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Exploring an Interdisciplinary BIM-Based Joint Capstone Course in Highway Engineering

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Abstract:

Enhancing students' interdisciplinary design ability in a highway engineering context is important for the development of building information modeling (BIM). This paper proposes a new paradigm for highway engineering and its service areas based on the BIM platform, integrating road, bridge, tunnel, engineering costing; architecture; structure; water supply and drainage; heating and ventilation; and electrical engineering for a senior year capstone course. An overall and breakdown work system is constructed of the joint design process guided by the highway engineering discipline. BIM technology is utilized to integrate the design work content of nine majors, linking the originally separated design stages, and articulating the flow of interoperability information in highway engineering. A case study tests the course, evaluates the students' performance, and identifies improvements in software training, time schedule, technology connection, interoperability issues, as well as how BIM affects teamwork. In applying BIM in an interdisciplinary situation, a visualization tool is used to enrich the body of knowledge of BIM education as it relates to highway engineering.

Author keywords:

Building information modeling (BIM) education; Highway engineering; Interdisciplinary design; Building information modeling (BIM)-based joint capstone course; Student performance.

Introduction

Highway engineering includes roads, bridges, and tunnels, as well as service structures (Fu et al. 2012), and constitutes a significant portion of the global economy, as well as the Chinese economy (Hall et al. 2016). The implementation of building information modeling (BIM) in the highway engineering industry has surged over the last five years, and is expected to continue into the future (Jones et al. 2017). BIM, as an interdisciplinary communication and collaboration platform (Alreshidi et al. 2017), is designed to deal with cumbersome approval processes, high volumes of data, and the potential impediments of interdisciplinary communication during the highway design stage (Volk et al. 2014). Despite burgeoning industry demand, there are limited resources for personnel training of staff who teach and facilitate BIM-based interdisciplinary highway engineering for undergraduate students, in order for them to acquire the necessary BIM software, BIM team collaboration, and joint design skills. Therefore, colleges and universities need to respond appropriately to ensure they develop well-rounded civil engineering talent.

Recent studies, including the authors', have articulated how to teach BIM as an integral part of civil engineering and management studies (e.g., Abbas et al. 2016; Hsieh et al. 2017; Sacks and Barak 2010; Zhang et al. 2016, 2017) by applying a team-based learning approach (Jin et al. 2018; Zhang et al. 2018), and by transferring traditional computer-aided design to three-dimensional (3D) models (Kim 2012). Several pilot studies have focused on a range of relevant areas, including enhancing the incorporation of BIM concepts as part of interdisciplinary teamwork that architectural engineering students engage in Parfitt et al. (2013); introducing guidelines for the integration of BIM topics into construction engineering and management curricula (Pikas et al. 2013); applying integrated BIM in the education of structural engineering and building technology students (Hjelseth 2015); and proposing a process framework for the planning of BIM project execution to enhance student competencies in BIM-focused education (Zhang et al. 2019).

However, most of these initiatives have been applied in the general building industry rather than in highway engineering. Previous studies that have addressed the use of BIM in infrastructure projects have generally focused on the development and coordination of functional uses (Chong et al. 2016), ranging from a BIM-deliverable submission system to a comparison between traditional and BIM methods in highway infrastructure, and using BIM and big data to deliver well-maintained highways (Aziz et al. 2017; Omoregie and Turnbull 2016). Even when highway engineering-related research has applied BIM, the focus has mainly been theoretical, rather than practical, with the enhancement of students' interdisciplinary design abilities in a highway engineering context still in a state of underdevelopment.

In response, this paper's aim is to: (1) propose a BIM-based joint design pattern to combine road engineering, bridge engineering, and tunnel engineering management, as well as architecture, structure, etc.; (2) apply BIM to an interdisciplinary capstone course as a visualization and design checking tool; (3) evaluate a combination of classroom instruction with team practice; and (4) report on the establishment of an information interoperability system in a linear structure design. In providing a novel paradigm of a joint design mode for BIM applications and describing the process and operation of interdisciplinary design, the study enriches the body of knowledge related to BIM-based highway engineering education, with the potential to be widely utilized in educating highway engineering-related professional personnel.

Literature Review

BIM Education in Highway Engineering

There have been several studies of BIM technology in highway engineering. Shaaban and Nadeem (2015), for example, have explored the implementation characteristics of BIM in highway and infrastructure projects, while Shi et al. (2016) have studied how the application of BIM technology has played a role in the construction of the Yongchuan Yangtze Bridge in China. In addition, Bongiorno et al. (2019) have used the highway optimization procedures in a BIM environment to exploit the alignment optimization algorithms and to simplify the highway alignment design problem. Of the benefits involved, Aziz et al. (2017) have, for instance, identified the role BIM can play in bridging inefficiencies resulting from loss of information during the handover phases to promote efficient information management throughout an asset's lifecycle, with Fu et al.'s (2012) combined BIM and GIS highway construction management platform shown to render construction more efficient and effective. However, since research to date has mainly focused on BIM application to roads and bridges (Costin et al. 2018), it is less clear how to train BIM personnel in highway engineering.

Schools have a mission to provide training workshops to prepare students for professional activity, and they therefore need to include knowledge of implementing BIM (Sampaio 2019).

Universities could introduce BIM into undergraduate civil engineering curricula, where both theoretical and practical aspects are taught, which could help provide personnel with BIM skills (Sacks and Barak 2010). In support of this idea, Sacks and Pikas (2013) have compiled a framework for construction engineering and management degree programs that provides educators with essential knowledge as they develop and implement BIM content in their programs. Experiments at the Technion-Israel Institute of Technology have further shown that BIM should be introduced not only as a topic in its own right, but also as a tool for performing engineering tasks taught within design, analysis, and management courses (Pikas et al. 2013). An investigation by Zou et al. (2019) has revealed that students' perceptions and expectations of BIM implementation or industry practice can be affected by their field of study, prior industry experience, and gender, which has provided insights for BIM educators in terms of optimizing BIM education resources for both industry practice and academic research.

A range of teaching methods has been proposed. For example, Kim (2012) has designed a BIM visualization-based teaching approach with two-dimensional (2D) drawings using traditional computer-aided design (CAD) programs, which was ultimately developed into a 3D BIM model at California State University; Killong and Mahabaleshwarkar (2011) have proposed a virtual world on the Second Life platform to address communication issues and effectively complement traditional teaching approaches while integrating BIM to enhance construction engineering education; Zhang et al. (2018) have adopted a team-based learning (TBL) pedagogy into a civil engineering and management capstone project to enhance students' BIM competency, and they have evaluated how TBL could help students develop essential BIM knowledge, skills, and abilities through a project lifecycle, including design, tendering and bidding, construction, closeout, and handover; and Jin et al. (2018) have presented a project-based pedagogy in interdisciplinary building design by adopting BIM. Currently, the leading program in the field of industrial and civil construction is Autodesk Revit, and Zolotova et al. (2015) have provided an example of students' design work and the importance of a good overview of Autodesk Revit as part of professional training.

Interdisciplinary BIM-Based Design

Currently, the demand for mega public construction projects and technological change, in a highly interconnected world with complex problems that require multidisciplinary solutions, calls for interdisciplinary endeavors (Becerik-Gerber and Kensek 2010). In response, BIM is offered by some as the panacea to address the interdisciplinary inefficiencies in remote construction projects (Arayici et al. 2012). Wenchi et al. (2014) have applied BIM and lean concepts to practical maintenance in order to improve interdisciplinary efficiency, while Grilo et al. (2013) have proposed a business interoperability quotient measurement model that used an interdisciplinary approach to capture the key elements responsible for collaborative performance and BIM platform configuration. However, the interdisciplinary use of 3D object models is affected by many potential interdependencies, relations, and interfaces embedded in highly complex and partly unpredictable realworld practices. It is therefore difficult and time-consuming to adequately balance these relationships across multiple levels, processes, and activities (Moum 2010).

Researchers are therefore studying how to improve students' interdisciplinary skills. To date, the challenges facing civil engineering students in interdisciplinary work have been identified as including limitations in available curriculum time, a perceived lack of certain background knowledge, and differences in student skill sets between disciplines (Boulanger et al. 2015). In response, Heinendirk and Cadez (2013), for instance, have proposed courses involving project work with a focus on self-dependent learning, supported by tutors, for the interdisciplinary education of engineers. In this context, Brokbals and Cadez (2017) have indicated a need for higher education institutions to increase their BIM modules with interdisciplinary BIM-projects. Furthermore, a workshop by Gnaur et al. (2015) has indicated that students can develop professional skills by solving complex real life problems in problembased, interdisciplinary environments based on the principles of BIM. Jin et al. (2018) have identified pedagogical practices in their study of BIM-based interdisciplinary building design work, involving teams of architecture, civil engineering, and architectural environmental engineering with students at the University of Nottingham Ningbo in China. Meanwhile, Kovacic et al. (2015) have found the feedback received from students of Vienna University of Technology's interdisciplinary BIM design course to be beneficial for creating guidelines for further BIM teaching activities. To summarize, limited education-based research has been carried out into interdisciplinary highway engineering capstone design courses, in particular as it relates to the application of BIM in undergraduate education. As engineers in mega infrastructure design projects are required to work across-disciplines, especially when applying BIM to projects, this study addresses this gap by proposing a new interdisciplinary capstone design course based on the application of BIM technology, guided by highway engineering, and grounded in the basic professional knowledge of road, bridge, tunnel, cost, architecture, structural, and electromechanical engineering. In this way, this paper fulfils an identified need to explore the implementation of an integrated interdisciplinary capstone course that applies highway engineering-based BIM.

Methodology

Research Framework

This research was carried out in a number of stages, which are discussed in turn in this paper. First, the literature relating to BIM education in highway engineering and interdisciplinary design of

BIM projects has been reviewed and the knowledge gaps have been determined. Next, a discussion is offered of a BIM-based joint course that was designed to guide students and instructors in the teaching, training, and practice of highway engineering and its service areas. Then, a case study of the application of the BIM-based joint course at Chongqing Jiaotong University is described, which investigated the performance and challenges to the students and instructors involved. The final section discusses the problems encountered in course implementation, which can be used to help BIM educators improve the course in the future, and which also makes clear how BIM affects teamwork. Fig. 1 provides the overall research framework.

Performance Evaluation

Both quantitative and qualitative approaches were used to evaluate the performance of the course and students after the graduation report. The quantitative approach included a summative evaluation by the students themselves. Identifying the strengths and weaknesses of self-evaluated guided student-learning activities helped them check on the effects of their learning (Lind et al. 2002). Three indicators were used as part of the evaluation to measure the students' performance:

1. Software operation skills: proficiency and accuracy of operating the software
2. Joint design skills: familiarity with other professional design processes
3. Teamwork skills: ability to work and communicate with others

Each indicator was measured by three detailed questions, as summarized in Table 1, and designed as a questionnaire with a Likert scale for students after they finished their graduation report.

In addition to the questionnaire, a semi structured interview about the training capstone was conducted with the students and instructors after the graduation report. The interview questions were as follows:

1. What did you think of the course's arrangements?
2. What did you think of the design requirements?
3. What did you think of the interdisciplinary schedule?
4. What problems have you encountered in the design process?
5. What have you learnt from the joint design?

Fifteen students and three instructors participated in the individual interviews voluntarily, and each interview lasted approximately one hour.

Course Design

Overview

This interdisciplinary design-based BIM course combined road engineering, bridge engineering, tunnel engineering, architecture, structure, water supply and drainage, heating and ventilation, electrical engineering, together with engineering costing. The main content consisted of a schematic design, construction drawing design, and building information model design of a highway and its service area. Each student was responsible for completing the corresponding design. This was divided into two major tasks: a route design, including the design of a road, bridge, and tunnel; and a service area design, including a service area and a commercial experience area. Students in related majors were required to complete the architecture, structure, water supply and drainage, heating and ventilation, and electrical design.

Design Requirements

In engineering design, the likelihood of a successful and efficient completion of the design task is enhanced by a clear expression of a well-formulated design requirement (Darlington and Culley 2002). The BIM-based design requirements comprised two parts: design task content and BIM model depth, with students being required to submit both design content and models at the end of the design process. Table 2 shows the design task content and model depth requirements for the nine majors. The instructors measured the amount, difficulty, and complexity of the overall task based on three aspects:

1. The body of knowledge of undergraduate education in each major
2. The duration of the design
3. The corresponding relationship between the students' ability and the theoretical knowledge structure of the nine majors

Capstone Arrangements

Students were required to complete various tasks using software, and identifying the software needed was therefore important to instructors as it determined the file forms needed. The software requirements are listed in Table 3, combined with the design requirement and model depth in Table 2.

The instructors, who guided the design, prepared as follows: (1) determined the implementation of the BIM model; (2) established the objective environment for BIM implementation, such as team organization, software, and classroom; and (3) established the teaching and training resource library, including course content, instructors, and storage devices for saving and sharing data. Students from all nine majors undertook the training. The course content and schedule are shown in Table 4.

Work System and Work Breakdown Structure

The design teams consisted of instructors and students; the instructors clarified the tasks of the design and decomposed the tasks into stages, while the students in different majors performed the tasks together. The work system is shown in Fig. 2.

Based on the relationship between the work breakdown structure and the design task, the design was divided into three stages in chronological order. The preparation stage involved the teaching and training in BIM software skills and joint design theory, as discussed in section "Capstone Arrangements." The second stage consisted of three phases: schematic design, construction drawing design, and BIM. As part of the schematic design, the road engineering major took responsibility for route selection, route development, and determining the control point, while the architecture major selected the location of the service area and carried out the site analysis. The students finished the design task content in the construction phase (Table 2). The bridge and tunnel-engineering majors coordinated the respective bridge and tunnel line with the road engineering major, considering their own design code. After the form evolution and functional analysis had been carried out by the architecture major, the structure students determined the structural form, structure selection, and layout. The electro-mechanical students (water supply and drainage, heating and ventilation, and electrical) developed their own professional designs. Based on the construction drawing design, the BIM models were built to ascertain where the 3D rendition revealed clashes in the designs. Then the models automatically counted the amount of work involved to obtain a bill of quantities. The third stage was the graduation report, in which the students made a team presentation and the instructors scored their performance and the quality of their designs.

Information Interoperability Workflow

Because of the large amount of data and various formats generated in the design process, its effective integration and sharing needed the support of the BIM information integration platform.

Interoperability is defined as the capability to communicate, execute programs, or transfer data between various functional units (Baldoni et al. 2006), and the information thus needed to be entered into the design information technology network only once, and was then available to all students instantaneously. The information interoperability workflow aimed to shape the sharing and integration of resources throughout the joint design process. Fig. 3 illustrates this process.

In the early stage, before the road design, the instructors provided the original topographical maps and then the students established a 3D atlas, which played an important role in their site selection. Grounded in the atlas, the land use was analyzed as part of planning the design elements, and formed the design information integration database as part of a required data exchange specification. Students from all majors utilized the database to create a detailed design. Subsequently, the information was passed to the 3D model to generate the quantity and price information.

Results

Background and Project Implementation

The case study was a course called “Typical Unit Design of Expressway Based on BIM Application” at Chongqing Jiaotong University, China. The design process began on January 2, 2018, and ended June 14, 2018. It was led by the university’s Civil Engineering College in cooperation with the Architecture College, Hehai College, Mechatronics College, and Economics and Management College. Fig. 4 shows the organizational chart.

In total, 52 students from the 9 majors were divided into 4 teams, with each team consisting of final year undergraduate students, the number in each major determined based on workload. One road engineering student, two bridge engineering students, two tunnel engineering students, two architecture students, two structural engineering students, one water supply and drainage student, one heating and ventilation student, one electrical engineering student, and one engineering cost student worked together to deliver the schematic design, construction drawing design, and building information model design of the highway and its service area. The student leader of each team was a volunteer. Nine teachers of the corresponding majors served as project instructors, each guiding the students of the associated major. During the training phase, consultants from a software company provided training to students. With the general theme of “the expressway and its service area,” each of the four teams was provided with one project, namely the Chongqing Yurong Expressway Wailong Service Area, Chongqing Changyi Expressway Wushan Service Area, Chongqing Jiuyong Expressway Dingjia Service Area, and Guizhou Renzun Expressway Jindingshan Service Area.

The design process comprised four stages: preparation, training, implementation, and graduation report. The specific timing of each stage in the course is shown in Table 5.

Sample of Student Work

Because the design process and content were similar for each group, Team 1 was chosen as a sample to show the students’ design results. Team 1’s project—the Chongqing Yurong Expressway Weilong service area—had a total route length of 10,943.190 m, which included one long tunnel and five short tunnels. The main buildings of the project included a comprehensive service area, business experience area, hotel accommodation area, and ancillary structures, the total area was 19,746.6 m^2. First, unified BIM software training was conducted, which included a

Revit building model, a Revit structure model, a Revit electromechanical model, a Revit bridge model, a Revit tunnel model, a Civil 3D precise route selection and route design, and a vertical section design. After the training, the students organized themselves to carry out a field survey as part of the project, to study highway and service area-related case visits and research, and to develop research reports. Fig. 5 shows Team 1's design exhibit.

Student and Instructor Feedback

The questionnaire was distributed to all 52 student participants and 42 were collected, a recovery rate of 80.77%. The questionnaire used a Likert scale ranging from 1 (very little) to 5 (very much). The weighted averages of the software operation skills, joint design skills, and teamwork skills were 3.53, 3.61, and 3.38, respectively, out of 5. Each score was a comprehensive self-evaluation of the three phenomena, and the distribution of the evaluation was approximately normal. The statistics show that the students had a positive perception and attitude at the end of the teaching, training, and practice period. Table 6 summarizes the results.

During the interviews, the students described their perceptions of their skill acquisitions in a range of ways. For example, one student who had engaged in the engineering cost activity mentioned: "Over the past five months, we (the team members) have almost mastered the process of a BIM design project, which is helpful for innovation work. I constantly needed to ask for data from other majors and everyone cooperated very well." A bridge student was similarly positive and noted that "regular BIM group meetings helped me understand the design content of other majors. The harmonious atmosphere of discussion improved our efficiency." One of the architecture students specifically discussed the benefits of interdisciplinarity: "I didn't know about the other majors' design work before and only knew my own field. I'm glad that now my knowledge has broadened, and that I know what data other majors need. Therefore, the joint design skill has indeed improved my knowledge." Finally, one of the road engineering students appeared to value the learning experience and the opportunity to improve into the future: "The more 3D civil software we operate, the more skilled we are in using shortcuts. However, we sometimes encountered a flaw in the BIM model, but had no time or energy at the end to improve it. From this experience, we will make sure to avoid such mistakes in our future work."

The instructors provided a different perspective, and thus provided an additional data stream as part of the evaluation. Instructor A, for example, provided an insight into the grading of the students' work: "We graded the students' models according to: (1) model completion; (2) model depth requirements; (3) modelling rules and information requirements; (4) model colour requirements; and (5) the consistency of the CAD drawings, models and text description. Overall, they (the students) had mastered software operation skills although there were some flaws in their models. For example, 'a sloping floor was not connected to the wall' or 'the gradient of the floor was inconsistent with the construction drawings.' They even explored many software-operating skills outside the classroom." By contrast, Instructor B provided a slightly broader perspective: "Observing the students' design process and testing their design results, we found that the course was effective. Students were interested in the BIM concept in the beginning, and now they have mastered basic modelling skills and can cooperate with interdisciplinary majors."

It is important to recognize that these results were perceptions of skills acquired, and while they strongly suggested a positive impact, they cannot be claimed as actual skills acquired without hard data to support that. The interviewed students and instructors further provided insights into the problems they encountered during the course and their designs, and what suggestions they would like to provide, and these are discussed further in the next section.

Discussion

Software Training

The content of the course was not separated for each major, but was unified for all majors. The unification of the teaching content involved the basic operation of the Revit and Civil 3D softwares in the design process. According to the interviews with 15 classmates and 3 instructors, the advantages included: (1) offering a chance of open communication and enhanced team spirit in the nine majors because they had a class together; (2) the unified curriculum enabled them to understand the design content of the eight other majors, which benefitted the design process; and (3) the teaching models of the later design practice increased the students' understanding of the BIM system, while they gradually understood the design mode and process. However, some disadvantages were noted: (1) the theoretical part of the lecture was very basic for each major, so the content was felt to lack sufficient depth; and (2) because of time constraints, there was no software training for engineering costing, and provision for this is therefore needed in the future.

The suggestion is that it may be necessary to set up unified multidisciplinary joint training and as well as creating one or two exclusive and targeted professional training opportunities for different majors.

Irrational Schedule

The architecture major needed to put forward the design plan as soon as possible in order to carry out the follow-up work, so when the road engineering students carried out their preliminary route selection, the architecture students also started to carry out the service area location selection. The service area had to be set within a certain range along the highway, with the same designed elevation. However, with the entry of the bridge engineering and tunnel engineering majors, the road route selection had to be continuously adjusted, and the line and elevation control point changed. Further minor adjustments also had to be made after the final precise alignment, resulting in the location of the service area not meeting requirements, so the elevation of the vertical section of the original scheme could not be connected. Therefore, the elevation and control points of the service area needed to be replanned, with large design changes as a consequence.

Fig. 6 first shows the drawbacks of the schedule, and then the workload after adjusting the optimized schedule.

As shown, the lead/lag of a design with multiple disciplines had a significant impact. If the preliminary design of the road was carried out ahead of time, the bridge and tunnel engineering input needed to be moved forward for the architecture major to start the design, in order to reduce rework, optimize the design process, and enable the structure major to start as soon as possible.

Technology Connection Problems

The work system in Fig. 2 indicates the task connections between the nine majors as well as the detail and some connection problems that occurred in the case study. The practice of work paths reflected some defects in terms of major connections. Pior activities also failed to consider workload and difficulty of the activities that followed. This included failing to consider the capacities of the other majors. For example, the architecture students proposed a curved roof for the commercial experience area during the schematic design stage, but the structure students were unable to carry out a force analysis and therefore the scheme had to be changed to a straight roof. In another example, road selection through the mountain needed a long-bending tunnel but the tunnel engineering majors were unable to handle such complexity.

Another issue consisted of a failure to consider indirect effects. For example, the distance between the service area and the tunnel entrance did not conform to the design specifications because this was overlooked by the road engineering students.

To reduce rework and improve design performance, the instructors needed to be reminded of these technical issues in advance. Most importantly, students needed to have strengthened their communications and compared schemes to ensure that the design conformed to the specifications, and the design requirements were satisfied by each major.

Interoperability Issues

The interoperability of information, as shown in Fig. 3, made the design data, once inputted, usable by other professions at the same time, reducing the need to reinput the data. For example, once the control points were marked in Civil 3D by the road engineering students, the students majoring in bridge, tunnel, and architecture could use the marked atlas at the same time to obtain the required information and reduce the reinput of information. It was easy for students to access information in a timely manner since they had social media to communicate and share documents. However, it was still a challenge for them to understand and utilize the data from other majors. The major interoperability challenges are recorded in Table 7.

Because the design software was developed by the same company, the file formats were interoperable. In addition, because the model depths were required as a visualization model in Table 1, the final visualization was not affected even if the property information was lost after merging the Revit and Civil 3D models. These challenges were almost all related to experience or management. As four students mentioned: “These (the interoperability challenges) are actually experience problems, once we have experienced them, we can effectively avoid making mistakes again.” Therefore, when designing together in the laboratory, it is necessary to increase interdisciplinary learning, while more experience in software operation needs to be accumulated in practice. Future educators should provide a management list recording the interoperability points to help students avoid problems.

How BIM Affects Teamwork

BIM’s effect on teamwork varied for different majors. For road engineering, the requirements and workload increased compared with traditional 2D design, and some complained about the BIM design. This result is similar to Jin et al. (2018), in that BIM design added an extra requirement for architects so they became somewhat resistant to BIM. For engineering cost students, some extra work was needed to help with scheme comparisons, but the traditional computational effort was reduced. These advantages of BIM need to be built upon, based on the premise that team members understand the design content.

In general, compared with traditional graduation design, BIMbased teamwork design was better in terms of its integration, efficiency, and visualization. In traditional design, each of the student majors work separately (Czmoch and Pekala 2014) and the learner and learning context are detached (Becerik-Gerber et al. 2012). By contrast, in joint design, BIM provided an interdisciplinary collaboration platform, which linked the originally separated design stages of the different majors. Meanwhile, teamwork made it possible for the students to gain a broader knowledge of other majors. Furthermore, the software presented a 3D atlas of the initial topographic at the beginning of the joint design, which helped students understand real-world engineering practice more intuitively and profoundly. This is consistent with the findings of Kim (2012), in that BIMbased design can improve the students’ understanding of real-world projects.

Conclusion

This paper has provided a BIM-based mode of design that can be combined with students majoring in highway engineering and architecture. It has described the teaching curriculum, the overview and breakdown of the design work, design process, assignment of design tasks and the information interoperability system under this model. An evaluation system has been proposed to evaluate software operation skills, joint design skills, and teamwork skills. The case study evaluation results suggested that the training and practice helped students master the necessary skills involved as well as provided ideas for improvement for other engineering educators.

The research constructed a joint design working mode and evaluation system based on a real project. The associated teaching paradigm (1) constructed the overall and breakdown work system of the design process guided by the highway engineering major, (2) utilized BIM technology to integrate the design work content of nine majors and linked the originally separated design stages, and (3) articulated the flow of interoperability information during the design process in a highway engineering context. Overall, the case study helped enrich the body of knowledge of highway engineering BIM education.

The real-world highway and its service area design project identified possible problems when implementing the work system. It showed that the connection of time nodes between professional associations were particularly important. Thus, it is necessary to analyze and consider the association between different majors, arrange a design schedule according to an effective transmission of information, and rationally adjust the intervening time points of other majors. In order to reduce rework, the instructors need to remind students of the technology connection point. As for teaching and training, the curriculum arrangements should be designed based on arranging unified training for all majors, with some tailor-made specific courses for individual majors.

The design of each major should not be isolated, but should instead be combined with other majors to meet the students' work capability needs in the future. Based on this paper, future research can also enrich students' BIM ability by deepening the application of the BIM technology, thus further improving the accuracy requirements of the BIM model, and using the model to simulate BIM applications in real-world construction contexts.

Data Availability Statement

The data generated or analyzed during the study are available from the corresponding author upon request.

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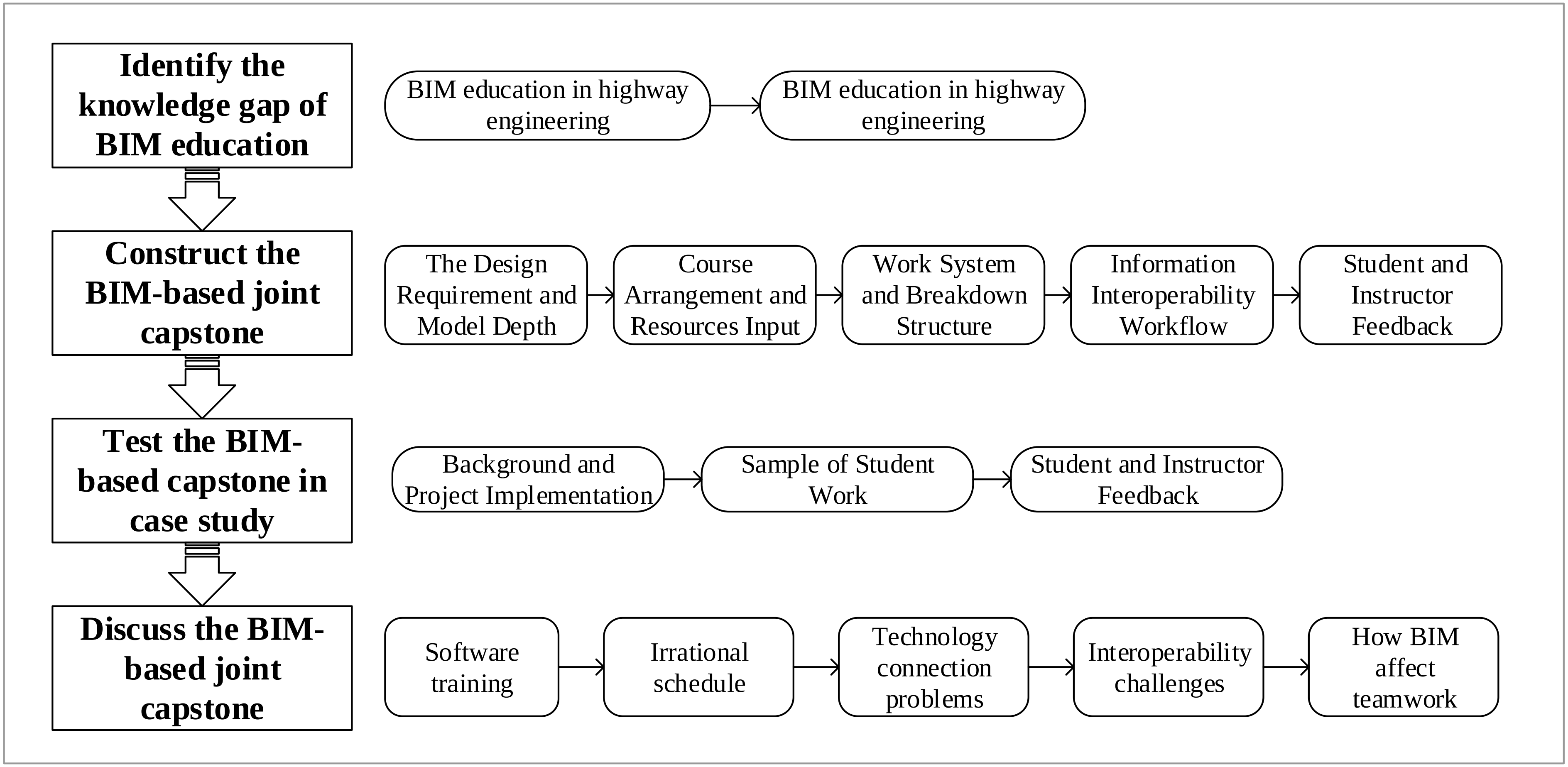

Fig. 1. Research framework

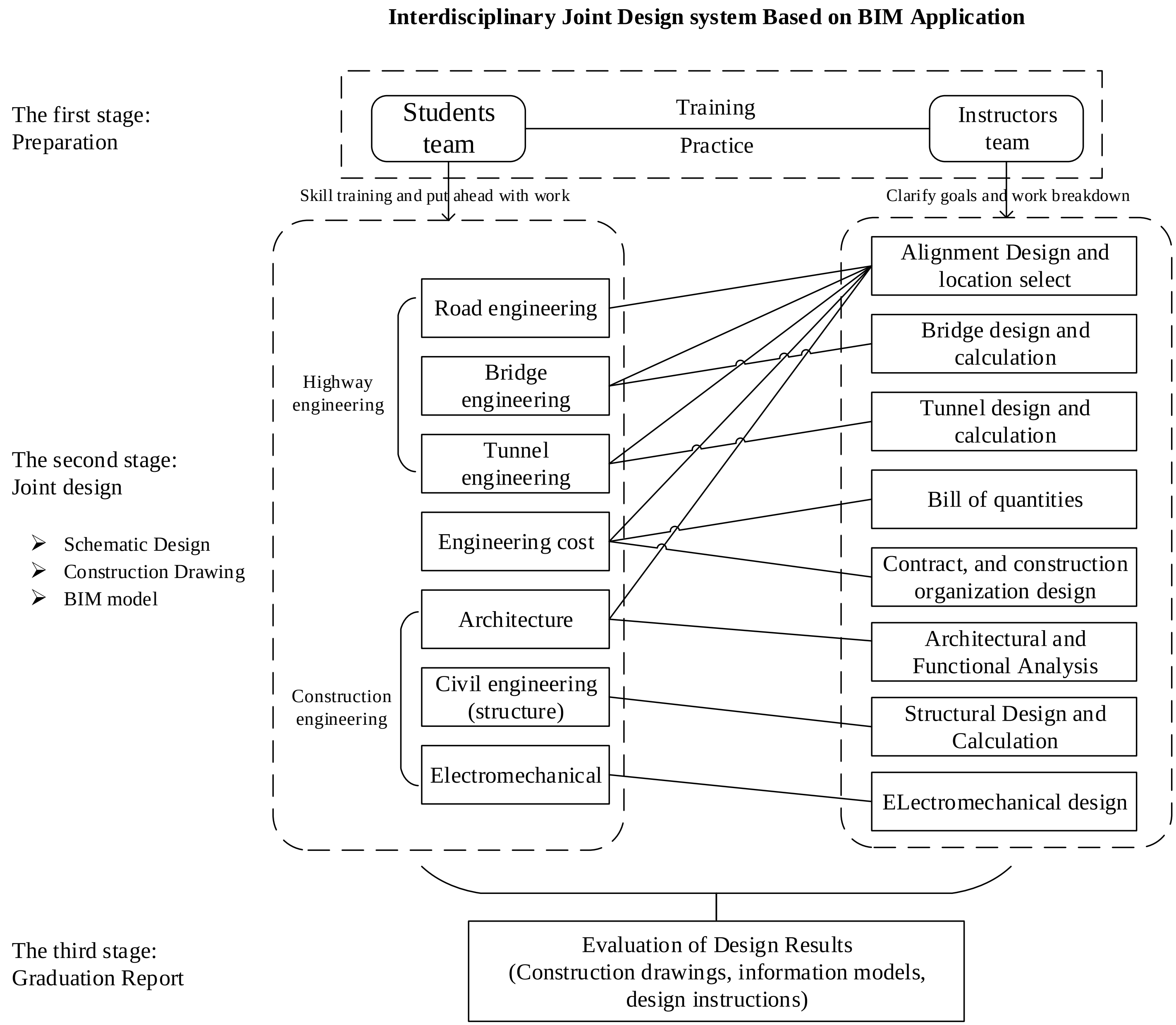

Fig. 2. Work system of the design

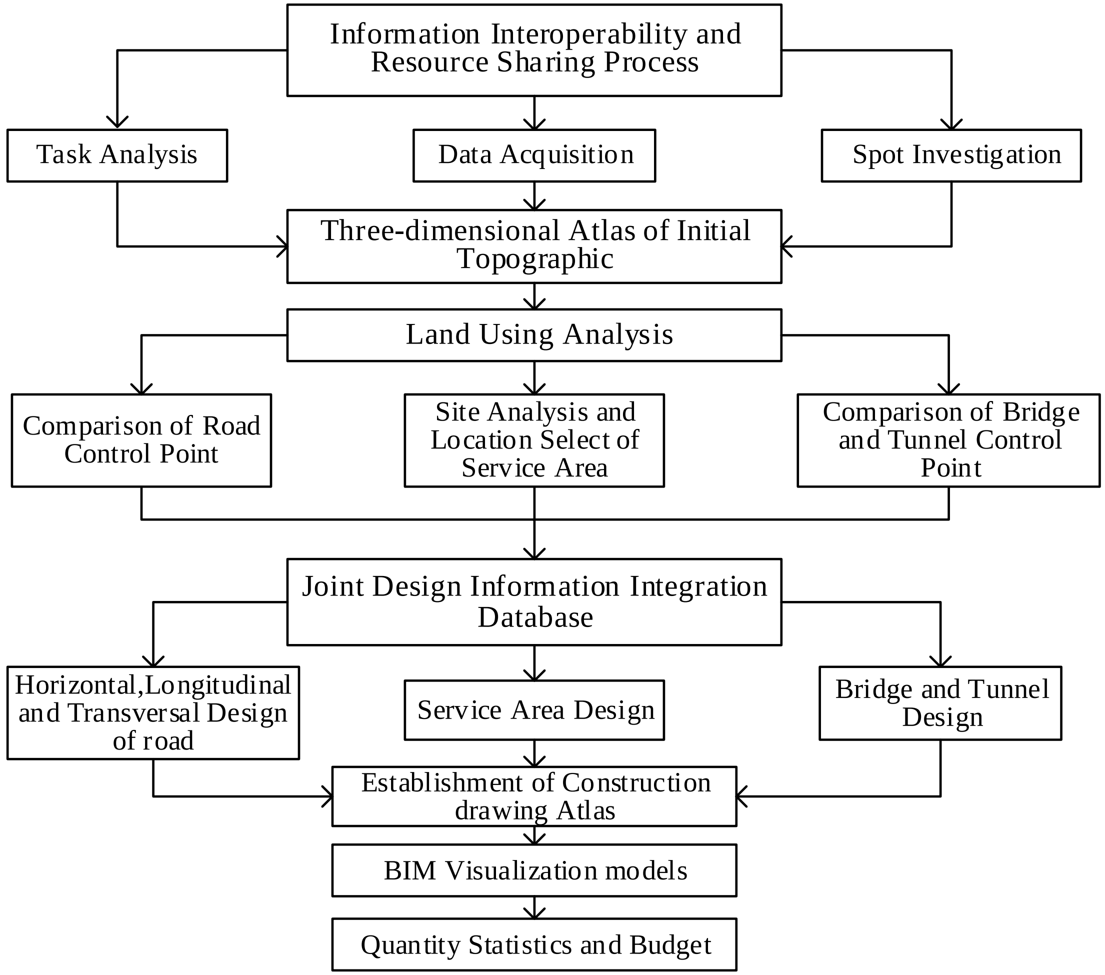

Fig. 3. Information interoperability and resource sharing process

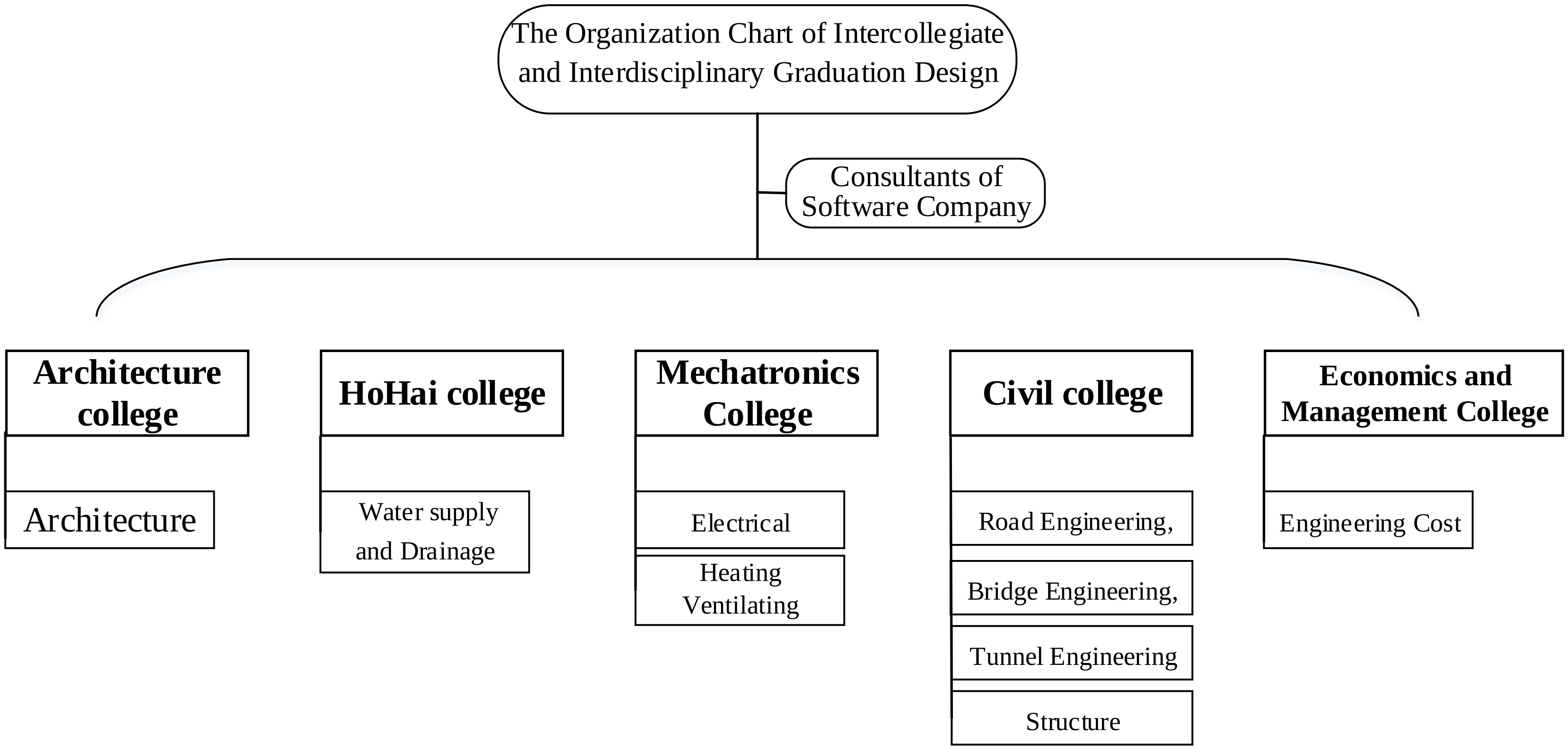

Fig. 4. Organization chart of the intercollegiate and interdisciplinary design

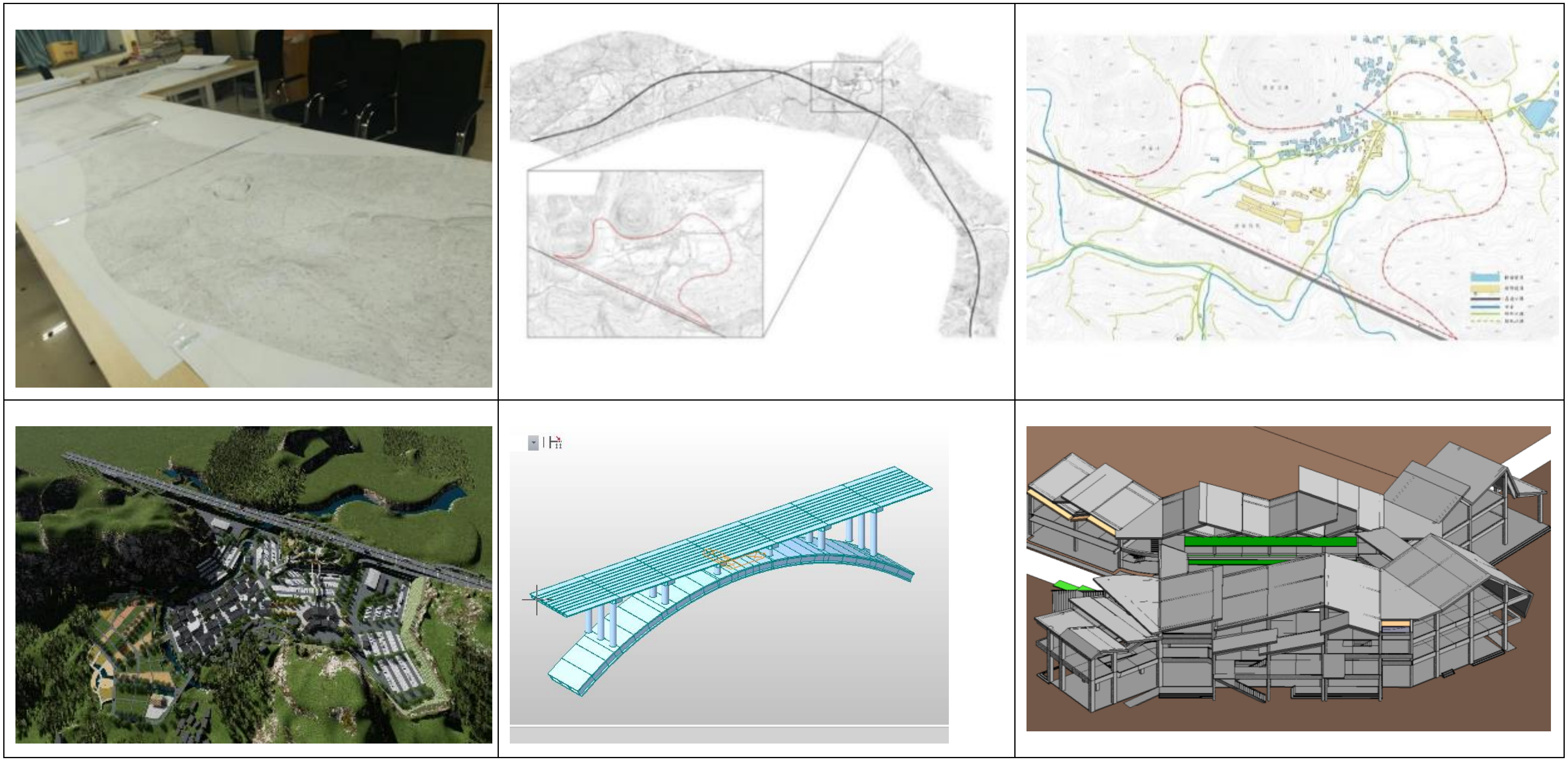

Fig. 5. Design exhibit of Team 1 (Images courtesy of Student Team 1, with permission from Chuandang Zhao, Weicheng Huang, Xin Zhou, Linhu Li, Keqiang Li and Xiyang Guo)

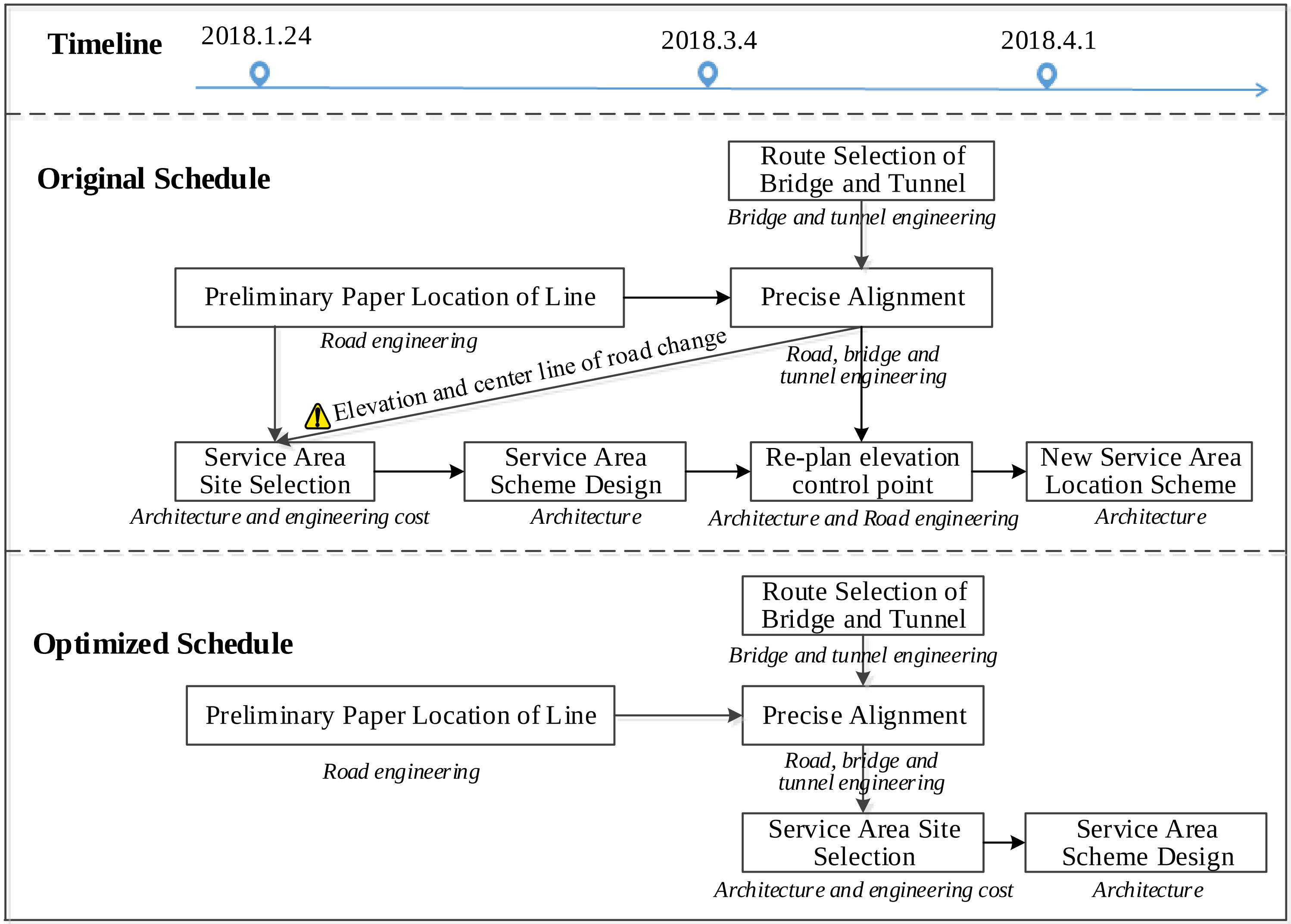

Fig. 6. Original and optimized schedule

Table 1. Indicators and Question Description

Indicator	Question description
Software operation skill	S1: Overall mastery of modeling software
	S2: Used shortcuts to increase efficiency
	S3: Self-perception of the model quality and reliability
Joint design skill	J1: Understood the design content of other majors
	J2: Mastered the time node of each professional intervention
	J3: Ability to make effective recommendations to other professions
Teamwork skill	T1: Good performance in the BIM group meeting
	T2: Timely communication with other professionals when encountering questions
	T3: Establishment of good teamwork and a collaborative relationship with others

Table 2. Design tasks guidance and model depth requirements for the nine majors

Major	Design task content	Model depth
Road engineering	Plan view, vertical profile map, intersection angle table; subgrade cross-sectional profile, subgrade design table, subgrade earthwork volumes table, central reserve map, super-elevation; pavement structure layer, curve widening table, pavement quantity table; traffic safety device, side slope protection, retaining wall; culvert design drawing; channelization, cross walk, separate facilities, guard rail, lighting facilities of road, road planting	Civil3D Road Visualization Model
Bridge engineering	Three preliminary design plans for different bridge-type; scheme comparison and selection, arrangement drawings, engineering drawing of the bridge, drawing of main parts of superstructure and substructure in detail	Revit Bridge Visualization Model
Tunnel engineering	Tunnel cross section report, design the inner outline of tunnel, scheme comparison and selection of tunnel portal, tunnel lining, waterproof and drainage drawing, auxiliary design, ventilation, lighting and emergency equipment	Revit Tunnel Visualization Model
Engineering cost	Conceptual (pre-budget) estimate report; provide reference for design optimization, bill of quantities and detailed estimate report	Export engineering quantity
Architecture	Schematic design text, design instruction, overall area master plan, overview of the whole area drawing	Revit architecture model
Civil engineering (structure)	Type of structure, determination of the most suitable; proportions, dimensions and details of the structural elements and connections for constructing each alternative structural arrangement, structural elevations and specifications	Revit structure model
Water supply and drainage	Water supply and drainage plan of each floor, drawing of building water supply and drainage system, pipeline profile; drawing of water treatment structures, pumping station process chart, large drawings of toilets, water tanks and other necessary large drawings	Revit electromechanical model
Heating and ventilation	Air and water system plan and profile of air conditioning, air system and water system plan and profile of air conditioning room and cold and heat source room, principle diagram of air conditioning system, drawing of ventilation system and smoke control and exhaust system, principle diagram of automatic control for air conditioning system, main equipment table	
Electrical	Transformer room low voltage distribution system diagram, distribution trunk system diagram, lighting distribution floor plan, lightning protection and ground plan	

Table 3. Software requirements list

Major	Software
Road engineering	AutoCAD®, Autodesk Civil 3D®, HintCAD ®
Bridge engineering	AutoCAD®, MIDAS Civil 2017®
Tunnel engineering	AutoCAD®, MIDAS Civil 2017®, ANSYS®
Engineering cost	Smartcost®, Glodon®
Architecture	Tarch (Architecture)®, SkechUp®, Photoshop®, Lumion®, InDesign®, Autodesk Revit 2017®
Civil engineering (structure)	Tarch (Structure)®, PKPM®, Autodesk Revit 2017®
Water supply and drainage	Tarch (Water)®, AutoCAD®, Autodesk Revit 2017®
Heating and ventilation	Tarch (HVAC)®, AutoCAD®, Autodesk Revit 2017®
Electrical	Tarch (Electrical)®, AutoCAD®, Autodesk Revit 2017®

Table 4. Course content and schedule

Class	Content	Hours(h)
Autodesk Revit	Revit installation, user interface, view control and property, elevation of the axis network, basic wall, laminated wall, column drawing, door drawing, window drawing	6
	Revit floor drawing, curtain wall drawing, standard layer copying, roof drawing, step drawing, and ramp drawing	12
	Revit staircase drawing, railing handrail drawing, site drawing, foundation drawing, beam drawing, structural column drawing, structural plate drawing.	18
	Revit link model, create sanitary ware device, layout water supply and drainage pipeline, add pipefittings, fire protection systems, collision detection.	18
	Revit mass modeling, family classification, family template, family category, and family parameters.	18
	Revit simply supported beam bridge modeling.	6
	Revit arch bridge modeling.	6
	Revit tunnel modeling	6
Autodesk Civil 3D®	Civil 3D functional principle; measuring data generating three-dimensional terrain model	6
	Civil 3D site leveling, regional excavation and landfill (slope).	6
	Civil3D precise line selection, route design, and profile design.	12
	Civil3D standard cross-section assembly, road model, and road surface, cross-section plotting quantity statistics, label style customization.	12
	Civil 3D component editor, custom parametric cross section (principle, example)	12

Table 5. Timeline and stage goal of the design process

Phase	Phase goal	Timeline
Preparation	Taking the lead, Civil Engineering College students were organized to sign up for the design team.	2018.1.2~2018.1.5
Training	Unified software training for students participating in the joint design process	2018.1.3~20.18.1.23
Implementation	Students majoring in road engineering began to select routes, and cost majors assisted in optimizing technical and economic indicators.	2018.2.1~2018.3.16
	After route selection, the architecture students began to plan the location of the service area, and started the schematic design.	2018.3.4~2018.4.10
	The bridge and tunnel design followed closely by the beginning of the route and service area design work. Meanwhile, after the preliminary design of the service area was completed, the mechanical and electrical designs began.	2018.3.10~2018.5.25
	With the completion of the construction drawings, the modeling of various majors and engineering costing began.	2018.5.25~2018.6.7
Graduation report	Integrating the design results of the various majors and producing the exhibition materials.	2018.6.7~2018.6.14

Table 6: Questionnaire result of students' self-evaluation

Indicator	Question	1	2	3	4	5
Software operation skills	S1	0.00%	14.29%	33.33%	42.86%	9.52%
	S2	4.76%	2.38%	11.90%	52.38%	28.57%
	S3	7.14%	14.29%	42.86%	28.57%	7.14%
Average		3.97%	10.32%	29.37%	41.27%	15.08%
Joint design skills	J1	2.38%	42.86%	16.67%	19.05%	19.05%
	J2	2.38%	2.38%	7.14%	59.52%	28.57%
	J3	4.76%	11.90%	16.67%	47.62%	19.05%
Average		3.17%	19.05%	13.49%	42.06%	22.22%
Teamwork skills	T1	0.00%	4.76%	23.81%	47.62%	23.81%
	T2	0.00%	38.10%	19.05%	30.95%	11.90%
	T3	2.38%	42.86%	21.43%	11.90%	21.43%
Average		0.79%	28.57%	21.43%	30.16%	19.05%

Table 7. The interoperability challenges

Document format	Operation	Issue
Alta. dwg	Road engineering students mark the road control points in *Alta.dwg*, and then the Architecture, Bridge, and Tunnel students continue with their own design.	Because of the long and tedious process of route selection, the participation of other professions is not high. Finally, the other majors did not understand the design plan, and their amendments were not put forward until later.
Bridge. rvt; Tunnel. rvt	Bridge and tunnel students create models by lofting and fusion in Revit®.	The coordinate files need to be imported into Revit® in Excel® form, but there was no coordinate data in Excel® format, so that students need rework the data to record it in Civil 3D®.
Service area. rvt Bridge. rvt Tunnel. rvt Road.dwg	MThe models are merge into a whole in Revit®.	The students did not unify the coordinate system in each model, which led to problems and rework.