Development of BIM-Based Innovative Workflow for Architecture, Engineering and Construction Projects in China

Chao Chen and Llewellyn Tang

***Abstract*—With the dramatic development of technologies and the coming of the digital era, most industries are experiencing innovation and restructure due to more energy-efficient and sustainable requirements. As one of the most energy-intensive industries, the architecture, engineering and construction (AEC) is facing great challenges in the future sustainable development. In China, due to numerous AEC projects are launched and completed every year, the traditional drawing-based workflow cannot meet the increasing demands of project digitalization anymore and even is losing the overall control of project management. In recent years, an emerging digital technology named Building Information Modelling (BIM) is leading an innovative development trend in the global AEC industry. It can provide professional services to bring both technical and economic benefits across the AEC project lifecycle from planning to facility management by using advanced management workflow and software tools. Therefore, this paper proposes a BIM-based project workflow for the future development of the AEC industry in China. This workflow was developed based on both literature review and empirical data. In addition, a case study was also used to validate the potential value of this BIM-based workflow for the application of a real project. This workflow not only can realize multidisciplinary collaboration and multidimensional digital services, but also can improve the productivity and efficiency of project to promote a sustainable development in AEC industry.**

***Index Terms*—AEC industry, building information Modelling (BIM), digitalization, innovative workflow.**

I. Introduction

There is no doubt that the constructions of all the infrastructures and buildings depend on the architecture, engineering and construction (AEC) industry, which is one of the most energy-intensive industries all over the world. As it consumes nearly 40% of the global energy use every year [1], the industry is facing technological innovation and industrial restructuring due to the requirements of sustainable development and the coming of digital information era. For a traditional AEC project, computer aided design (CAD) technology plays an important role throughout the whole project lifecycle from planning phase to operation and maintenance (O&M) stage [2]. It produces computer-plotted drawings that are much more accurate and intelligent than manual sketches. However, with the rapid development of digital technologies and practical demands, the limitations and drawbacks of two-dimensional (2D) drawings and three-dimensional (3D) models provided by CAD are being revealed. Lack of effective visualization, losses of detailed information and conflicts of multi-disciplinary collaboration have seriously affected the project efficiency and industrial productivities in recent years [3]. Therefore, an emerging technology named Building Information Modelling (BIM) has become one of the most promising developments for the AEC industry. Compared with CAD, it not only provides 3D digital models, but also implements visualization, simulation, estimation and coordination to meet further demands from the AEC project stakeholders, such as duration shortening, cost saving, waste reduction, quality control and complexity management [4]. In addition, BIM supports integrated data delivery based on multi-dimensional forms throughout the project lifecycle. It is convinced that BIM will make a significant contribution to the sustainable development of the AEC industry in the near future [3].

This paper aims to propose a BIM-based innovative workflow for the AEC projects in China and validate its feasibility and performance. Therefore, the objectives of this paper can be summarized as follows:

1) Combining theoretical literature reviews and empirical data to develop a BIM-based project workflow, which involves multi-disciplines and stakeholders in conventional China’s AEC industry;
2) Based on the developed workflow, using various BIM software tools to realize multi-dimensional digitalization for a case study in China and validate the performance and feasibility of this workflow;
3) Analyzing the future applications and challenges of this BIM-based workflow in facility management (FM) domain, which is closely related to the studies of smart city concept.

II. Literature Review

A. BIM in the World

Constructions are experiencing significant developments in automation and digitalization all over the world [5]. Particularly for those new modern AEC projects in the U.S. and some developed countries, BIM is becoming widely used from planning stage to construction phase [6]. A growing number of governments and industrial associations have

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realized its importance and prospect in the near future. For instance, the U.S. Federal Government has announced a five-year program to encourage BIM adoptions elsewhere and give supports and recommendations on their lessons; the UK Government Construction Strategy (GCS) has required 3D BIM in fully collaborations (all information electronic) as a minimum for all construction projects since April 2016. Royal Institution of Chartered Surveyors (RICS) has organized annual BIM conference since 2012 to release expertized BIM guidance for AEC projects; the Building and Construction Authority (BCA) of Singapore announced that BIM would be introduced for architectural submission by 2013 [7].

B. *BIM in China*

As the largest AEC market in the world, China is undergoing a slow development of BIM application in its native AEC industry. Compared with those developed countries like the UK, which has formed a mature BIM-based AEC industrial chain, China's BIM development is still at an initial level. According to a market survey by the China Construction Industry Association (CCIA) in 2012, less than 15% of in total 388 Chinese AEC firms indicated that they have adopted BIM, and even 45% of them stated that they had never heard of BIM [8]. The Chinese Ministry of Housing and Urban-Rural Development (MOHURD) and industrial associations have announced BIM relevant policies and data standards which will promote digitalization and informatization during the national 13th Five-Year Plan period (2016-2020) [7].

The reason why Chinese government and industrial organizations show such great interests in BIM is also obvious. Based on powerful BIM software and digital documentation delivery, a growing number of project stakeholders are benefitting from this innovative technology, particularly in production control, efficiency improvement, waste reduction, time and cost saving, etc [3]. The characteristics BIM brings for the AEC industry are also shown in different project phases. For instance, in design phase, BIM provides more accurate visualization of design, earlier collaboration of multiple design disciplines and easier verification of design intent consistency. BIM can also realize automatic clash detection of design before construction, quick reaction to design changes, virtual simulation of construction process, synchronization of procurement with design and construction; in O&M phase, BIM supports smarter handover of facility information and integration with operation and management systems [3]. To meet demands and requirements in different project phases, BIM also can implement multi-dimensional digitalization that are described as following [4].

C. *3D BIM*

According to 2D design drawings, BIM can create a 3D model that provides various perspectives for designers to view their initial design and discover errors or omissions. The 3D visualization also improves the clash detection of multiple design disciplines (architectural, structural, mechanical, electrical and plumbing (MEP) designs) in order to reduce wastes and consumptions caused by rework [3]. 3D BIM model not only reveals massive information for infrastructure and building design details including geometry, dimensions and materials, but also provides opportunities for multi-disciplinary collaboration and coordination [9].

D. *4D BIM*

Four-dimensional (4D) BIM can be defined as a 3D model linked with schedule simulation [10]. It brings technical capabilities for the management of construction phase in an AEC project, such as visualization of the time and space relationships among construction activities, analysis of the construction plan and node schedule, simulation of construction process and quick response to alterations of planning [11]. 4D BIM enhances the coordination among different stakeholders including designers, civil engineers, contractors and project managers, meanwhile, it significantly improves the construction performance and efficiency.

E. *5D BIM*

Five-dimensional (5D) BIM can be defined as a 3D model integrated with schedule simulation and cost estimation [12]. Although the 3D design model can give a parametric cost estimation based on building project parameters including perimeter length, site area, component volume, material type, number of furniture, number of equipment, etc. [3]. These information resources are still not adequate to allow for accurate takeoff quantity extraction and approximate cost estimation. Because the resource and energy cost which occurs during transportation and construction process is not revealed. Therefore, 4D models need to be imported to external cost estimate tools. These tools not only produce detailed information and accurate numbers of takeoff quantity, but also integrate the construction process with procurement and logistics for dynamic cost estimation [13].

F. *6D BIM*

When the construction is as-built, stakeholders are still concerned about its commissioning and daily operation performance in O&M phase. To meet the demands and requirements of project latter-phase management, six-dimensional (6D) BIM which integrates 5D BIM with FM knowledge is developed [14]. It focuses on a visual representation of the schedule for building maintenance work and daily monitoring of energy consumptions of building systems. This concept is closely related to smart city researches which involve monitoring of building performance, control of resource allocation, forecast of disasters, provision of functional services and the like [15].

III. METHODOLOGY

In literature review section, a brief introduction of BIM-based multi-dimensional modelling has been given. The next step is to investigate how BIM can impact the traditional workflow of an AEC project which involves multi-disciplines and various stakeholders. A scientific research methodology based on the grounded theory is developed for data collection and result analysis. The grounded theory was initially proposed by Glaser and Strauss in 1967, in order to generate theoretical conclusions for complex topics based on empirical researches [16]. It is chosen as the methodology reference for this research due to its capability of discovering similarities and correlations among different workflow elements by using empirical data [17]. The schematic process of our research methodology is shown in Fig. 1.

This developed methodology can be mainly divided into three stages:

1) **Preparation stage**: a traditional workflow of an AEC project is partitioned according to different project phases and relevant stakeholders. Each partitioned element can be called as a code. Then each code is given by index weight from 1 to 5, which represent the significance of BIM application for each workflow element from "no need" to "essential". After that, professional respondents from AEC industry including designers, civil engineers, contractors, owners, scholars, governmental consultants and project managers, are invited to participate in the interview and questionnaire survey for data collection purpose;
2) **Data collection stage**: after the data collection, all results will be filtered to ensure the integrity and validity of raw data;
3) **Data analysis stage**: based on the collected results, the importance of each code can be determined. Then according to the interview content and empirical studies about BIM application in AEC projects, we are able to modify each code by integrating with BIM application. This process is also named "theoretical coding" [18].

When all new theoretical codes are saturated, the next step is to establish a BIM-based innovative workflow for modern AEC projects in China. This new BIM-based workflow then will be in contrast to the traditional drawing-based workflow in order to find out the improvement of each project phase.

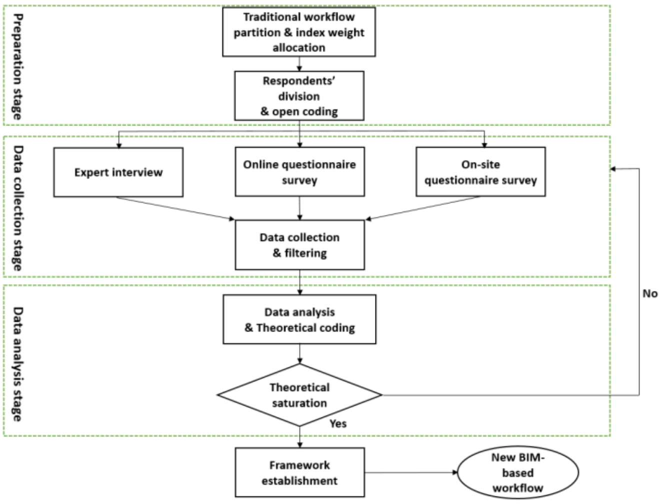

Fig. 1. Schematic process of grounded-theory-based research methodology.

IV. Result Analysis

Over 100 respondents from the global and domestic AEC industry participated in the interview and survey of this research. After raw data filtering, we obtained 81 valid surveys. In addition, 10 industry experts were invited to take an interview for more details about BIM application throughout the building lifecycle. The backgrounds of these experts are shown in Table 1 and the professional distribution of survey respondents is shown in Fig. 2. The result indicates that all of them are AEC project stakeholders who may benefit from the adoption of BIM so that they can present intuitive attitudes and professional insights to help with this study.

TABLE I: Background of Industry Experts (Interviewee)

Background Factors	Factor No.	Interviewee No.	Background
Project manager	1	A	2,3,5,6,7
Civil engineer	2	B	2,5,6
Governmental consultant	3	C	1,2,5,6
UK university professor	4	D	1,2,5
International enterprise general manager	5	E	1,2,3,5,6,7
International institute member	6	F	1,4
Regional chairman of international association	7	G	3,6,8
Building designer	8	H	1,5,6
		I	6,8
		J	2,7

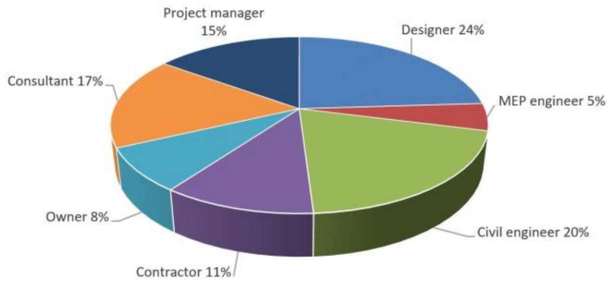

Fig. 2. Professional distribution of survey respondents.

The results indicate that 75 (93%) respondents and 10 (100%) interviewees hold a positive attitude on BIM application in project workflow. After the index weight analysis, the significance ranking of BIM application throughout the project lifecycle is shown in Table II.

TABLE II: Significance Ranking of BIM Application in Various Project Phases

Project phase	BIM application	Ranking
Design & Construction	3D visualization	1
Design	Design optimization	2
Design	Clash detection	3
Construction	Schedule control	4
Design & Construction	Cost estimation	5
Design & Construction	Takeoff quantity calculation	6
Construction	Virtual simulation	7
Construction	Safety management	8
Design, Construction, O&M	Digital documentation delivery	9
Planning, Design, Construction, O&M	Project database creation & update	10
O&M	Web-based facility management	11
Planning	Digital site analysis	12

A traditional drawing-based workflow for AEC projects is shown in Fig. 3. This workflow indicates main steps of each project phase from planning to O&M. According to that, a new BIM-based workflow that integrates each project phase with corresponding BIM application is developed as shown in Fig. 4. It not only provides opportunities for effective collaborations among various project stakeholders including designers, engineers, contractors, owners, consultants, project managers and the like, but also displays a more digital, more efficient and more sustainable framework of the AEC project workflow in the future.

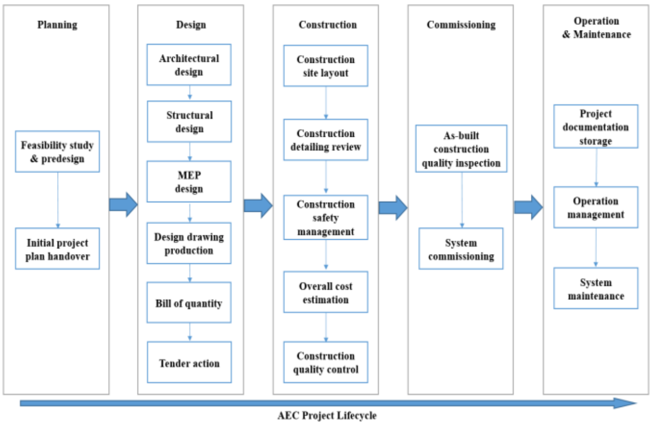

Fig. 3. Traditional drawing-based workflow for AEC projects.

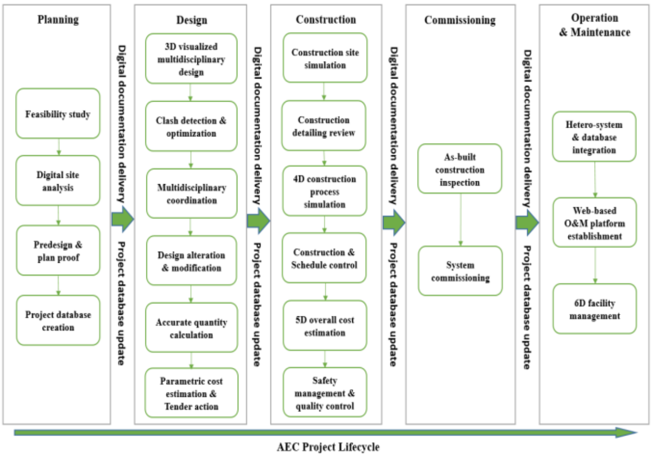

Fig. 4. BIM-based innovative workflow for AEC projects.

V. Validation

To verify the feasibility and validity of this BIM-based innovative workflow, a pilot project has been launched since the end of 2016. This project is a public commercial building located in Sichuan, China. It has a building floor area over 3,000 m^2. The BIM applications in each project phase can be summarized as follows:

A. 3D Model Visualization and Material Rendering

Based on the 2D drawings, designers used BIM software (Autodesk Revit) to convert 2D layout to 3D model that can be viewed in various perspectives [3]. In addition, the model was attached by real construction material surfaces for rendering purpose, which can help designers and owners to check the visual effect before the practical construction process (shown in Fig. 5). All the building design elements and materials were stored and updated in a customized project database, which will serve throughout the whole project lifecycle.

B. Clash Detection and Design Optimization

An important application of BIM in design phase is the clash detection, which improves the collaboration and coordination among multi-disciplines [19]. In this project, by using BIM design software such as Autodesk Naviswork and Revit, architects, structural engineers, MEP engineers and other disciplines discovered over 300 design errors and omissions during the drawing review process. According to the detection report (shown in Fig. 6), they checked the clashes through 3D visualization (shown in Fig. 7) and collaborated to optimize the design model (shown in Fig. 8).

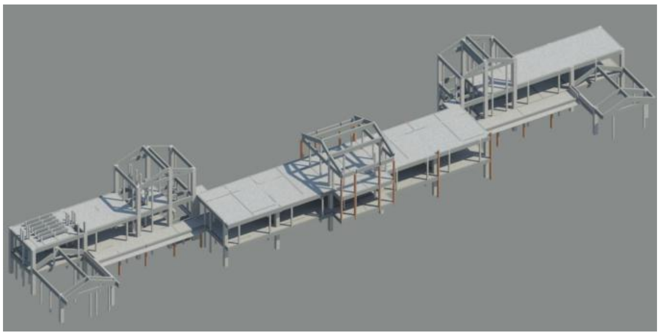
Fig. 5. Rendered BIM model for 3D visualization.

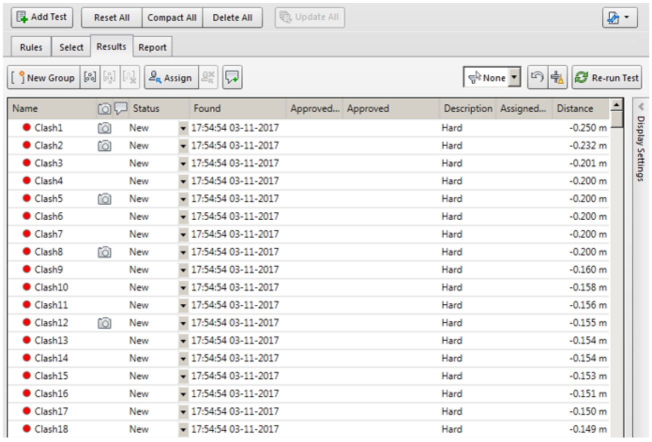
Fig. 6. BIM-based clash detection report.

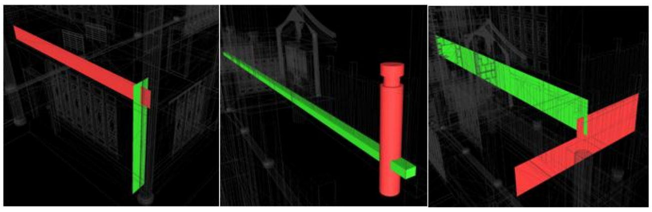
Fig. 7. Design clashes in 3D visualization.

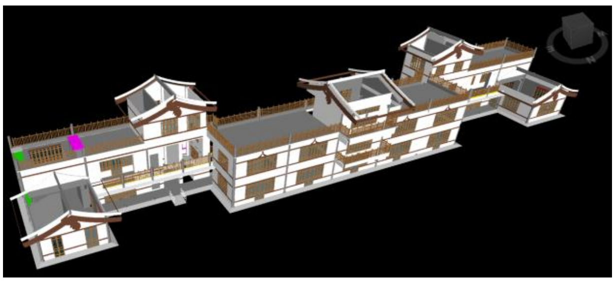
Fig. 8. Multi-disciplinary integrated design model.

C. Takeoff Quantity and Construction Schedule Management

Before the on-site construction process, designers, civil engineers, contractors and the project manager need to review the overall takeoff quantities (shown in Fig. 9) and made a schedule simulation to control the construction progress at each time node (shown in Fig. 10). Based on this schedule, project manager can clearly know the progress of each construction task. If any task alteration or unexpected circumstance occurs, by consulting with civil engineers, contractors and construction crews, project manager can make a quick response and take an action to ensure the construction tasks will be completed in time [3]. In this project, under the assistance of BIM 4D software (such as Synchro and Trimble Vico Office), the as-built construction was completed almost two weeks in advance and the overall efficiency was highly improved.

Code	Name	Type	Mapped	Count
0001	East F1 column		Yes	54
0002	East F1 beam		Yes	53
0003	Mid F1 column		Yes	36
0004	Mid F1 beam		Yes	67
0005	West F1 column		Yes	32
0006	West F1 beam		Yes	33
0007	F1 floor		Yes	3
0008	East F2 column		Yes	42
0009	East F2 beam		Yes	36
0010	Mid F2 column		Yes	42
0011	Mid F2 beam		Yes	63
0012	West F2 column		Yes	26
0013	West F2 beam		Yes	24
0014	F2 floor		Yes	1
0015	East F3 column		Yes	46
0016	East F3 beam		Yes	26
0017	Mid F3 column		Yes	18
0018	Mid F3 beam		Yes	21
0019	West F3 column		Yes	15
0020	West F3 beam		Yes	15

Fig. 9. Construction takeoff quantities from 4D BIM.

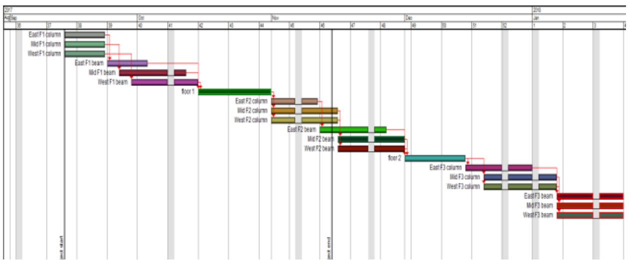

Fig. 10. Simulated construction schedule in Gantt view.

D. 4D virtual Simulation and Schedule Control

When all the construction tasks and the schedule are determined, the next step is to create a 4D virtual simulation before the on-site construction. This simulation is integrated with the Virtual Reality (VR) technology to enhance the site layout and safety management [20]. Through this immersive virtual on-site experience, the project manager and construction crews can have a forecast of potential on-site hazards and accidents that may occur during the construction process [21]. Furthermore, the 4D simulation also gives the project manager an intuitive perspective to check and control the overall construction process. Some details of the 4D virtual simulation in this project are shown in Fig. 11 (using Vico Office) and Fig. 12 (integrated with Bentley LumenRT, which is a VR software tool).

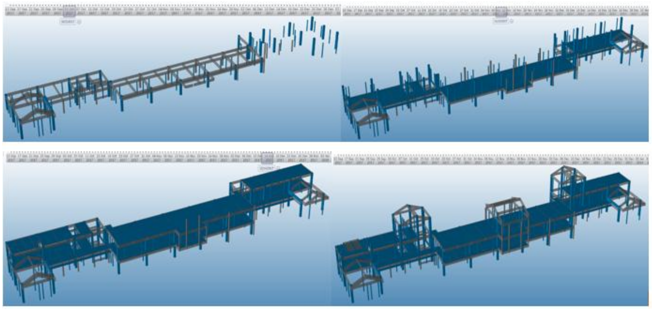

Fig. 11. 4D virtual simulation of construction process.

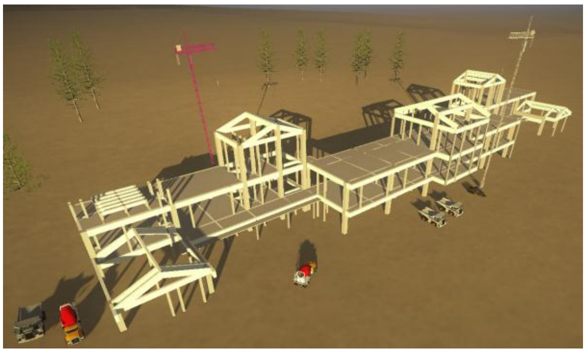

Fig. 12. Construction on-site simulation based on VR.

E. 5D Cost Estimation and Capital Management

The 5D BIM also provides an accurate cost estimation of the overall takeoff quantities and other resources such as labors and construction equipment (shown in Fig. 13). Based on that, the project manager, owners and contractors not only can understand the capital flow through each project step clearly, but also can merge the construction process with the production, procurement, transportation and even maintenance of building materials and components for total cost estimation [3]. It dramatically improves the cost efficiency and meanwhile prevents a massive waste of money and resources. In this project, benefiting from the 5D cost estimation and capital management, the owners had a cost saving of more than £200,000 (pounds) during the construction process.

Description	Source Qty	Consumption	Consumption Inv	Waste	Qty	UOM	Unit Cost	Base Cost	Cost/Parent Assembly	%/Parent Assembly
Project Cost	1.00	1.000	1.000	1.000	1.00		1,593,795.48	1,593,79...	N/A	N/A
Backfill moving inward	20,600.00	1.000	1.000	1.000	20,600.00	m3	7.20	148,320.00	148,320.00 /	9.31 %
Backfill earthwork	20,600.00	1.000	1.000	1.000	20,600.00	m3	5.84	120,304.00	120,304.00 /	7.55 %
Earth moving outward	52,400.00	1.000	1.000	1.000	52,400.00	m3	5.42	284,008.00	284,008.00 /	17.82 %
Rock moving outward	8,720.00	1.000	1.000	1.000	8,720.00	m3	6.16	53,715.20	53,715.20 /	3.37 %
Earth excavation	52,400.00	1.000	1.000	1.000	52,400.00	m3	7.47	391,428.00	391,428.00 /	24.56 %
Rock excavation	8,720.00	1.000	1.000	1.000	8,720.00	m3	50.88	443,673.60	443,673.60 /	27.84 %
Floor	**143.89**	**1.000**	**1.000**	**1.000**	**143.89**	**m3**	**361.25**	**51,980.26**	**51,980.26 /**	**3.26 %**
Floor 2	67.36	1.000	1.000	1.000	67.36	m3	361.25	24,333.80	169.11 / m3	46.81 %
Floor 1	76.53	1.000	1.000	1.000	76.53	m3	361.25	27,646.46	192.14 / m3	53.19 %
F1 column	**72.07**	**1.000**	**1.000**	**1.000**	**72.07**	**m3**	**349.37**	**25,179.10**	**25,179.10 /**	**1.58 %**
East	**42.21**	**1.000**	**1.000**	**1.000**	**42.21**	**m3**	**349.37**	**14,746.91**	**204.62 / m3**	**58.57 %**
West	**29.86**	**1.000**	**1.000**	**1.000**	**29.86**	**m3**	**349.37**	**10,432.19**	**144.75 / m3**	**41.43 %**
F2 column	**24.54**	**1.000**	**1.000**	**1.000**	**24.54**	**m3**	**349.37**	**8,573.54**	**8,573.54 /**	**0.54 %**
East	15.16	1.000	1.000	1.000	15.16	m3	349.37	5,296.45	215.83 / m3	61.78 %
West	9.38	1.000	1.000	1.000	9.38	m3	349.37	3,277.09	133.54 / m3	38.22 %
F3 column	**13.34**	**1.000**	**1.000**	**1.000**	**13.34**	**m3**	**332.23**	**4,431.95**	**4,431.95 /**	**0.28 %**
East	7.10	1.000	1.000	1.000	7.10	m3	332.23	2,358.83	176.82 / m3	53.22 %
West	6.24	1.000	1.000	1.000	6.24	m3	332.23	2,073.12	155.41 / m3	46.78 %
F1 beam	**192.02**	**1.000**	**1.000**	**1.000**	**192.02**	**m3**	**323.83**	**62,181.84**	**62,181.84 /**	**3.90 %**
East	99.15	1.000	1.000	1.000	99.15	m3	323.83	32,107.74	167.21 / m3	51.64 %
West	92.87	1.000	1.000	1.000	92.87	m3	323.83	30,074.09	156.62 / m3	48.36 %

Fig. 13. BIM-based 5D cost estimation and management

F. 6D-Based Facility Management

There is no doubt that O&M phase accounts for the longest period of the whole building lifecycle [3]. Combined with the local regular rules and standards for infrastructure and building maintenance, BIM can convert the O&M information of each element including lifetime determination, service measures, operation performance and maintenance cost analyzing to 6D modelling, which integrates with BIM 3D, 4D and 5D [22]. By establishing a web-based platform, project administrators and owners can access, store, exchange and integrate the O&M information such as the schedule for execution for maintenance work, material properties of building element, environmental monitoring data from sensors, energy cost and the like [23]. The prerequisite conditions of 6D BIM implementation in this project include a large database and a web-based platform that is connected with external sources or systems.

VI. Discussion and Outlook

The study results of the pilot project indicate that the BIM-based innovative workflow is feasible and has brought significant benefits for a real construction project in different phases. These benefits include reduction of design errors and clashes, shortening of construction period, overall cost saving, improvement of productivity, etc. [7], [24]. But what BIM can really do are more than these. A lot of studies have investigated its integration with other advanced heterogeneous systems, such as the Geographic Information System (GIS). As BIM focuses on an infrastructure or a building itself, the GIS provides the information of the district environment where the building is [25]. The integration of these two technologies can be used for energy monitoring, urban planning, topographic analysis, disaster simulation and other public services in both building-scale and city-scale [26]. In addition, the BIM application in building performance simulation and monitoring is another concerned research domain. Some studies have indicated that BIM is able to improve the efficiency of energy and resource usage for building design, retrofit and operation [25], [27]. Therefore, the integration of BIM with GIS and other contextual simulation systems will be the kernel of the smart city concept, which is defined as urban operation, management and development based on various digital and information systems [28]. Moreover, BIM is also anticipated to be merged with the prefabricated construction in order to enhance the productivity and sustainability of an AEC project [8]. According to the framework of the BIM-based workflow developed in this research, more automated concepts and digital technologies are able to be organically merged into the new workflow, in order to help increase the total asset values of modern constructions, and furthermore promote the sustainable development of China's AEC industry.

However, there are still some limitations and barriers needed to be overcome before the BIM can be widely used for numerous AEC projects in China, and even around the world. These limitations and barriers can be summarized as follows:

A. Technical Limitations and Barriers

There are different types of BIM software that are developed based on heterogeneous structures, which means the interoperability among them is a great challenge [3]. As the core of BIM is data integration throughout the whole lifecycle, if this technical barrier cannot be overcome, the data integrity and consistency will not be guaranteed when information is delivered, exchanged and stored among related stakeholders in different project phases. In addition, not only for BIM software, the interoperability with other systems such as GIS and energy simulation software also will limit the functions and values that BIM can realize. Therefore, uniform compatible data schemas and common interfaces are required for the exchange, transfer, storage and sharing of project information [29].

B. Economic Limitations and Barriers

The high cost of BIM investment in software and hardware also will limit the rapid development of BIM [24]. For large AEC enterprises and organizations that have already started to use BIM for projects, this may be not a problem. However, for those small-sized and medium-sized firms, this costly investment may stop them looking forward to BIM. In addition, the BIM applications in projects also will increase the overall cost and sometimes the owners will think BIM is not necessary if there is no compulsory requirement.

C. Normative Limitations and Barriers

To implement the BIM more validly, industrial standards and market regulations of BIM are required to ensure its application in each project phase can be effective, reliable and secure [24]. Although some countries and regions have announced native BIM policies and standards, currently there is still no global standard for the implementation of BIM in both international and local projects.

D. Educational Limitations and Barriers

The implementation of BIM also needs lots of professionals who have a high proficiency in software operation and knowledge of project management [7]. Lack of talents will slow down the development of BIM. Therefore, it is necessary to launch BIM relevant trainings and curriculums in enterprises and higher institutions. Meanwhile, more BIM research centers should be established all over the world. source of information for science writers is [9].

VII. Conclusion

To sum up, our research indicates a new BIM-based innovative workflow, which has been preliminarily validated to bring significant benefits such as reduction of clashes, cost saving, period shortening, prevention of resource waste and quality control for the lifecycle of AEC projects in China. Compared with traditional 2D-drawing-based workflow, it uses multi-dimensional BIMs to realize 3D visualization, virtual simulation, accurate cost estimation and digital documentation delivery for planning, design, construction and O&M of projects. These implementations not only enhance the collaboration and coordination among multi-disciplines and different stakeholders, but also improve the overall efficiency and productivity of the projects. Although this developed workflow still needs further improvements due to the rules and standards in different countries and regions, it provides a framework concept for further studies about how BIM can fit into the management of

AEC projects for the aim of automation and digitalization. In addition, its application in FM is also becoming an emerging research domain as it is closely tied with the smart city concept. If the challenges mentioned above can be overcome in next few decades, we will look forward to the significant contributions BIM can make for the China's and global AEC industries in the future.

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- Building Information Modelling Interfaces for Production Management in Construction and Marine Engineering Sectors
- Design for the future: studying immersive user interaction with BIM and the immersive visualization environments
- Business continuity management in construction with a focus on digital information value and security