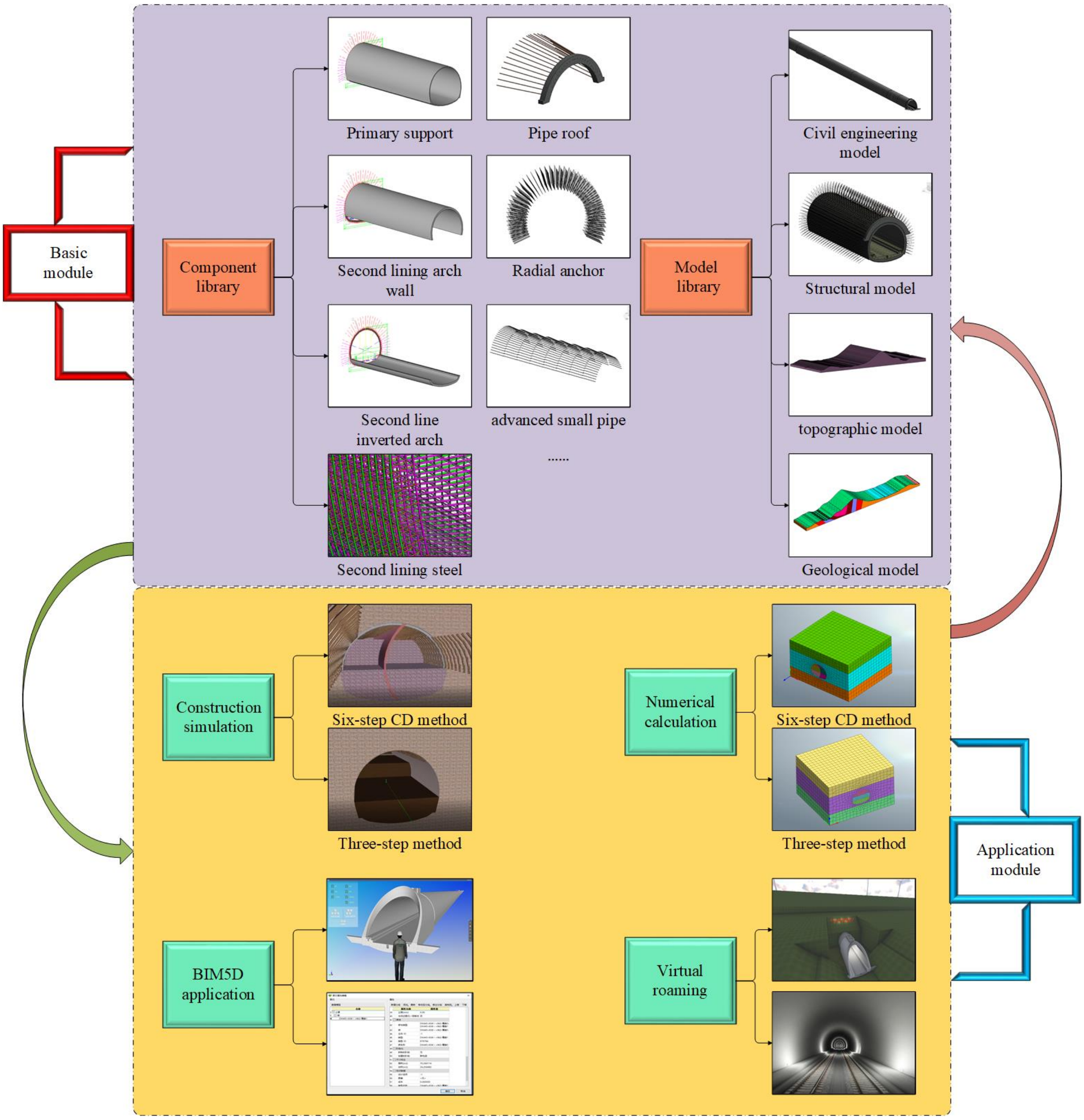

Figure 9. Diagram of the standardized delivery of BIM results in Daliangshan Tunnel.

8.4. Standard Degree Evaluation

According to the standard degree model proposed in this paper, the standardization degree of BIM technology in Daliangshan Tunnel is evaluated as follows: in terms of data state, most of the data are still discrete and have not yet been integrated. In terms of information transformation, the utilization rate of data is not high, most of the data are still in the initial state and have not been converted into effective information. In terms of project participants, the synergy of all participants is not high and there is still a long way to go to the goal of platform synergy management. In the whole lifecycle, single-stage applications are mainly used to solve engineering problems within a single stage, whereas multi-stage joint applications and information exchange and transmission between stages have not yet been realized. Based on the above factors, the BIM technical standard degree grade of Daliangshan Tunnel is judged to be level 1, which belongs to data level.

It can be found that the implementation of BIM technology standardization in Daliangshan Tunnel is still in its infancy, and only a part of standardization work has been performed in the process of model building; however, this part of the work improves the accuracy of the model to a certain extent and enhances the feasibility of the model, which lays a precise model foundation for later design changes and optimization of construction schemes. On the other hand, the preliminary standardization work is conducive to the extraction, filtering and collation of model information, which is in line with the concept of lean engineering management.

9. Discussion

BIM has been widely applied in the construction field; however, compared with the real estate field, the tunnel field lacks a professional BIM platform. With the rapid development of internet technologies such as HTML5 and WebGL, the cross-border integration of BIM and geographic information systems has become a new trend. However, there are still some problems in the practical application process of BIM + WebGLS technology, such as the different industries and objects of BIM and GIS services resulting in differences in their models and that WebGLS is limited by network and server performance, resulting in low efficiency in transmission and rendering of the model.

BIM is a combination of digitization and informatization of building models but currently has compatibility with Deng Wenti and digital information cannot be fully shared. With the continuous development of BIM, it is not only about the transformation from two-dimensional to multidimensional but also about achieving information exchange and sharing, achieving collaborative work among various disciplines and participants throughout the entire lifecycle of tunnel engineering and completing the integrated management of information at all stages.

The existence of secondary development provides the possibility for all the above implementations, providing a continuous source of power and sufficient expansion space for the continuous development of BIM. The importance of secondary development is self-evident, and it is believed that with the continuous advancement of development in tunnel engineering, BIM technology will also become more mature. BIM is not just a technology, to be precise, it is more of a concept. With the arrival of the big data era, the integration of computer science, Internet plus, Cloud technology virtual integration and tunnel engineering, BIM technology has become a major direction of future development. The concept of "BIM+" will gradually become popular, and secondary development will become the most powerful means to achieve "BIM+".

10. Conclusions

Tunnel engineering contains a large amount of engineering data and information. In order to achieve integration, informatization and collaborative management, it is of great significance to study BIM standardization in tunnel engineering. Firstly, from the point of view of data development based upon the existing international standard framework, a new maturity model in the field of tunnel engineering is proposed. Secondly, the professional data and information in the field of tunnel engineering are preliminarily classified and the coding rules with reference values are given. Then, a series of professional studies on modeling, application and the delivery of results are carried out. Finally, in order to evaluate the standardization degree of BIM technology in the field of tunnel engineering, the concept of “standard degree” is put forward and several influencing factors of standard degree are discussed in detail. The specific research contents are as follows:

(1) Basis and theoretical framework of standardization research: This is mainly for the application of BIM technology in the field of tunnel engineering, including topographic and geological informatization, tunnel entrance location and route planning, main body structure design optimization, construction progress and process simulation, information and intelligent advanced geological prediction, dynamic information feedback of monitoring and measurement, tunnel health monitoring and intelligent maintenance, real-time fire monitoring and intelligent positioning.

(2) Stage information and maturity model: This paper classifies the data and information in the field of tunnel engineering from the four stages of planning, design, construction and operation and maintenance. According to the application status of BIM technology in tunnel engineering and the characteristics of BIM technology and tunnel engineering, the application maturity of BIM technology is divided into nine grades.

(3) Information classification and coding: It is divided into four parts: geology, component, model and document. The classification is carried out and the preliminary coding and naming rules are formulated for future research.

(4) Standardized modeling and application: It includes four aspects: standardized naming, standardized labeling, standardized color matching of surrounding rock grade and T-LOD accuracy model. Each aspect is discussed in detail.

(5) Information delivery: According to the requirements of each stage of the new T-LOD accuracy model proposed in this paper, the content and delivery form of the results in different stages are given.

(6) Standardization degree and its influencing factors: A new concept of measuring the standardization degree in the field of tunnel engineering is put forward, that is, the standard degree. A model of standard degree is established and several influencing factors are summarized.

The research results of this paper are mainly based on the current situation of information management of tunnel engineering in China. It also has certain reference significance for the expansion of IFC standards in the field of tunnel engineering and the establishment of the BIM technical standard system of tunnel engineering in other countries. It should be pointed out that the information classification in this paper only aims at a relatively unique part of the object in the field of tunnel engineering. For the classification of process management information such as schedule, cost, quality, safety and change, which is similar to that in the field of construction engineering, the classification criteria in the field of construction engineering can be referred to. This part of the content is not repeated in this paper. In addition, the other influencing factors of BIM standardization in tunnel engineering, as well as the quantitative relationship between standard degree and influencing factors, need to be further studied.

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References

1. Mansuri, D.; Chakraborty, D.; Elzarka, H.; Deshpande, A.; Gronseth, T. Building Information Modeling enabled Cascading Formwork Management Tool. *Autom. Constr.* **2017**, *83*, 259–272. [CrossRef]
2. Oldfield, J.; Oosterom, P.V.; Beetz, J.; Krijnen, T.F. Working with Open BIM Standards to Source Legal Spaces for a 3D Cadastre. *Int. J. Geo-Inf.* **2017**, *6*, 351. [CrossRef]
3. Song, Z.; Shi, G.; Wang, J.; Wei, H.; Wang, T.; Zhou, G. Research on management and application of tunnel engineering based on BIM technology. *J. Civ. Eng. Manag.* **2019**, *25*, 785–797. [CrossRef]
4. Fang, Y.; Cho, Y.; Zhang, S.; Perez, E. Case Study of BIM and Cloud–Enabled Real-Time RFID Indoor Localization for Construction Management Applications. *J. Constr. Eng. Manag.* **2016**, *142*, 05016003. [CrossRef]
5. Ninić, J.; Meschke, G. Model update and real-time steering of tunnel boring machines using simulation-based meta models. *Tunn. Undergr. Space Technol.* **2015**, *45*, 138–152. [CrossRef]
6. Sigalov, K.; König, M. Recognition of process patterns for BIM-based construction schedules. *Adv. Eng. Inform.* **2017**, *33*, 456–472. [CrossRef]
7. Wong, P.F.; Salleh, H.; Rahim, F.A.M. A Relationship Framework for Building Information Modeling (BIM) Capability in Quantity Surveying Practice and Project Performance. *Inf. De La Construcción* **2015**, *67*, e119. [CrossRef]
8. Ryu, D.W.; Kim, J.I.; Suh, S.; Suh, W. Evaluating risks using simulated annealing and Building Information Modeling. *Appl. Math. Model.* **2015**, *39*, 5925–5935. [CrossRef]
9. Marzouk, M.; Abdelaty, A. Monitoring thermal comfort in subways using building information modeling. *Energy Build.* **2014**, *84*, 252–257. [CrossRef]
10. Lee, S.; Tae, S.; Roh, S.; Kim, T. Green Template for Life Cycle Assessment of Buildings Based on Building Information Modeling: Focus on Embodied Environmental Impact. *Sustainability* **2015**, *7*, 16498–16512. [CrossRef]
11. Liu, S.; Meng, X.H.; Tam, C.M. Building information modeling based building design optimization for sustainability. *Energy Build.* **2015**, *105*, 139–153. [CrossRef]
12. Porwal, A.; Hewage, K.N. Building Information Modeling-Based Analysis to Minimize Waste Rate of Structural Reinforcement. *J. Constr. Eng. Manag. -Asce* **2012**, *138*, 943–954. [CrossRef]
13. Martinez-Aires, M.D.; Lopez-Alonso, M.; Martinez-Rojas, M. Building information modeling and safety management: A systematic review. *Saf. Sci.* **2018**, *101*, 11–18. [CrossRef]
14. Oti, A.H.; Kurul, E.; Cheung, F.; Tah, J.H.M. A framework for the utilization of Building Management System data in building information models for building design and operation. *Autom. Constr.* **2016**, *72*, 195–210. [CrossRef]
15. Zhou, W.H.; Qin, H.Y.; Qiu, J.L.; Fan, H.B.; Lai, J.X.; Wang, K.; Wang, L.X. Building information modelling review with potential applications in tunnel engineering of China. *R. Soc. Open Sci.* **2017**, *4*, 170174. [CrossRef]
16. Zhou, Y.; Ding, L.Y.; Rao, Y.; Luo, H.B.; Medjdoub, B.; Zhong, H. Formulating project-level building information modeling evaluation framework from the perspectives of organizations: A review. *Autom. Constr.* **2017**, *81*, 44–55. [CrossRef]
17. Alves, M.; Carreira, P.; Costa, A.A. BIMSL: A generic approach to the integration of building information models with real-time sensor data. *Autom. Constr.* **2017**, *84*, 304–314. [CrossRef]
18. Cheung, W.F.; Lin, T.H.; Lin, Y.C. A Real-Time Construction Safety Monitoring System for Hazardous Gas Integrating Wireless Sensor Network and Building Information Modeling Technologies. *Sensors* **2018**, *18*, 436. [CrossRef] [PubMed]
19. Lai, J.X.; Qiu, J.L.; Chen, J.X.; Wang, Y.Q.; Fan, H.B. Application of Wireless Intelligent Control System for HPS Lamps and LEDs Combined Illumination in Road Tunnel. *Comput. Intell. Neurosci.* **2014**, *2014*, 429657. [CrossRef]
20. Macher, H.; Landes, T.; Grussenmeyer, P. From Point Clouds to Building Information Models: 3D Semi-Automatic Reconstruction of Indoors of Existing Buildings. *Appl. Sci.* **2017**, *7*, 1030. [CrossRef]
21. Mahdjoubi, L.; Moobela, C.; Laing, R. Providing real-estate services through the integration of 3D laser scanning and building information modelling. *Comput. Ind.* **2013**, *64*, 1272–1281. [CrossRef]
22. Cheng, W.C.; Song, Z.P.; Tian, W.; Wang, Z.F. Shield tunnel uplift and deformation characterisation: A case study from Zhengzhou metro. *Tunn. Undergr. Space Technol.* **2018**, *79*, 83–95. [CrossRef]
23. Meschke, G.; Kropik, C.; Mang, H.A. Numerical analyses of tunnel linings by means of a viscoplastic material model for shotcrete. *Int. J. Numer. Methods Eng.* **1996**, *39*, 3145–3162. [CrossRef]
24. Zheng, Y.L.; Zhang, Q.B.; Zhao, J. Challenges and opportunities of using tunnel boring machines in mining. *Tunn. Undergr. Space Technol.* **2016**, *57*, 287–299. [CrossRef]
25. Song, Z.P.; Cao, Z.L.; Wang, J.B.; Wei, S.F.; Hu, S.C.; Niu, Z.L. Optimal Analysis of Tunnel Construction Methods through Cross Passage from Subway Shaft. *Adv. Civ. Eng.* **2018**, *2018*, 5181954. [CrossRef]
26. Song, Z.P.; Yang, T.T.; Jiang, A.N. Elastic-Plastic Numerical Analysis of Tunnel Stability Based on the Closest Point Projection Method Considering the Effect of Water Pressure. *Math. Probl. Eng.* **2016**, *2016*, 2569345. [CrossRef]
27. Wang, T.; Song, Z.P.; Yang, J.Y.; Wang, J.B.; Zhang, X.G. Experimental research on dynamic response of red sandstone soil under impact loads. *Geomech. Eng.* **2019**, *17*, 393–403. [CrossRef]
28. Tian, X.; Song, Z.; Zhang, Y. Monitoring and reinforcement of landslide induced by tunnel excavation: A case study from Xiamaixi tunnel. *Tunn. Undergr. Space Technol.* **2021**, *110*, 103796. [CrossRef]
29. Song, Z.; Xu, X.; Liu, W.; Li, L. A Review of Study on Energy-absorbing Rockbolts and Static/Dynamic Test Methods. *Mod. Tunn. Technol.* **2023**, *60*, 1–13. [CrossRef]

30. Zheng, Y.; Zheng, S. Parametric modeling and application of tunnel based on BIM. *Int. J. Interact. Des. Manuf.* **2022**, 1–8. [CrossRef]
31. Sharafat, A.; Khan, M.S.; Latif, K.; Seo, J. BIM-based tunnel information modeling framework for visualization, management, and simulation of drill-and-blast tunneling projects. *J. Comput. Civ. Eng.* **2021**, *35*, 04020068. [CrossRef]
32. Fabozzi, S.; Biancardo, S.A.; Veropalumbo, R.; Bilotta, E. I-BIM based approach for geotechnical and numerical modelling of a conventional tunnel excavation. *Tunn. Undergr. Space Technol.* **2021**, *108*, 103723. [CrossRef]
33. Hussain, M.; Zheng, B.; Chi, H.L.; Hsu, S.C.; Chen, J.H. Automated and continuous BIM-based life cycle carbon assessment for infrastructure design projects. *Resour. Conserv. Recycl.* **2023**, *190*, 106848. [CrossRef]
34. Guo, K.; Zhang, L. Multi-source information fusion for safety risk assessment in underground tunnels. *Knowl. -Based Syst.* **2021**, *227*, 107210. [CrossRef]
35. Yin, X.; Liu, H.; Chen, Y.; Wang, Y.; AI-Hussein, M. A BIM-based framework for operation and maintenance of utility tunnels. *Tunn. Undergr. Space Technol.* **2020**, *97*, 103252. [CrossRef]
36. Succar, B. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Autom. Constr.* **2009**, *18*, 357–375. [CrossRef]
37. East, E.W. An Overview of the US National building Information Model Standard (NBIMS). *Comput. Civ. Eng.* **2007**, 59–66. [CrossRef]
38. Liu, N.; Guo, D.; Song, Z.; Zhong, S.; Hu, R. BIM-based digital platform and risk management system for mountain tunnel construction. *Sci. Rep.* **2023**, *13*, 7585. [CrossRef]
39. Badenes, R.O.; Gómez, H.G.; Navarro, V.G. Metodología para la selección de sistemas ERP para pymes. *3c Empresa: Investig. Y Pensam. Crítico* **2018**, *7*, 10–33. [CrossRef]
40. Zheng, G.Q.; Qiu, Q.N. Review of BIM standards at home and abroad. *Civ. Archit. Eng. Inf. Technol.* **2012**, *4*, 32–34+51.
41. Song, Z.P.; Shi, G.L.; Wang, J.B.; Zheng, W.J.; Wang, J.J.; Wang, T. Research on the framework of tunnel cooperative management platform based on BIM technology. *J. Geotech. Eng.* **2018**, *40*, 117–121.
42. Rodríguez, C.A.; Rodríguez-Pérez, Á.M.; López, R.; Hernández-Torres, J.A.; Caparrós-Mancera, J.J. A finite element method integrated with Terzaghi's principle to estimate settlement of a building due to tunnel construction. *Buildings* **2023**, *13*, 1343. [CrossRef]
43. Rallu, A.; Berthoz, N.; Charlemagne, S.; Branque, D. Vibrations induced by tunnel boring machine in urban areas: In situ measurements and methodology of analysis. *J. Rock Mech. Geotech. Eng.* **2023**, *15*, 130–145. [CrossRef]
44. Paulk, M.C.; Curtis, B.; Chrissis, M.B.; Weber, C.V. Capability maturity model, version 1.1. Software. *IEEE* **1993**, *10*, 18–27. [CrossRef]
45. Chaves, F.J.; Tzortzopoulos, P.; Formoso, C.T.; Biotto, C.N. Building information modelling to cut disruption in housing retrofit. *Proc. Inst. Civ. Eng. -Eng. Sustain.* **2017**, *170*, 322–333. [CrossRef]
46. Jin, R.Y.; Hancock, C.M.; Tang, L.; Wanatowski, D. BIM Investment, Returns, and Risks in China's AEC Industries. *J. Constr. Eng. Manag.* **2017**, *143*, 04017089. [CrossRef]
47. Zhang, S.R.; Pan, F.; Wang, C.; Sun, Y.J.; Wang, H.X. BIM-Based Collaboration Platform for the Management of EPC Projects in Hydropower Engineering. *J. Constr. Eng. Manag.* **2017**, *143*, 04017087. [CrossRef]