Automation in Construction 141 (2022) 104398

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Construction quality evaluation of asphalt pavement based on BIM and GIS

Chengjia Han [a,1], Fanlong Tang [b,1], Tao Ma [a,*], Linhao Gu [a], Zheng Tong [a]

[a] School of Transportation, Southeast University, Nanjing, China
[b] College of Hydraulic & Environmental Engineering, China Three Gorges University, Hubei, China

A R T I C L E I N F O

Keywords:
Building information model
Geographic information system
Construction simulation
Analytic hierarchy
Construction quality

A B S T R A C T

Construction quality evaluation is critical to guarantee the long-term performance of asphalt pavement. Exiting evaluation approaches lag and limit the efficiency of quality control. To solve this problem, this study proposed a new construction quality evaluation framework, which was a combination of the building information model (BIM) and geographic information system (GIS). The framework performed the real-time and full-process quality evaluation on asphalt pavement construction. The framework was applied in the Phnom Penh-west Halluk highway construction project, in which the GIS early located and warned the sections with poor construction quality and the BIM models acquired the comprehensive information on the road sections. The framework made it possible to understand the construction quality in real time and full procedure. The results demonstrated that the framework provided a good information environment for construction quality evaluation. The future study will focus on construction quality control using the quality evaluation results

1. Introduction

Construction quality significantly affects the investment benefit and long-term performance of road engineering [1–3]. Many studies have demonstrated that the poor construction quality of asphalt pavement directly and significantly increases the maintenance costs [4–8]. However, the evaluation of road construction quality is extremely difficult because of various factors, such as the qualities of materials, equipment, transportation, personnel, construction processes, and schedule. Many methods have been proposed to evaluate the asphalt pavement construction quality. For example, Wilson et al. [4] used a ground-penetrating radar to evaluate the construction quality of hot-mix asphalt pavement. Hoegh et al. [5] used the degree of compaction as the evaluation standard of asphalt pavement construction quality. Zhang et al. [6] indicated that non-uniformity and anti-rutting performances were effective metrics to evaluate the construction quality of asphalt pavement. In order to build a system for monitoring and evaluating the construction quality of asphalt pavement, Dong et al. [8] developed a real-time data collection program in an asphalt mixing station. The experiment results showed that the system was able to collect and analyze the relevant parameters in real time to provide alarm feedback about abnormal data. Xu and Chang [9] proposed an in-situ framework to evaluate the effectiveness of intelligent compaction technology. Tang et al. [10] developed a model to evaluate the segregation degree in the paving process based on computer vision. Although these studies have established many effective methods for quality evaluation, their evaluation models only focus on one or two processes of asphalt pavement construction. Asphalt pavement construction is a complete and compositive process, mainly including material preparation, paving, and compaction. The quality of each step is affected by its own factors and the quality of the previous steps. Therefore, the real-time and full-process record and analysis is the key to guarantee the accurate evaluation of pavement construction quality. However, there is a lack of a quality evaluation model for the whole process of pavement construction. In addition, most of the traditional quality evaluation methods sample and evaluate at the end of pavement construction, which is non-representative and lagging.

With the continuous development of intelligent construction, building information model (BIM) technology has shown a strong potential [11–15] for construction quality evaluation, such as data visualization, data sharing, real-time transmission, and construction simulation. Therefore, this study tries to apply BIM technology to the quality evaluation of pavement construction. BIM, first introduced in buildings construction, is a digital representation of the physical and functional characteristics of a facility [16–18]. In recent years, BIM has been applied to many infrastructure constructions thanks to its

* Corresponding author.
E-mail address: matao@seu.edu.cn (T. Ma).
[1] Both authors contributed equally to this work.

https://doi.org/10.1016/j.autcon.2022.104398
Received 18 May 2021; Received in revised form 16 May 2022; Accepted 1 June 2022
Available online 6 June 2022

advantages of digitalization and automation [11–15]. Fig. 1 summarizes the application scenarios of BIM-based lifecycle management of civil engineering construction.

Many studies reported the applications of BIM in the field of road engineering. There are three main directions of the BIM applications in road engineering: road design, construction, and maintenance. In the road design stage, BIM realizes the transformation from 2D visual design to 3D one. By parameterizing the road alignment and structure in a 3D structural model, design errors and cycles can be reduced [19,20]; In the road construction stage, BIM was combined with road construction technologies, such as intelligent compaction [9], paving process of segregation detection [10], mixing quality monitoring of mixture production [8], etc. By modeling the road construction (e.g., road structure, construction apparatus, material production equipment) and transmitting the indicators of construction quality in real time, BIM makes it possible to achieve feedback adjustment of the construction process. In the road maintenance stage, BIM was combined with life cycle cost analysis technologies to estimate the benefit of the maintenance programs and manage assets of the maintenance construction [21,22].

Despite the strong potential of BIM in road construction management, it still has many application limitations. One is from the shapes of road structures, a length of hundreds of kilometers. Therefore, BIM needs support for the macro-graphic level management of the road network. The geographic information system (GIS) is the mainstream choice for the support. GIS, as a 2D data management tool for road network information, has the potential to quantify the various real-world situations in pavement construction [23–25]. Meanwhile, recent advancements in GIS have brought the Web Map Service to provide a comprehensive interactive layout and tool for big data analysis [26–30]. However, the level of details in GIS now is too shallow to perform the road construction analysis (e.g., the visualization and simulation of the construction process), which is easy for BIM. The combinations of GIS and other modern information intelligent technologies were demonstrated as an important direction for future road development [18,30]. Therefore, it is advantageous to combine GIS and BIM for the quality evaluation of road construction (Fig. 2).

This study proposed a combined framework of BIM and GIS to evaluate the whole-process quality of asphalt pavement construction. The combination of BIM and GIS used a digital map to display the overall road route conditions and the important road section details. Besides, compared to the traditional evaluation technologies, the framework was convenient for the overall and local construction quality evaluation. The contribution of this study is summarized as follows.

- A BIM-based model has been proposed to make the visual simulation of asphalt pavement construction using the real-time construction data, which inspected the follow-up construction plan, the real-time quality of the current process, and the assistance for the subsequent construction changes that may exist.
- A model based on the analytic hierarchy process (AHP) has been proposed to evaluate the whole-process quality of asphalt pavement construction, which performed the quantitative construction quality evaluation based on the data flow of the whole construction processes.
- A platform combined with BIM and GIS has been established for asphalt pavement construction quality evaluation. In the platform, the construction quality of each road section was visualized in GIS. The road mileage information was used as the connection to locate the corresponding BIM models for the subsequent fine control of construction quality.

The rest of the paper is organized as shown in Fig. 3. Section 2 describes the details of the proposed framework, including the method to visually simulate the entire process of asphalt pavement construction, a system for the construction quality evaluation, and an approach to represent the quality results. Section 3 reports a case study, which used the Phnom Penh-West Halluk Highway construction project to demonstrate the applicability of the proposed framework. Finally, Section 4 summarizes the research and gives further research plans for the future.

2. Methodology

2.1. Visual simulation using building information modeling

The long-term performance of asphalt pavement is effect by its quality in the construction phase. However, traditional construction and management cannot evaluate the quality owing to some real-world factors, including complex and varying construction technologies [31,32], long and irreversible construction processes [33–35], lagging information management [36,37], and difficult professional coordination [38]. Therefore, the first step in the proposed framework is the visual simulation of full-cycle pavement construction using BIM, which parameterizes the various real-world factors of a project.

A visual simulation based on BIM intuitively describes the logical relationship between the time and space of pavement construction by various links or parameters [39,40]. It provides accurate models and parameters information for the evaluation of construction quality. Fig. 4

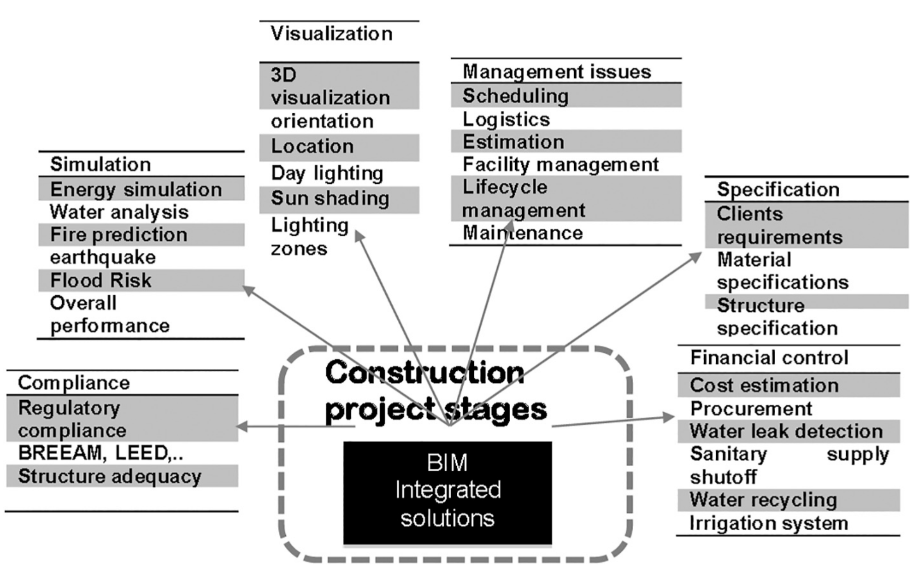

Fig. 1. BIM solutions.

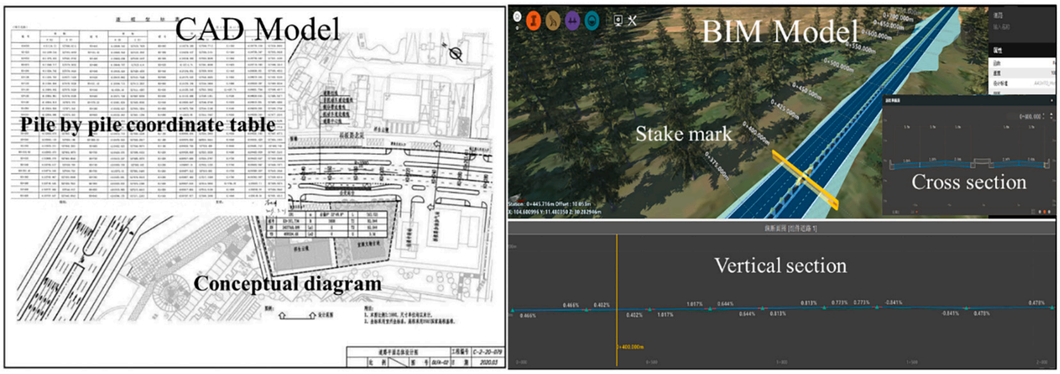

Fig. 2. BIM with a smart 3D data, while 2D CAD data is tedious and error prone.

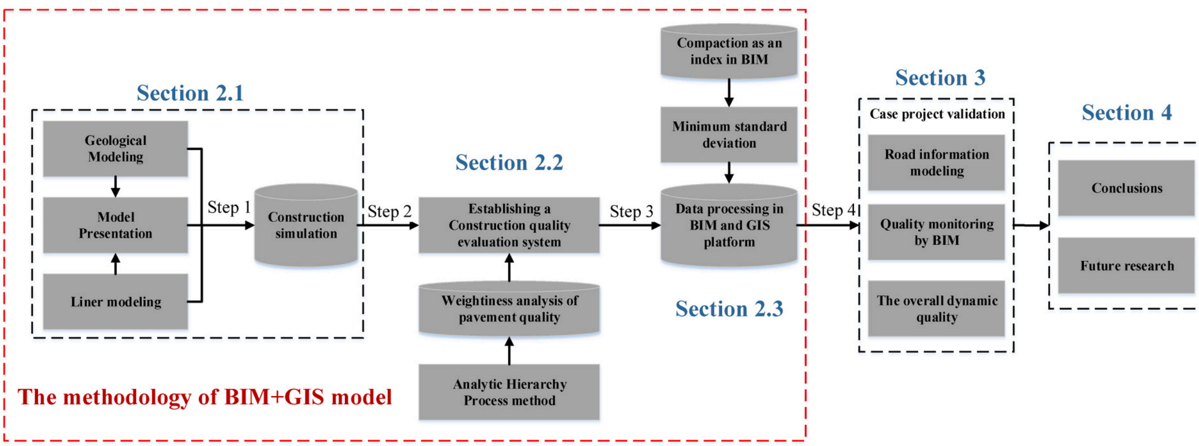

Fig. 3. Flow chart of this study.

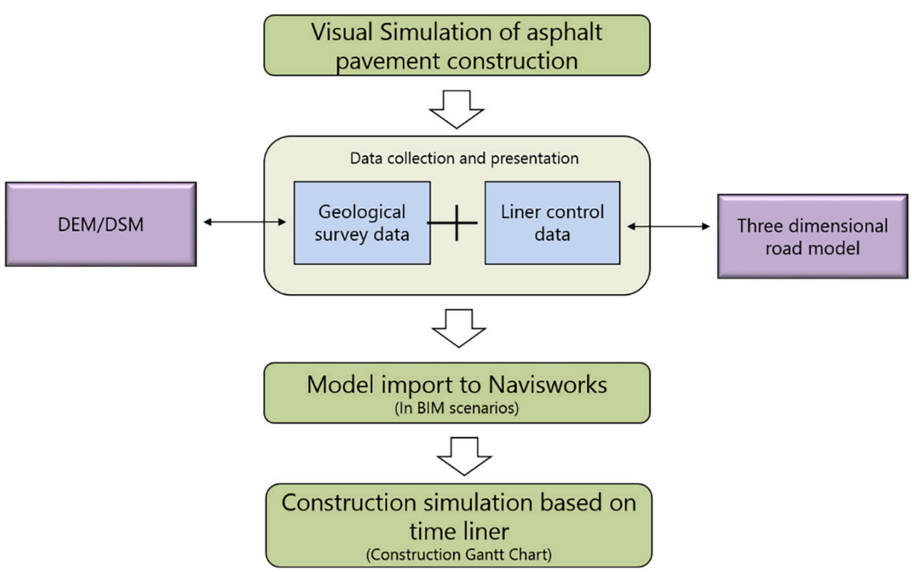

Fig. 4. Proposed framework and methodology for visual simulation.

presents the procedure of the visual simulation, which can be summarized by the following three stages:

Stage 1: Collect geological survey data to create a digital surface model (DSM).

Stage 2: Set up the linear control to guide the construction of dominant works, such as paving surface layers.

Stage 3: Build a 3D pavement model and import the model and DSM into Navisworks to perform the construction simulation.

2.1.1. Stage 1: Geological survey data and 3D modeling

As a plug-in for BIM, Dynamo has the capability of visual programming to deal with large and complex geological survey data. It can perform 3D modeling once given geological survey data in the form of Microsoft Excel. In addition, Dynamo supports Python programming for secondary development, which can further optimize and reduce unnecessary operations. The procedure in Dynamo to read geological survey data and build a DSM can be summarized in the following three steps, as shown in Fig. 5.

Step 1. Dynamo creates a node program with the capacity of reading data from Excel, as shown in Fig. 5.

Step 2. The created node program reads geological survey data from a Microsoft Excel spreadsheet. This step requires the data form that pairwise *x*-*y* coordinates in geological survey data should be disjoint.

Step 3. The data from Step 2 are converted into *xyz* coordinate points based on *topography*. These points are used to build a DSM and import it into Revit for Stage 2. The DSM is still made up of editable coordinate points, such as the example in Fig. 6.

2.1.2. Stage 2: Liner data controlling and road modeling in Revit

This stage aims to build a 3D road model. Fig. 7(a) presents the overall procedure of this stage, which can be summarized as three steps as follow.

Step 1: Create a toolbar for the visual parameter control, including the parameters of structural design and linear control, as shown in Fig. 7(b). After the control points are determined according to the design documents, the road alignment is fixed and used for road structure modeling through parameterization.

Step 2: The road structure is divided into the upper and lower parts. The upper part includes a central reservation in Fig. 7(c) and a pavement layer. The central reservation is simplified as a layer with a width of 2 m since it does not involve the construction quality evaluation. To ensure the accuracy of structural analysis, the parametric design of the pavement layer is divided into left and right lanes with surface-, middle- and sub-layers, as shown in Figs. 7(d) and (e). The pavement layer has a width of two-way and four-lane, which is common and widely used in asphalt pavements.

Step 3: Build the lower part of the road structure, including base and subbase layers, as shown in Fig. 7(f). The design procedure of this part is the same as the upper part in Step 2 except for the thicknesses of the base and subbase layers. Therefore, we only need to establish a new thickness parameter control tool for the lower part. The parameters of the 3D road model are visualized and editable. A designer can change the parameters at any time according to the new needs.

2.1.3. Stage 3: Visual simulation of asphalt pavement construction

In Stage 3, the 3D road model from Stage 2 is imported into Navisworks for the 4D time process simulation based on a construction schedule, which has been worked out in advance by the construction management personnel. Navisworks, as an important part of BIM, can perform a four-dimensional dynamic simulation. Thus, this stage intuitively displays the potential risks, such as the possible collisions among construction equipment, road structure, and underground pipelines. The construction schedule can be iteratively optimized using the results of this stage. In this part, it is necessary to record each step of asphalt pavement construction during simulation, which will be used to evaluate the construction quality in Section 2.2. In the simulation process, the start and end of each step, as well as all task categories in each step, shall be allocated in detail to guarantee that the whole process is consistent with the actual asphalt pavement construction, as shown in Fig. 8.

The visual simulation of asphalt pavement construction has been achieved after Stages 1–3. In this study, BIM-based visual simulation makes the construction processes clear, so that even non-professionals can have a clear and direct understanding of the entire construction processes. Thus, the simulation improves the technical level of construction personnel from another point of view. Moreover, the construction companies can optimize the construction schedule that significantly improves construction efficiency without consuming any physical resources [41–43].

2.2. Construction quality evaluation system

The AHP, first proposed by Saaty [44], is an approach for quantifying some subjective factors to make scientific and reliable multi-objective decisions. The procedure of AHP can be summarized as six steps: 1) define the decision problem and goal; 2) construct a hierarchical analysis structure; 3) construct judgment matrixes; 4) calculate hierarchical single sorting; 5) check the consistency of the judgment matrix; 6) calculate hierarchical total sorting [45]. In this study, the AHP is used to quantify the effects of different factors of asphalt pavement construction and reduce the subjective.

Fig. 9 shows an AHP-based structural diagram for the quality

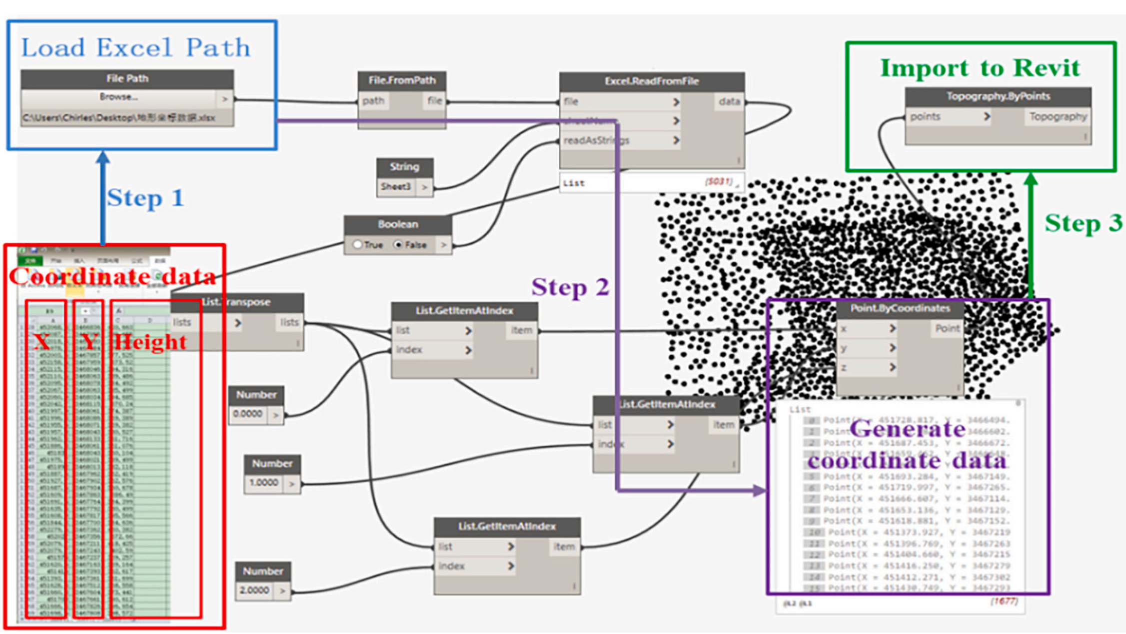

Fig. 5. Visual programming to generate point model in Dynamo.

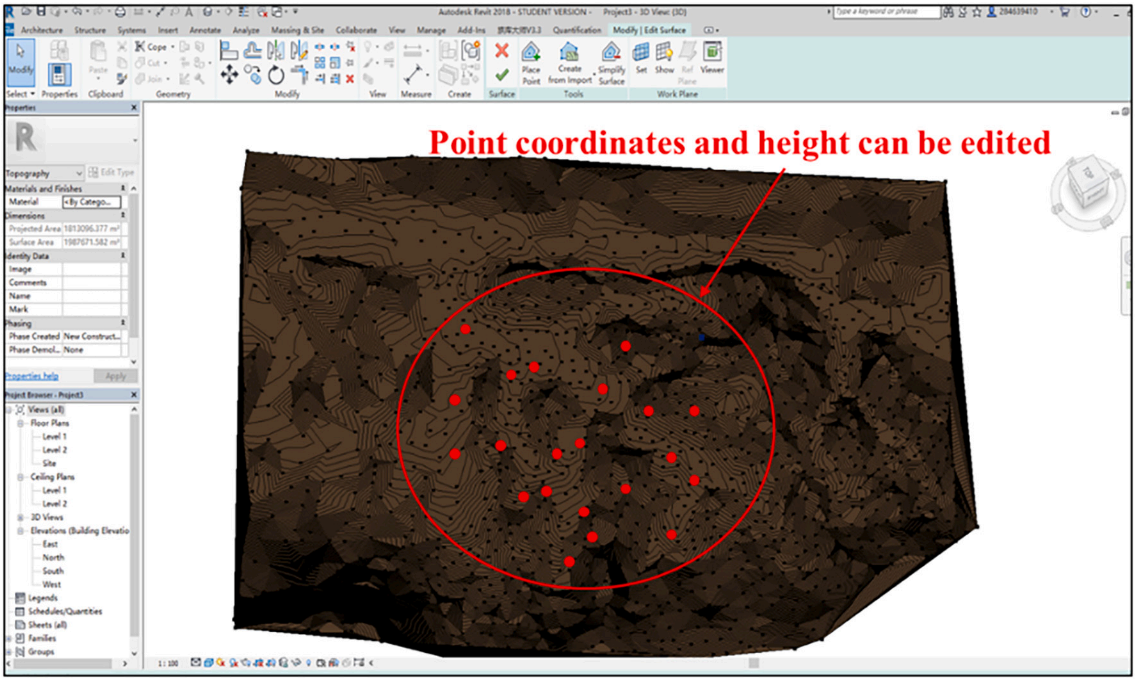

Fig. 6. A digital surface model in Revit.

evaluation of asphalt pavement construction, which is consisted of a target layer A, an object layer B_1-B_4, and an indicator layer C_1- C_{10}. The object layer is constructed according to the processes of asphalt pavement construction, while the indicator layer is made up of the key quality factors of each construction process. The construction of asphalt pavement can be divided into four main processes: asphalt mixture preparation (denoted as B_1), mixture transportation (denoted as B_2), pavement paving (denoted as B_3), and pavement compaction (denoted as B_4). Specifically, the key factors in the mixture preparation process are the mixture composition (denoted as C_1) and mixing temperature (denoted as C_2); the main factors during transportation are the transportation time (denoted as C_3) and driving behavior (denoted as C_4); the paving quality is mainly affected by paving temperature (denoted as C_5), thickness (denoted as C_6) and speed (denoted as C_7); the compaction quality is mainly affected by compaction temperature (denoted as C_8), speed (denoted as C_9) and rolling frequency (denoted as C_{10}). In Fig. 9, the indicator layer consists of the construction quality parameters that can be collected and transmitted in the construction field, while the object and target layers are made up of the quality in each process and the final quality in road construction, respectively.

It is necessary to determine the relative importance of low-level factors to high-level ones during the structural analysis. The AHP determines the importance weights of a layer by analyzing the effect of the low level on it, such as the weights of C_1, C_2…C_m on B_n in Fig. 9. Take the indicator and object layers in Fig. 9 as an example. In the AHP method, K experts first give their scores $S_i^k \in [1,9]$, $i = 1, \ldots, m$ and $k = 1, \ldots, K$, where C_i^k represent the beliefs about the effects of C_i on B_n from expert k and m is the number of alternatives in the indicator layer. Then the scores S_i^k, $k = 1, \ldots, K$, are averaged to determine the final scores of S_i that represents the effects of the indicator C_i on the object layer. These averaged scores are used to build a judgment matrix with a general term c_{ij}, in which c_{ij} is the ratio of S_i and S_j. Table 1 present the general form of a judgment matrix.

The weight of C_i to B_n, notated as ω_i, can be computed as

$$\theta_{ij} = \frac{c_{ij}}{\sum_{i=1}^{m} c_{ij}} \tag{1a}$$

$$\omega_i = \frac{\sum_{j=1}^{m} \theta_{ij}}{\sum_{i=1}^{m} \sum_{j=1}^{m} \theta_{ij}} \tag{1b}$$

The weight of B_n to A is calculated by the same procedure as above. After determining all the weights, the AHP method can evaluate the construction quality using the monitoring data, as the one will be shown in the case study of Section 3.

2.3. Monitoring data preprocessing for BIM + GIS platform

The AHP-based system in Section 2.2 requires real-time monitoring data to evaluate the construction quality. This study has proposed a real-time method to acquire and pre-process the monitoring data using the BIM + GIS platform. The method uses the division of minimum standard deviation to deal with large and complex monitoring data. In addition, the method improves computational efficiency by using partial monitoring results to represent the overall situation of the road sections. This section takes the metric "*degree of compaction*" as an example to illustrate the method, which corresponds to the rolling quality of the object layer in Fig. 9.

The degree of compaction, as an important indicator in the construction quality evaluation, characterizes the overall density in asphalt pavement. An area with a poor degree of compaction always has uneven settlement and other distresses after suffering vehicle loading and water damage, which significantly reduces the life-cycle performance of asphalt pavement. Unfortunately, the number of compaction quality data from a road is huge and complex, such as the examples shown in Fig. 10. Therefore, this study uses a standard deviation-based method to group the compaction test data and then characterize the compaction quality with the representative results of these groups.

The standard deviation method, as a measure of the variation and dispersion of a set of values [47], is used to find the representative value

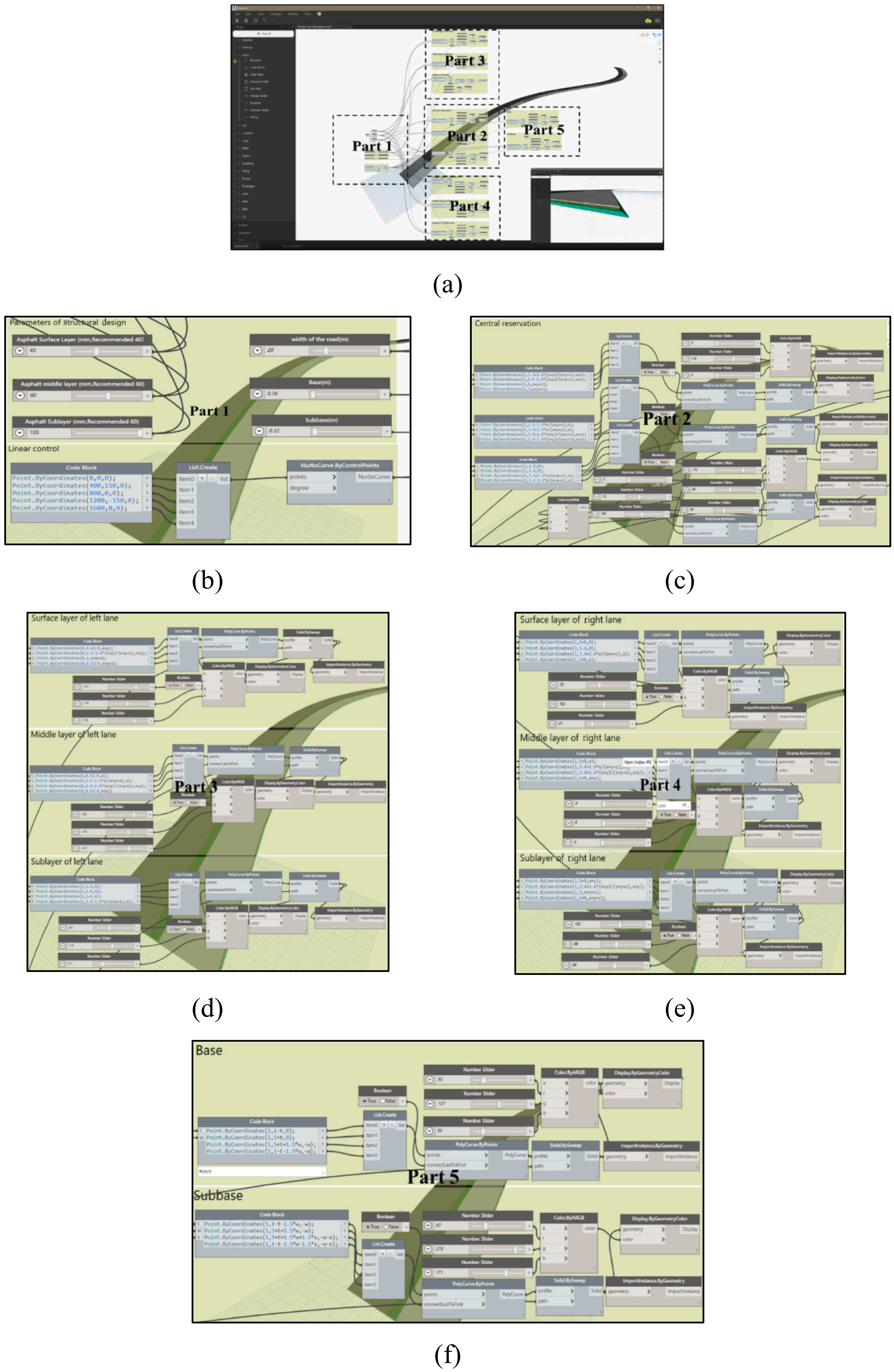

Fig. 7. Procedure of Stage 2 [18]: (a) overall, (b) Part 1 road alignment modeling, (c) Part 2 road central reservation modeling, (d) Part 3 left road surface layer structure modeling, (e) Part 4 right road surface layer structure modeling, and (f) Part 5 road overall base and subbase layer modeling.

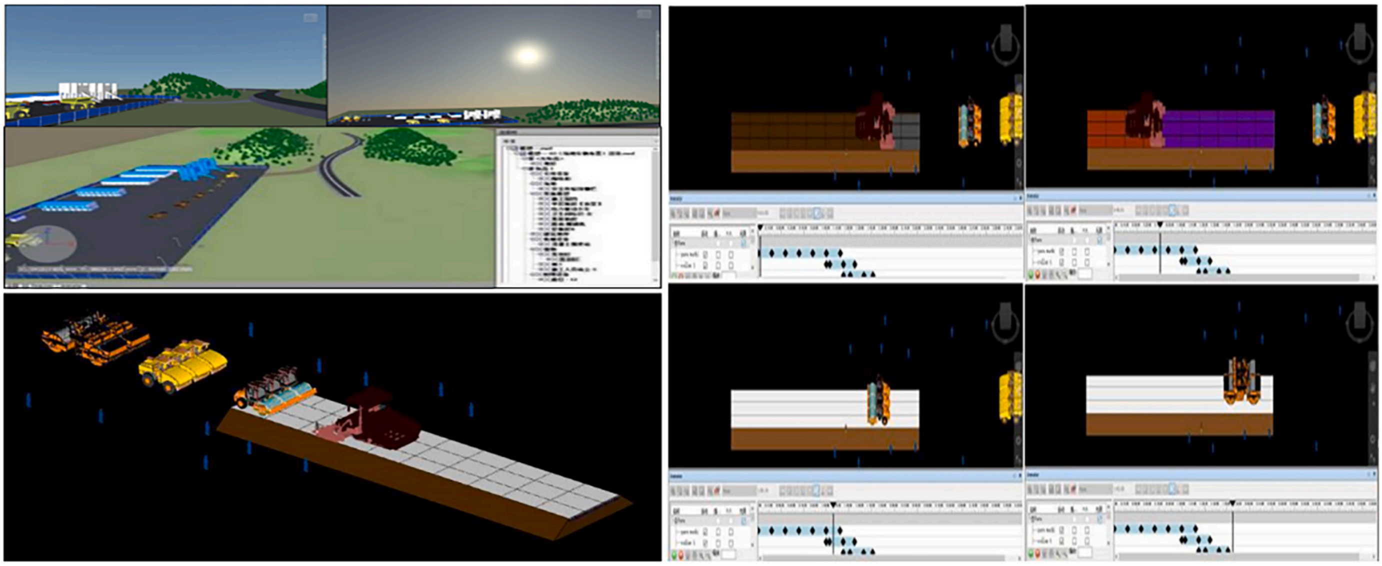

Fig. 8. Scene layout and construction simulation in *Navisworks*.

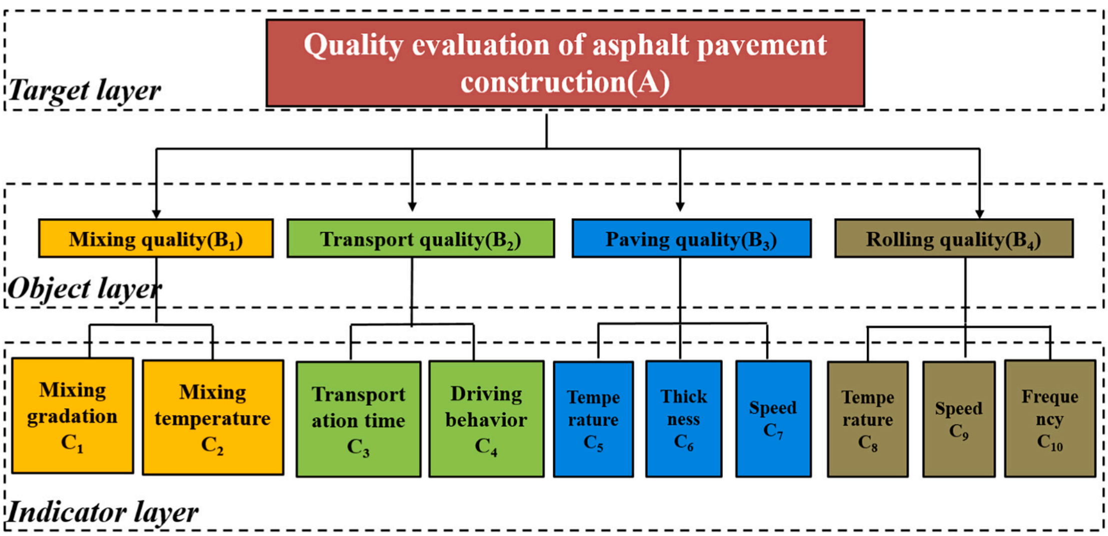

Fig. 9. Structural diagram for the quality evaluation of in asphalt pavement construction based on the AHP.

Table 1
Judgment matrix.

B_n	C_1	C_2	…..	C_m
C_1	c_{11}	c_{12}	…..	c_{1m}
C_3	c_{21}	c_{22}	…..	c_{2m}
…..	…..	…..	…..	…..
C_m	c_{m1}	c_{m2}	…..	c_{mm}

of the degree of compaction. The method first defines a threshold of minimum standard deviation, such as $S_0 = 0.5$ in the example shown in Fig. 11. The data of the degree of compaction from a road section is sorted by the number of road mileage. The first two data are selected as the initialization of the first group and the standard deviation S_1 of the group is then computed. The rest of the data are then sequentially appended to the group until achieving $S_1 < S_0$. The remaining data is then grouped by repeating the above way. Finally, the averaged degree of compaction in each group is used to characterize the degree of compaction of the road section. Fig. 11 presents an example of the method, in which 210 data of the compaction degree has been divided

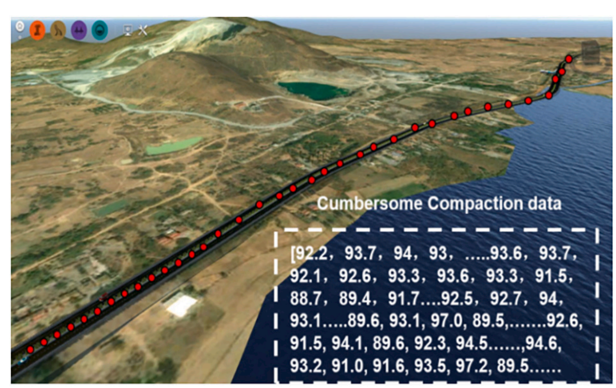

Fig. 10. Example of huge and complex compaction data that are collected by intelligent compaction technology that uses modern detection equipment and feedback system to collect the compaction quality information in real-time and automatically adjusts the amplitude and frequency of rolling to ensure the quality of road compaction [46].

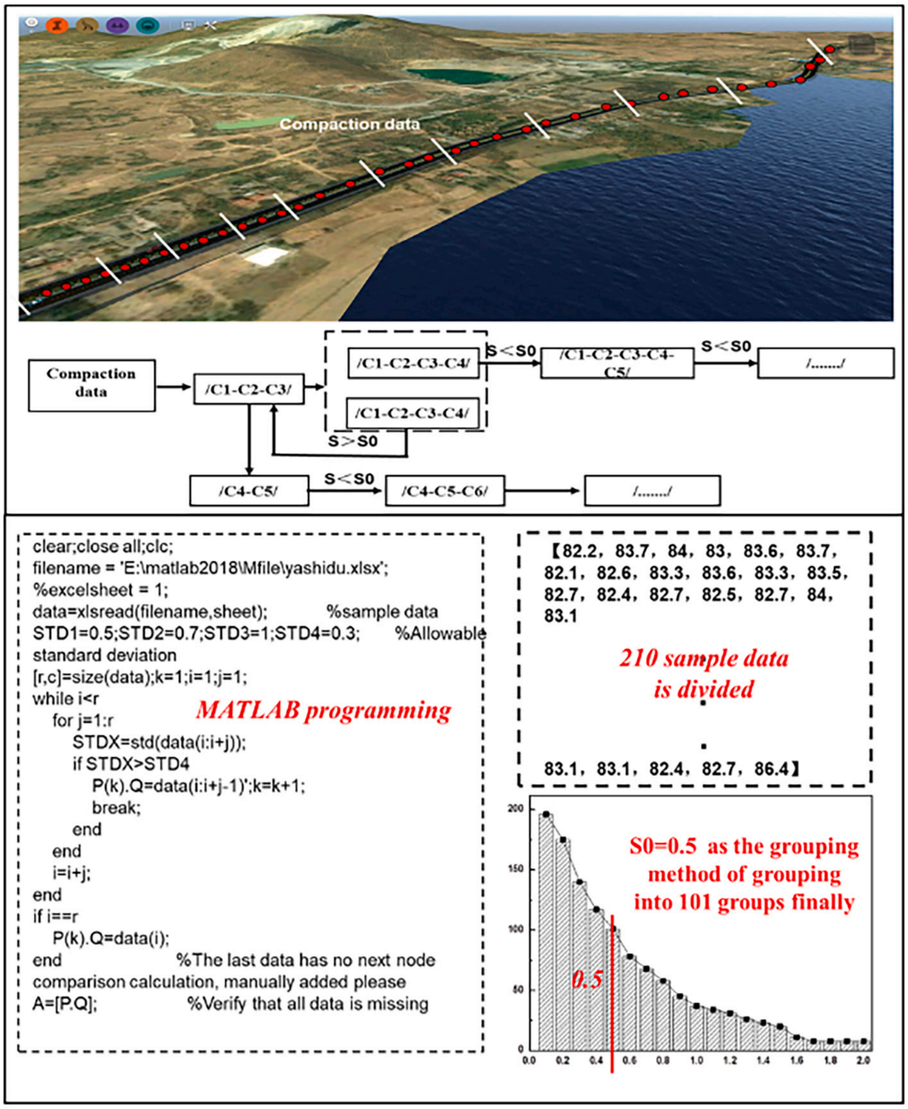

Fig. 11. Minimum standard deviation division method of asphalt pavement compaction data.

into 101 groups.

3. A case study

A case study on the Phnom Penh-West Halluk Highway was used to validate the effectiveness of the proposed platform. The case study used the ArcGIS and the BIM software of the Autodesk series: Revit, Navisworks, and Infraworks. Revit is a professional BIM modeling software, which can build high-precision 3D models. Moreover, Revit can establish project sample files and a Revit family library, which are used to conduct the parametric modeling of the full road based on the design of the standard road section. Navisworks is a professional collaboration platform, which performs highly accurate 3D construction process simulations and checks construction schedules to eliminate potential risks. Infraworks is an easy-to-use sketching tool that is widely used in BIM modeling of roads and bridges due to its broad modeling scope, such as hundreds of kilometers of a road. This tool can utilize a large range of terrain files to build a 3D road model based on the terrain, which is suitable for modeling road networks that do not require high accuracy.

Fig. 12 presents the workflow and collaboration of Revit, Navisworks, and Infraworks in the case study. Revit first built and parameterized a high-precision model of the road standard section. The model was then imported into Navisworks and Infraworks. Navisworks expanded the model area, established the BIM model of the construction area, obtained the real-time construction information of the construction site, simulated the construction process, checked the construction schedule, and eliminated the construction risk. At the same time, the real-time construction data was transmitted to the construction information database, and the construction quality of each construction link was calculated using the AHP-based method, as introduced in Section 2.2. Meanwhile, Infraworks built a complete road 3D model using the model of the road standard section from Revit, while ArcGIS established a 2D model of the road network. GIS displayed the macroscopic visual information of road construction quality, while Infraworks retrieved the multiple information of road sections. Both 3D and 2D models are associated with the database through the starting and ending mileage of the road section. In addition, after the construction quality evaluation, Navisworks checked the changes in construction information and schedule for the subsequent construction quality control (orange arrows and text in Fig. 12).

The rest of the section describes the details of the evaluation processes of pavement construction quality in the Phnom Penh-West Halluk Highway project. First, Fig.13 presents the road BIM model of the project built by Revit, Infraworks, and Navisworks. Specifically, Revit built a road section model, containing material parameters, structural parameters, construction parameters, and design information;

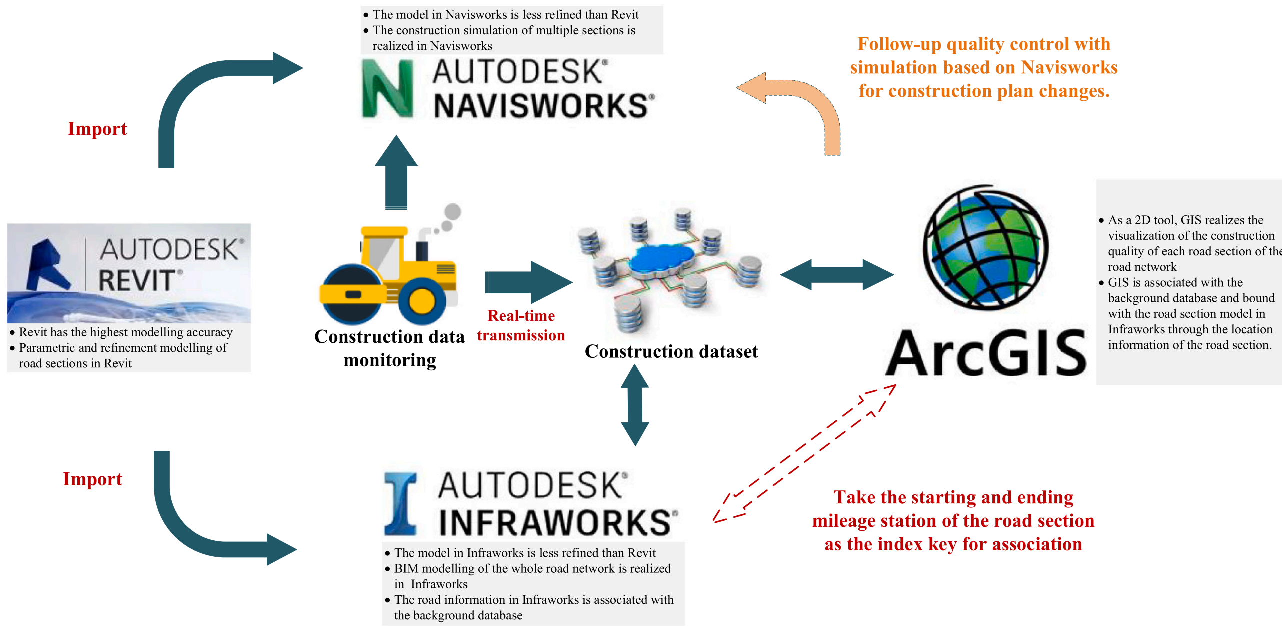

Fig. 12. The flowchart of the proposed combined framework with BIM and GIS in the Phnom Penh-West Halluk Highway project.

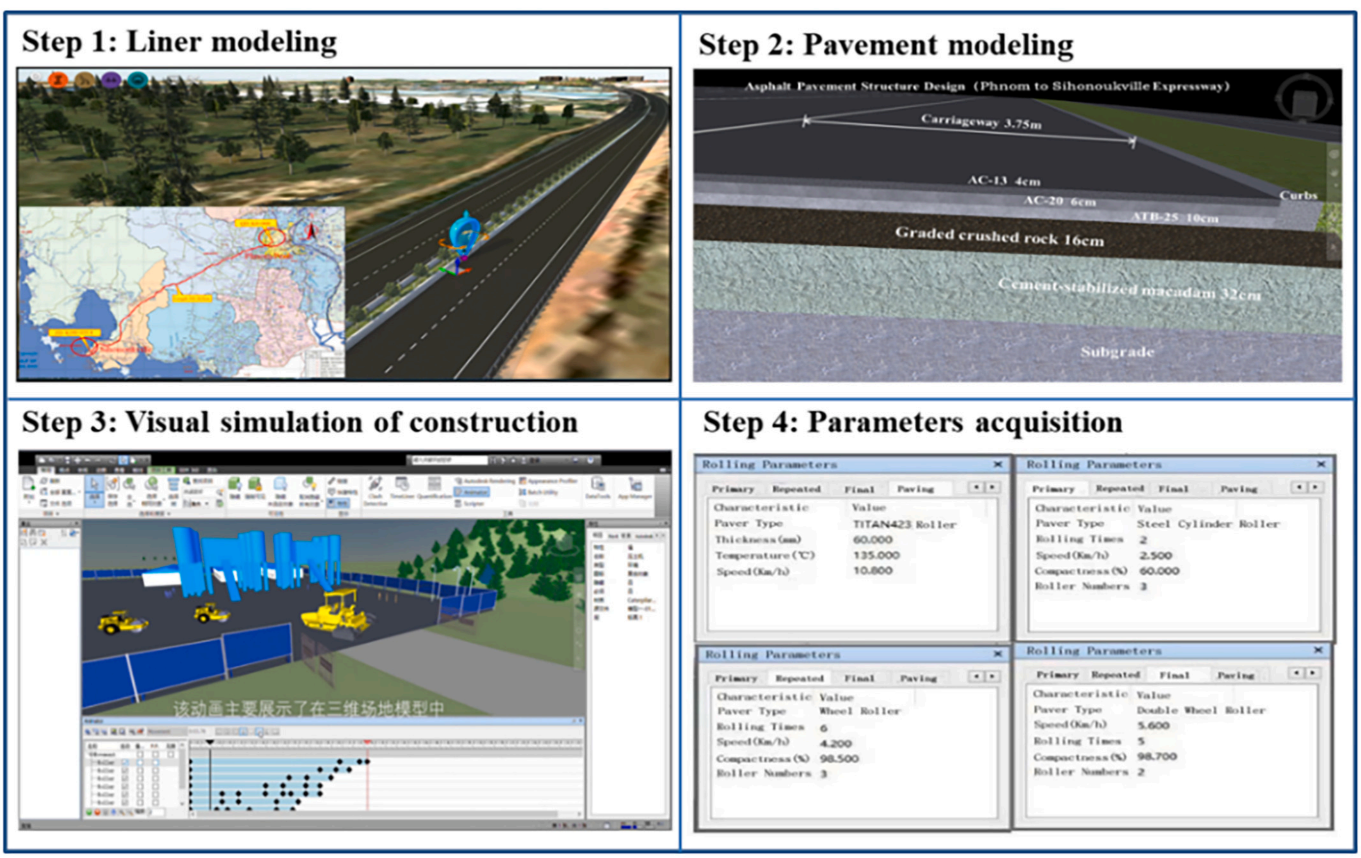

Fig. 13. The Establishment of the 3D road model and construction quality parameters [19].

Infraworks defined the road alignment and built the complete road 3D model; and Navisworks made the construction scenario and simulated the construction schedule. After that, the proposed framework collected and transmitted the monitoring data of each construction process in real time.

3.1. Real-time construction data monitoring

For the AHP method in this case study, we invited eight experts: a) three technical leaders responsible for asphalt mixture production, asphalt pavement paving, and pavement compaction; and b) five professors of the road engineering to score each weight matrix of the AHP method. Fig.14 presents the self-designed expert scoring system based on C++, which made it possible for subsequent experts to give additional scores and adjust the weight of AHP according to the actual situation.

Using the method introduced in Section 2.2, the AHP weights in this case were defined using the notations in Section 2.3 as

$$A = 0.244B_1 + 0.152B_2 + 0.252B_3 + 0.352B_4 \tag{2a}$$

$$B_1 = 0.425C_1 + 0.575C_2 \tag{2b}$$

$$B_2 = 0.225C_3 + 0.775C_4 \tag{2c}$$

$$B_3 = 0.517C_5 + 0.226C_6 + 0.257C_7 \tag{2d}$$

$$B_4 = 0.211C_8 + 0.282C_9 + 0.507C_{10} \tag{2e}$$

Since the material transportation process of the project was not monitored, we only collected the construction data from the asphalt mixture preparation process, pavement paving process, and pavement compaction process.

During the asphalt mixture preparation process, we collected the production data of the mixing plants and divided the whole highway into 5 sections with lengths of 30.18 km, 40.18 km, 40 km, 35 km, and 45.003 km according to the supplied mixing plants. The mixture gradation and temperature were monitored and scored according to the design gradation table and mixing temperature range. After that, the two scores were weighted according to 0.425:0.575 in Eq. (2b) to obtain the mixing process quality B_1.

During the paving process, the values of temperature, speed, and thickness are monitored in real time. In this study, the *Gini* index was used instead of the speed indicator [5]. This was because the control of paving speed is mainly related to the segregation variation, and we have proposed the *Gini* index in our previous study [10] to evaluate the degree of segregation, which has a better correlation to the segregation variation than the paving speed. The temperature and thickness were scored according to the preset range and then weighted with the normalized Gini index in a ratio of 0.517:0.226:0.257 in Eq. (2d) to obtain the paving quality B_3.

During the compaction process, the continuous changes of temperature, speed and frequency were collected. Since intelligent compaction technology was adopted for the compaction process, compaction measured value (CMV) [48] was used to replace the frequency indicator to represent pavement compactness, such that

$$CMV = C \times \frac{A_{2\omega}}{A\omega} \tag{3}$$

where $A_{2\omega}$ and A_ω are the acceleration amplitude of the fundamental component and the first harmonic component of the roller vibration, respectively; C is a constant established during site calibration ($C = 300$ was used in this study). The indicators of temperature, speed and CMV were then normalized and weighted according to the ratio of 0.211:0.252:0.507 in Eq. (2e) to obtain the pavement compaction quality B_4.

Since the quality of transportation process was missing, the weights of transportation quality on the AHP method were divided proportionally to the other three processes. Thus, the final pavement construction quality A was computed as

$$A = 0.288B_1 + 0.297B_3 + 0.415B_4 \tag{4}$$

3.2. Construction quality evaluation by BIM and GIS

Quality evaluation results of each construction process based on the real-time construction data were not visualized because they are in a digital form. Therefore, Infraworks was used to make a visible representation of monitoring and evaluation results. The road models from Revit were imported into Infraworks and divided into several construction sections. The construction information of each section was recorded, including the construction time, construction technologies, construction personnel, and evaluation results of construction quality. The information was represented in a user interface to perform the visualization, such as the example shown in Fig. 15.

Unfortunately, there was too much information in a small road area during each construction step, which made it difficult for a user to capture the overall information. Therefore, the proposed framework used a GIS map to represent the overall dynamic quality information, such as the example shown in Fig. 16. Infraworks used the same road segmentation method as the GIS map and implemented the associations with the GIS map based on the starting and ending mileage of the road segments.

Fig. 14. Expert scoring software for asphalt pavement construction quality evaluation.

Fig. 15. Local quality monitoring by Infraworks (BIM).

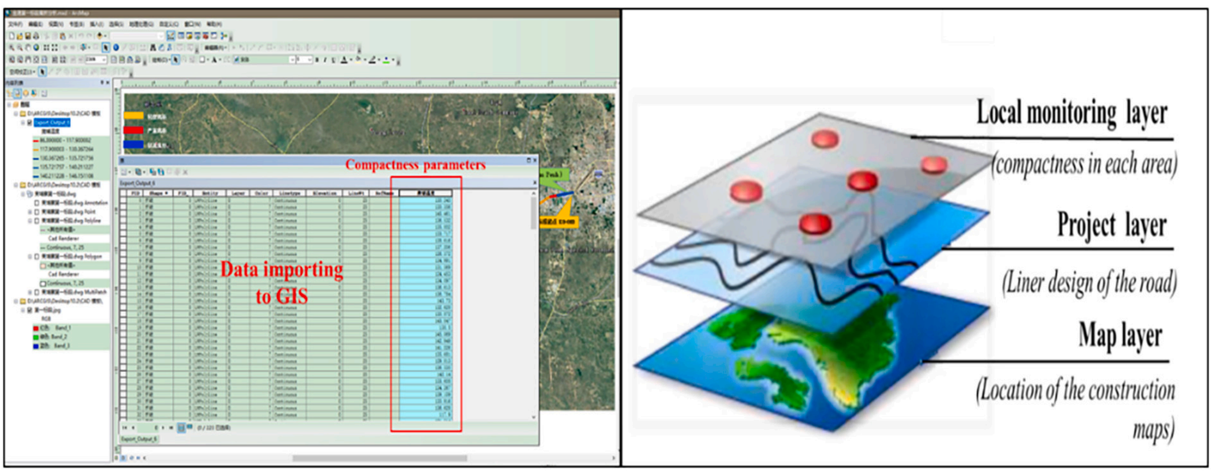

Fig. 16. Example of a GIS map representing the overall dynamic quality information [5].

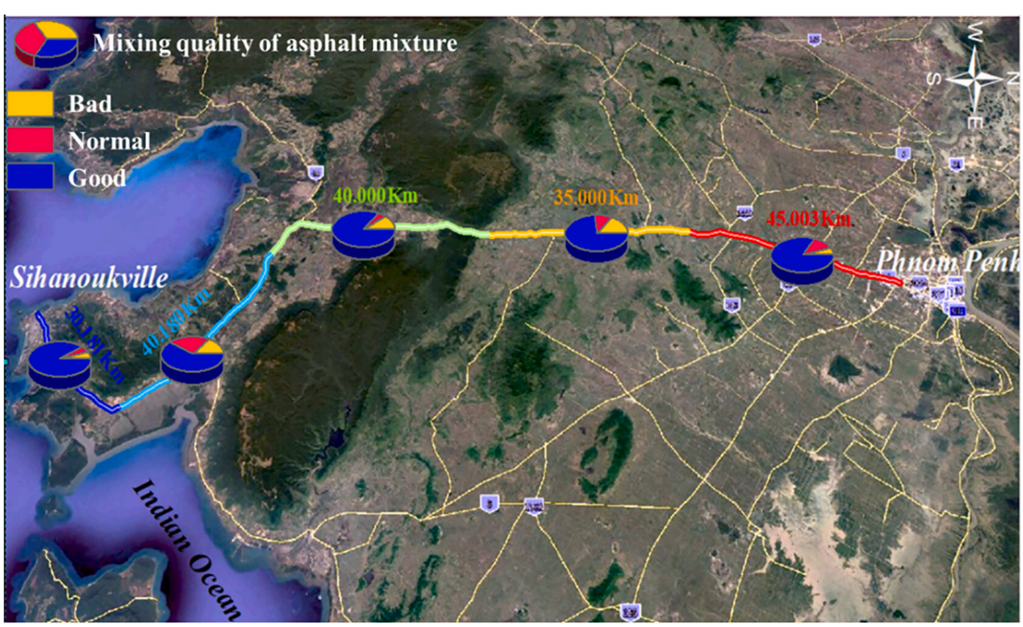

Fig. 17. Real-time monitoring of mixing quality of asphalt pavement construction in Phnom Penh to Sihanoukville highway project.

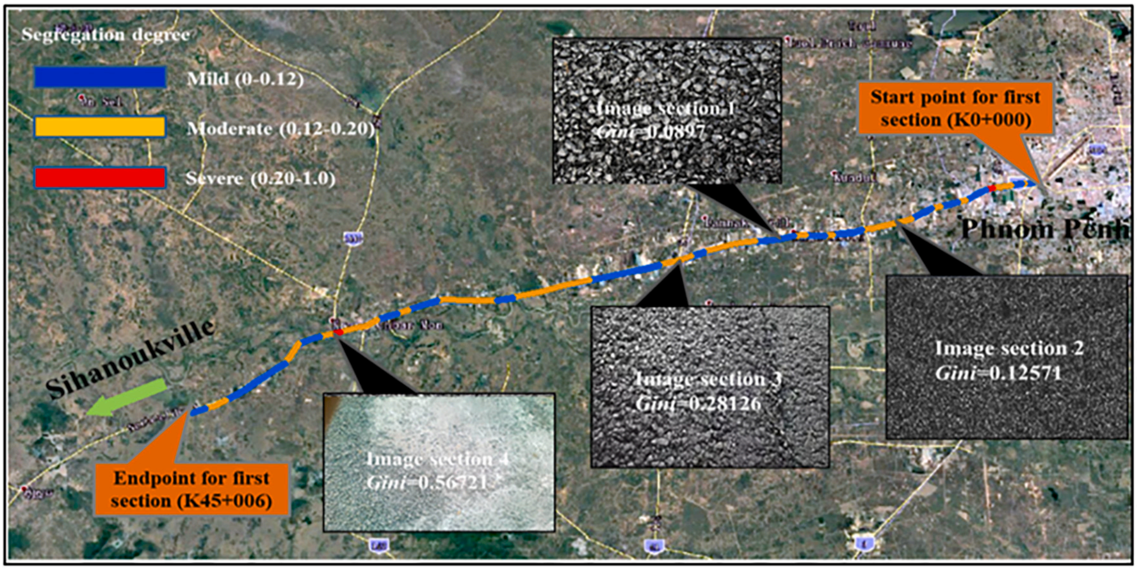

Fig. 18. Real-time monitoring of paving quality of asphalt pavement construction in Phnom Penh to Sihanoukville highway project [5].

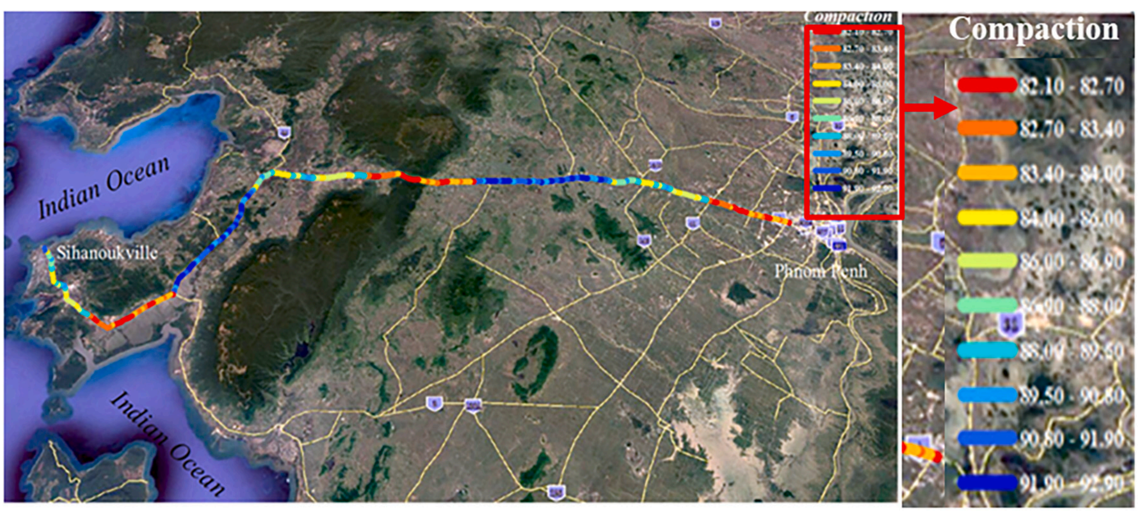

Fig. 19. Real-time monitoring of compaction quality of asphalt pavement construction in Phnom Penh to Sihanoukville highway project.

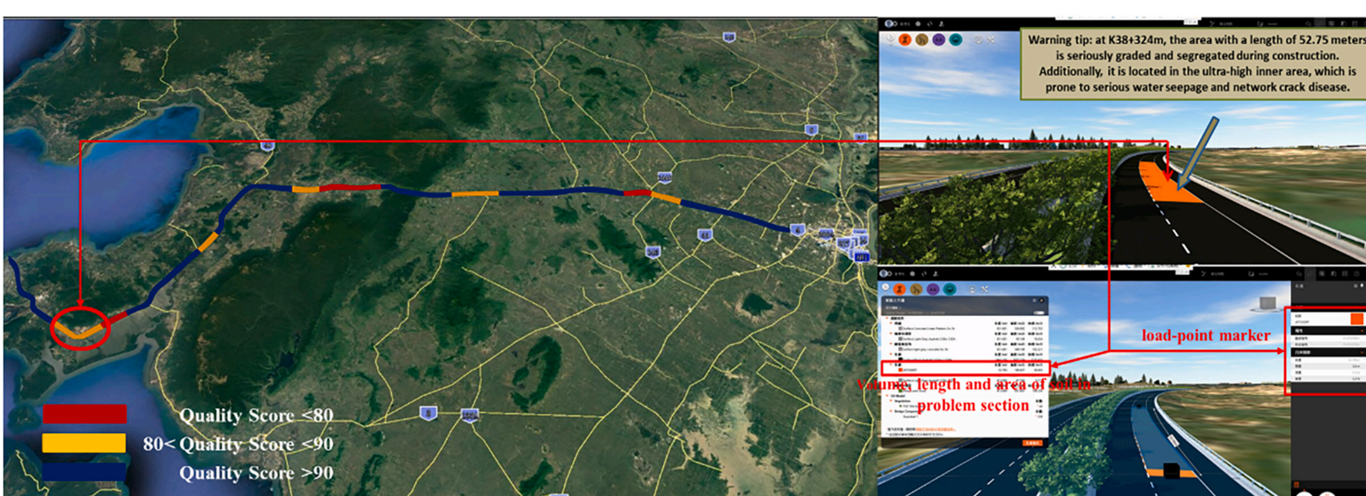

Fig. 20. Real-time monitoring of construction quality of asphalt pavement construction in Phnom Penh to Sihanoukville highway project.

The quality of each construction process in the whole road network and each section was displayed to the project management personnel through the GIS map. Figs. 17-19 show the GIS visualization of the construction quality in the mixture preparation phase, pavement paving phase, and pavement compaction phase, respectively. The GIS map used different colors to present different construction quality, and the sections with poor construction quality were visually identified as yellow.

Using the AHP method to weight the quality of the full-process construction, the final pavement construction quality was computed and visualized by the GIS map, as shown in Fig. 20. The final construction quality *A* was in a range of (0,100). Road sections with the scores less than 80 were marked in red, whose construction quality did not meet the standard and the sections were required to conduct remedial construction; Road sections with the scores between 80 and 90 were marked in yellow, whose construction quality was at risk and required the attention; Road sections with scores greater than 90 had rewarding construction quality.

The road sections with the construction quality problems were located by their ID in GIS and BIM. The multi-source information of the road sections with problems was extracted from the corresponding BIM model in Infraworks, which was used to analyze the causes of construction quality defects. The causes were then used to make the changes to the subsequent construction plan or to take targeted disposal measures.

The combination of Revit, Infraworks, Navisworks, and GIS has the potential to guarantee the share and record of the data flow of the whole construction process by construction participants, which will facilitate the construction quality control timely, accurate, and efficient construction quality control using the results of construction quality evaluation. This direction is what we need to further study in the future.

4. Conclusions

This study has proposed a framework to perform the real-time quality evaluation for asphalt pavement construction by combining BIM and GIS technologies. The following conclusions can be drawn.

(1) The proposed framework combining BIM and GIS realized real-time and comprehensive quality evaluation of the whole process of pavement construction. It allowed for the transmission, interaction, sharing, and application of construction information data in the BIM environment. The proposed framework utilized the advantages of GIS in the macro-information visualization of the road network to enhance the intelligence of the quality evaluation.

(2) A systemic BIM-based visible flow for pavement construction simulation has been built, including road alignment modeling, road structure modeling, digital surface modeling, and construction schedule modeling, which realized the BIM integration of the whole process of pavement construction.

(3) A new visualization method of construction quality evaluation was proposed. The AHP method was used to quantitatively calculate the quality of the whole process of pavement construction. The evaluation results were visualized in a GIS map. The BIM models of the concerned sections, as well as their multi-source data, were retrieved through the section mileage coordinates, which provided a good data basis for the construction quality control.

(4) The future study will focus on three aspects. First, other advanced methods, such as neural networks, will be considered to perform the scoring procedure in the AHP method, which has the potential to reduce subjectivity. Second, more factors in road construction should be considered in the simulation in Section 2.1, such as the quality of construction personnel and equipment. In addition, the construction quality control based on the quality evaluation results needs to be further studied.

Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgement

The study is financially supported by the Postgraduate Research & Practice Innovation Program of Jiangsu Province (KYCX21_0136), the National Key Research and Development Project, grant number 2020YFB1600102 and 2020YFA0714302, the National Natural Science Foundation of China, grant number 51878164 and 51922030, Southeast University “Zhongying Young Scholars” Project, Department of Transportation of Shandong Province, grant number 2018B51. The authors would also like to acknowledge the financial support provided by China Road and Bridge Engineering Co., Ltd. (grant number CRBC/KHM/2021/053).

References

[1] L.A. Ahmed, M. Kassem, A unified BIM adoption taxonomy: conceptual development, empirical validation and application, Autom. Constr. 96 (2018) 103–127, https://doi.org/10.1016/j.autcon.2018.08.017.
[2] C. Boton, Supporting constructability analysis meetings with immersive virtual reality-based collaborative BIM 4D simulation, Autom. Constr. 96 (2018) 1–15, https://doi.org/10.1016/j.autcon.2018.08.020.
[3] Z.T. Yang, Z.L. Ma, S. Wu, Optimized flowshop scheduling of multiple production lines for precast production, Autom. Constr. 72 (3) (2016) 321–329, https://doi.org/10.1016/j.autcon.2016.08.021.
[4] B. Wilson, A. Devadast, R. Lytton, S. Senesta, Ground penetrating radar as a quality assurance tool in hot-mix asphalt road construction, Mater. Eval. 78 (10) (2020) 1129–1139, https://doi.org/10.32548/2020.me-04140.
[5] K. Hoegh, S.T. Dai, T. Steiner, L. Khazanovich, Enhanced model for continuous dielectric-based asphalt compaction evaluation, Transp. Res. Rec. 2672 (26) (2018) 144–154, https://doi.org/10.1177/0361198118794068.
[6] K. Zhang, L.E. Xie, Z.Q. Zhang, Detection and evaluation method of construction quality on-site for asphalt pavement, J. Mater. Sci. Eng. 4 (2019) 604–611, https://doi.org/10.14136/j.cnki.issn1673-2812.2019.04.016.
[7] Z.Y. Ma, J.X. Zhang, S.P. Philbin, H. Li, J. Yang, Y.L. Feng, Dynamic quality monitoring system to assess the quality of asphalt concrete pavement, Buildings 11 (12) (2021) 577, https://doi.org/10.3390/buildings11120577.
[8] G. Dong, Y.B. Liu, N.X. Zheng, Study on real-time monitoring system of asphalt pavement construction process quality information, Journal of Highway and Transportation Research and Development. 32 (11) (2015) 27–32, https://doi.org/10.3969/j.issn.1002-0268.2015.11.005.
[9] Q. Xu, G.K. Chang, Evaluation of intelligent compaction for asphalt materials, Autom. Constr. 30 (2013) 104–112, https://doi.org/10.1016/j.autcon.2012.11.015.
[10] F.L. Tang, C.J. Han, T. Ma, T. Chen, Y.S. Jia, Quantitative analysis and visual presentation of segregation in asphalt mixture based on image processing and BIM, Autom. Constr. 121 (2021) 1–10, https://doi.org/10.1016/j.autcon.2020.103461.
[11] J.K.W. Wong, K.L. Kuan, Implementing “BEAM plus” for BIM-based sustainability analysis, Autom. Constr. 44 (2014) 163–175, https://doi.org/10.1016/j.autcon.2014.04.003.
[12] S. Azhar, W.A. Carlton, D. Olsen, I. Ahmad, Building information modeling for sustainable design and LEED (R) rating analysis, Autom. Constr. 20 (2) (2011) 217–224, https://doi.org/10.1016/j.autcon.2010.09.019.
[13] A. Bradley, H.J. Li, R. Lark, S. Dunn, BIM for infrastructure: an overall review and constructor perspective, Autom. Constr. 71 (2016) 139–152, https://doi.org/10.1016/j.autcon.2016.08.019.
[14] W. Smits, M. van Buiten, T. Hartmann, Yield-to-BIM: impacts of BIM maturity on project performance, Build. Res. Inf. 45 (3) (2017) 336–346, https://doi.org/10.1080/09613218.2016.1190579.
[15] Z.L. Ma, Z.T. Yang, S.L. Liu, S. Wu, Optimized rescheduling of multiple production lines for flowshop production of reinforced precast concrete components, Autom. Constr. 95 (2018) 86–97, https://doi.org/10.1016/j.autcon.2018.08.002.
[16] A. Costin, A. Adibfar, H.J. Hu, S.S. Chen, Building information modeling (BIM) for transportation infrastructure - literature review, applications, challenges, and recommendations, Autom. Constr. 94 (2018) 257–281, https://doi.org/10.1016/j.autcon.2018.07.001.
[17] P. Bynum, R. Issa, S. Olbina, Building information modeling in support of sustainable design and construction, J. Constr. Eng. Manag. 139 (1) (2013) 24–34, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560.
[18] I. Hijazi, A. Donaubauer, T.H. Kolbe, BIM-GIS integration as dedicated and independent course for geoinformatics students: merits, challenges, and ways forward, ISPRS Int. J. Geo Inf. 7 (8) (2018) 33–42, https://doi.org/10.3390/ijgi7080319.
[19] F.L. Tang, T. Ma, J.H. Zhang, Y.S. Guan, L.F. Chen, Integrating three-dimensional road design and pavement structure analysis based on BIM, Autom. Constr. 113 (2020) 1–17, https://doi.org/10.1016/j.autcon.2020.103152.

[20] F.L. Tang, T. Ma, Y.S. Guan, Z.X. Zhang, Parametric modeling and structure verification of asphalt pavement based on BIM-ABAQUS, Autom. Constr. 111 (2020) 1–10, https://doi.org/10.1016/j.autcon.2019.103066.
[21] C. Oreto, S.A. Biancardo, N. Viscione, R. Veropalumbo, F. Russo, Road pavement information modeling through maintenance scenario evaluation, J. Adv. Transp. 2021 (2021) 1–14, https://doi.org/10.1155/2021/8823117.
[22] C. Oreto, S.A. Biancardo, N. Viscione, R. Veropalumbo, F. Russo, G. Dell'Acqua, BIM-LCCA integration for road pavement maintenance, Transp. Res. Rec. (2022) 1–15, https://doi.org/10.1177/03611981221074368.
[23] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, Autom. Constr. 19 (8) (2010) 988–999, https://doi.org/10.1016/j.autcon.2010.09.002.
[24] S. Zhang, D.J. Hou, C. Wang, F. Pan, L. Yan, Integrating and managing BIM in 3D web-based GIS for hydraulic and hydropower engineering projects, Autom. Constr. 112 (2020) 103–114, https://doi.org/10.1016/j.autcon.2020.103114.
[25] C. Cecchini, From data to 3D digital archive: a GIS-BIM spatial database for the historical Centre of Pavia (Italy), Journal of Information Technology in Construction. 24 (2019) 459–471, https://doi.org/10.36680/j.itcon.2019.024.
[26] M. Sun, X. Meng, Taxonomy for change causes and effects in construction projects, Int. J. Proj. Manag. 27 (6) (2009) 560–572, https://doi.org/10.1016/j.ijproman.2008.10.005.
[27] H. Wang, Y. Pan, X.C. Luo, Integration of BIM and GIS in sustainable built environment: a review and bibliometric analysis, Autom. Constr. 103 (2019) 41–52, https://doi.org/10.1016/j.autcon.2019.03.005.
[28] J.Y. Son, I. Benbasat, Organizational buyers' adoption and use of B2B electronic marketplaces: efficiency- and legitimacy-oriented perspectives, J. Manag. Inf. Syst. 24 (1) (2007) 55–99, https://doi.org/10.2753/MIS0742-1222240102.
[29] H.Y. Chong, R. Lopez, J. Wang, X.Y. Wang, Z.Y. Zhao, Comparative analysis on the adoption and use of BIM in road infrastructure projects, J. Manag. Eng. 32 (6) (2016) 1–13, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000460.
[30] I.L. Wu, J.L. Chen, A stage-based diffusion of IT innovation and the BSC performance impact: a moderator of technology-organization-environment, Technol. Forecast. Soc. Chang. 88 (2014) 76–90, https://doi.org/10.1016/j.techfore.2014.06.015.
[31] W.J. Xue, L.B. Wang, D. Wang, C. Druta, Pavement health monitoring system based on an embedded sensing network, J. Mater. Civ. Eng. 26 (10) (2014) 1–8, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000976.
[32] K. Farghaly, F.H. Abanda, C. Vidalakis, G. Wood, Taxonomy for BIM and asset management semantic interoperability, J. Manag. Eng. 34 (4) (2018) 1–13, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000610.
[33] Y.M. Goh, S. Chua, Knowledge, attitude and practices for design for safety: a study on civil & structural engineers, Accid. Anal. Prev. 93 (2016) 260–266, https://doi.org/10.1016/j.aap.2015.09.023.
[34] J.W. Seo, H.H. Choi, Risk-based safety impact assessment methodology for underground construction projects in Korea, J. Constr. Eng. Manag. 134 (1) (2008) 72–81, https://doi.org/10.1061/(ASCE)0733-9364(2008)134:1(72).
[35] V. Benjaoran, S. Bhokha, An integrated safety management with construction management using 4D CAD model, Saf. Sci. 48 (3) (2010) 395–403, https://doi.org/10.1016/j.ssci.2009.09.009.
[36] M. Addis, Tacit and explicit knowledge in construction management, Constr. Manag. Econ. 34 (7) (2016) 439–445, https://doi.org/10.1080/01446193.2016.1180416.
[37] J.M. Li, N.P. Li, K. Afsari, J.Q. Peng, Z.B. Wu, H.J. Cui, Integration of building information modeling and web service application programming interface for assessing building surroundings in early design stages, Build. Environ. 153 (2019) 91–100, https://doi.org/10.1016/j.buildenv.2019.02.024.
[38] M. Arashpoura, Y. Bai, V. Kamat, M.R. Hosseini, I. Martek, Project production flows in off-site prefabrication: BIM-enabled railway infrastructure, Proceedings of the International Symposium on Automation and Robotics in Construction. 35 (2018) 1–8, https://doi.org/10.22260/ISARC2018/0011.
[39] Y. Rezgui, T. Beach, O. Rana, A governance approach for BIM management across lifecycle and supply chains using mixed-modes of information delivery, J. Civ. Eng. Manag. 19 (2) (2013) 239–258, https://doi.org/10.3846/13923730.2012.760480.
[40] L. Liao, E.A.L. Teo, Critical success factors for enhancing the building information modelling implementation in building projects in Singapore, J. Civ. Eng. Manag. 23 (8) (2017) 1029–1044, https://doi.org/10.3846/13923730.2017.1374300.
[41] E.K. Simpeh, R. Ndihokubwayo, P.E.D. Love, W.D. Thwala, A rework probability model: a quantitative assessment of rework occurrence in construction projects, The International Journal of Construction Management. 15 (2) (2015) 109–116, https://doi.org/10.1080/15623599.2015.1033814.
[42] J. Whyte, N. Bouchlaghem, A. Thorpe, R. Mccaffer, From CAD to virtual reality: modelling approaches, data exchange and interactive 3D building design tools, Autom. Constr. 10 (1) (2001) 43–55, https://doi.org/10.1016/S0926-5805(99)00012-6.
[43] Z.L. Ma, Z.H. Wei, X.D. Zhang, Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model, Autom. Constr. 30 (2013) 126–135, https://doi.org/10.1016/j.autcon.2012.11.020.
[44] H. Li, H.L. Guo, M. Skitmore, T. Huang, K.Y.N. Chan, G. Chan, Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong, Constr. Manag. Econ. 29 (3) (2011) 233–245, https://doi.org/10.1080/01446193.2010.545994.
[45] C.J. Han, T. Ma, G.J. Xu, S.Y. Chen, R.Y. Huang, Intelligent decision model of road maintenance based on improved weight random forest algorithm, International Journal of Pavement Engineering. 23 (4) (2020) 985–997, https://doi.org/10.1080/10298436.2020.1784418.
[46] Q.W. Xu, G.K. Chang, V.L. Gallivan, Development of a systematic method for intelligent compaction data analysis and management, Constr. Build. Mater. 37 (2012) 470–480, https://doi.org/10.1016/j.conbuildmat.2012.08.001.
[47] J.M. Bland, D.G. Altman, Statistics notes: measurement error, The British Medical Journal. 312 (41) (1996) 1654, https://doi.org/10.1136/bmj.312.7047.1654.
[48] S.A. Kumar, R. Aldouri, S. Nazarian, J. Si, Accelerated assessment of quality of compacted geomaterials with intelligent compaction technology, Constr. Build. Mater. 113 (2016) 824–834, https://doi.org/10.1016/j.conbuildmat.2016.03.117.