Automation in Construction 86 (2018) 199–209

Contents lists available at ScienceDirect

Automation in Construction

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

A dedicated collaboration platform for Integrated Project Delivery

Zhiliang Ma[a,*], Dongdong Zhang[a], Jiulin Li[b]

[a] Tsinghua University, Beijing, China
[b] Beijing Urban Construction Group Co., Ltd, China

ARTICLE INFO

Keywords:
Integrated Project Delivery (IPD)
Collaboration platform
Building Information Modeling (BIM)

ABSTRACT

To improve efficiency and reduce waste in Architecture, Engineering and Construction (AEC) projects, Integrated Project Delivery (IPD) has been proposed and used in some projects, revealing great advantages. However, IPD depends heavily on "big room" collaboration, which requires the constant presence of nearly all participants and is particularly difficult for small or medium projects. To overcome this problem, this research aims to develop a dedicated collaboration platform for IPD to achieve more efficient collaboration and replace the highly resource-consuming "big room". Based on requirement analysis and design of the system architecture, a prototype system is developed and tested in a virtual IPD project. When combined with a few meetings, this collaboration platform can replace the "big room". This will significantly reduce the difficulty associated with implementing IPD projects and thus promote the adoption of IPD.

1. Introduction

The outputs of Architecture, Engineering and Construction (AEC) projects are unique products, and AEC projects require close collaboration among project participants [1]. However, collaboration in traditional project delivery methods commonly adopted in AEC projects, such as Design-Bid-Build (DBB), Design-Build (DB) and construction manager at risk (CM-at-Risk) [2], is prevented by goal inconsistency and implementation fragmentation among project participants. With respect to goal inconsistency, the owners' goals are to achieve better quality, lower project costs and shorter project duration, whereas the constructors' and designers' goals are to receive greater construction fees and design fees, respectively. Thus, each participant fights for his/her own goals instead of for maximizing the value of the entire project. With respect to implementation fragmentation, participants generally conduct their work separately and simply deliver their work results to each other; thus, they cannot easily absorb knowledge and experience from the other participants. These two aspects both contribute to the inefficiency and waste of AEC projects.

Deficiencies caused by goal inconsistency and implementation fragmentation have become increasingly severe in recent years as buildings have become more complex and the AEC industry has become more specialized. A new project delivery method called Integrated Project Delivery (IPD) has been proposed to overcome these deficiencies and thus improve control over the cost, schedule and quality of projects compared to traditional delivery methods [3]. IPD is characterized by the early involvement of all participants, close collaboration among them, and the combination of each participant's unique contribution to the development and decision process, always with the aim of optimizing the entire project as opposed to seeking the self-interest of their respective organizations. According to the results of a survey on IPD projects, the most commonly observed benefits of IPD include fewer change orders, increased cost savings, shorter schedules and fewer requests for information (RFIs) [4]. Encouraged by these advantages, an increasing number of owners are attaching importance to IPD.

A project delivery method has three general aspects: the organization, which refers to how the participants in a project are organized to establish a project team; the commercial terms, which refer to the contractual responsibilities and associated compensation; and the operation system, which refers to how the project is performed and managed on an overall and day-to-day basis [5]. For an IPD project, the first two aspects are typically specified clearly in IPD contracts, which are signed before the project begins. Some standard IPD contracts have been published for adoption [6–9]. The core of the third aspect is collaborative work among participants. Because of frequent communication, complex processes, management and sharing of mass information and the large number of involved participants, collaborative work is difficult to perform and manage.

Thus far, collaborative work in IPD projects (hereafter referred to as IPD collaboration for brevity) has been conducted based on infrastructures such as the "big room" or collaboration platforms. Our previous review of the literature around the world indicated that 45.5% of IPD projects used a "big room," 59.1% used a collaboration platform,

* Corresponding author.
E-mail address: mazl@tsinghua.edu.cn (Z. Ma).

https://doi.org/10.1016/j.autcon.2017.10.024
Received 19 February 2017; Received in revised form 15 October 2017; Accepted 28 October 2017
Available online 21 November 2017
0926-5805/

27.3% used both of these infrastructure types, and only 22.7% used neither a 'big room' nor a collaboration platform [10]. A "big room" represents a large room facilitating the colocation of the entire project team, where participants work collaboratively. Because this infrastructure requires the near-constant presence of the project participants, it is applicable for large projects where the budget of the project for individual participants can justify full-time allocation of all participants, but it is difficult to implement for medium or small projects, where participants are typically working simultaneously on several projects in geographically disparate locations [11]. For some investigated cases in which a "big room" was not used, regular meetings were held instead, but the effect was rather limited, and considerable time and money must have been wasted on travel to attend meetings.

Due to the limitations of their functions, existing collaboration platforms have largely acted as shared information repositories and are not sufficiently powerful to replace the "big room" or the regular meetings used in previous IPD projects, which hinders the promotion of IPD, particularly for medium or small projects. With the development and maturation of information communication technology (ICT), there is an increasing trend of moving activities from offline to online, as has occurred in the fields of communication, shopping, and education. ICT is also expected to be beneficial for moving IPD collaboration from offline to online. Although current ICT technology cannot yet completely replace face-to-face communication in IPD projects [11], it is still possible and justified to develop more powerful collaboration platforms to reduce the dependence on face-to-face communication, i.e., replace the "big room" with regular meetings and further reduce the frequency of such meetings, which will lower the threshold for implementing IPD.

Collaboration platforms are used to improve the efficiency of collaboration, which can be further divided into synchronous and asynchronous collaboration, and management and sharing of information, which can further be divided into structured and unstructured information [12]. In the following, previous research on collaboration platforms will be reviewed in terms of these four aspects.

For synchronous collaboration, many technologies are already sufficiently mature to be applied, such as video meetings and instant messages. Some new technologies, such as 3D [13], virtual and mixed reality [14,15], have been used in synchronous collaborations.

For asynchronous collaboration, Chen et al. developed an online collaborative modeling platform to support team members from multiple disciplines in the collaborative creation of Building Information Modeling (BIM) models with fewer design iterations for conflict resolution. To achieve this objective, a multi-specialty BIM model to be developed is divided into BIM sub-models according to different parts of the building. Then, using the platform, these BIM sub-models are developed in parallel and separately from each other. Each part of the BIM sub-model corresponding to a different specialty, such as architecture, structure, and HVAC, is developed successively on the platform by the specialized teams following a linear workflow, such that each part is built based on a previous part [16,17]. Choo developed a collaboration platform that integrates the Analytical Design Planning Technique (ADePT) to automate the creation of the work plan and minimize design iterations and the Last Planner System (LPS) to guide the flow of the creation, execution and adjustment of the work plan to allow the work plan to be realized reliably [18].

Regarding the aspect of management and sharing of unstructured information, existing commercial platforms support the use of hierarchical folders along with authorities corresponding to the folders. Forcada et al. developed a web-based tool that can automatically generate an organizational document structure according to project information such as lifecycle phases, stakeholders, contractual arrangements, working areas, and document types. The structure can then be downloaded and applied in a collaboration platform with the aim of ensuring that all stakeholders work with the same well-structured folder and file structure [19]. Mao et al. proposed a method to connect elements in structured information, such as building components, construction process and project management information, to unstructured information to create its metadata and applied the method to the development of a collaboration platform on which project participants are able to quickly locate the relevant information needed to understand and process a construction document [20].

For management and sharing of structured information, Faraj et al. developed an Industry Foundation Classes (IFC)-based model server environment (WISPER) to facilitate BIM data exchange among project participants [21]. Rosenman et al. developed a virtual collaborative environment that integrates BIM models of different specialties by building mappings among the elements in the BIM models [22]. Plume et al. used a typical BIM-based collaboration platform in a project and identified the functional requirements that are necessary but not realized by current BIM-based collaboration platforms according to the problems encountered during the process [23]. By conducting Focus Group Interviews (FGIs) in a case study on an architectural project using a state-of-the-art BIM server and a critical review of current collaboration platforms, Vishal et al. established a theoretical framework of technical requirements for developing a BIM server to be used as a multi-disciplinary collaboration platform [24]. The platform BIMserver.org has been developed as an open-source BIM server that supports the storage, maintenance and query of industry foundation class (IFC)-based BIMs. The platform can be extended, and many applications have been developed, such as those for visualizations, clash detection and flexible queries and filters [25,26].

Although the abovementioned research studies have responded to the requirements of online collaborative work in traditional projects, few studies have focused on IPD projects. In a previous study, we analyzed IPD project cases, clarified functional requirements that are not implemented by existing collaboration platforms to serve IPD projects, and highlighted the necessity of developing a new collaboration platform dedicated for IPD projects [28].

The aim of this research is to clarify and implement the major functions in a collaboration platform dedicated for IPD projects to facilitate improving the efficiency of IPD collaboration and replacing or at least minimizing the "big room" or regular meetings. The remainder of this paper is organized as follows. In Section 2, a process model for IPD collaboration is established by investigating industry-accepted documents specifying the implementation of IPD projects, and the major functional requirements for the new collaboration platform are summarized. In Section 3, the architecture of the new collaboration platform is established based on the requirements. In Section 4, the technology and tools adopted in the development of a prototype system of the collaboration platform are briefly presented. In Section 5, the prototype system is tested in a virtual project, and feedback is collected from the project participants to validate its effectiveness.

2. Establishing the process model and major requirements

As noted above, our previous study clarified the functional requirements that are not implemented by existing collaboration platforms to serve IPD projects, such as supporting users in the creation of multidiscipline workflows and recording the proposals accepted by the IPD team [28]. Based on these unimplemented requirements, a more systematic analysis of requirements is conducted here to propose further functional requirements from the perspective of providing more powerful tools for IPD collaboration. The functional requirements summarized in the previous study and those presented in this paper will be used jointly as the basis for the development of the new collaboration platform.

2.1. Investigation of IPD collaboration

As the foundation of the requirement analysis, it is necessary to clarify how IPD collaboration is conducted. For this purpose, we collected and investigated industry-accepted documents, including those specifying the implementation of IPD projects [5,27,29,30] and typical standard IPD contracts [6–9]. The following describes our findings.

IPD collaboration mainly occurs in the design phase instead of the construction phase because the design results have been fully reviewed, optimized and understood by all participants before construction starts in IPD projects. Specifically, in the design phase, because of the early involvement of all participants, many works, such as construction planning and cost estimation, are brought forward to be performed along with the design, which makes IPD collaboration complex. In addition, frequent design optimizations are conducted to maximize the project value, which leads to a large number of design iterations and further complicates IPD collaboration.

For synchronous IPD collaboration, traditional communication methods, such as meetings, face-to-face discussions, and video conferences, continue to be used, and the frequency of the communication among the participants is higher than that in traditional projects. For asynchronous IPD collaboration, as described in the investigated documents, the use of lean methods, which are advanced technologies translated from the manufacturing industry, has been proposed due to their potential to improve the management of complex projects. The lean methods that are used in IPD projects mainly include the target value design (TVD) method, set-based design (SBD) method and LPS method. In our previous investigation of IPD project cases [10], 45.5% of the investigated projects used the TVD method, 45.5% used the SBD method, 50% used the LPS method, and 31.8% used all three methods. In addition, the participants of IPD projects that use lean methods have indicated that these lean methods contribute greatly to improvements in the efficiency of IPD collaboration [31]. Hence, the application of lean methods in IPD collaboration will be introduced and analyzed briefly in the following to facilitate their utilization in the new collaboration platform.

When the TVD method is used in IPD projects, designers must continually send design results immediately upon completion to the other participants over time. Then, the receivers will analyze and evaluate the received design and propose modifications. The designers further modify and optimize the design based on the analysis and evaluation result and the modification proposals [32]. Because of the TVD method, more design iterations and versions and more modification proposals are proposed, evaluated and implemented in IPD projects than in traditional projects. In addition, modification of a deliverable in the design results according to accepted modification proposals may trigger more modifications of other deliverables that are created based on the initial deliverable, which can be referred to as "modification propagation".

When the SBD method is used in IPD projects, a set of design solutions is defined and developed concurrently. During the development, some solutions are disputed by evaluation and comparison to gradually narrow the set while increasing the level of detail of the remaining design solutions [33]. To evaluate and compare these solutions, the "choosing by advantages" (CBA) method is typically used to decide which design solutions are superior to the others. There are four key concepts in the CBA method: "alternative", which refers to two or more design solutions, from which one or more must be chosen; "factor", which refers to an element, part or component of a decision, such as cost, constructability, energy consumption; "attribute", which refers to a characteristic, quality, or consequence of one alternative design solution, which can be seen as the value of the factor; and "criterion", which refers to a decision rule. A 'must' criterion represents conditions that each alternative must satisfy, and a 'want' criterion represents the preferences of one or multiple decision makers [11]. Due to the use of the SBD method and CBA method in IPD projects, parallel design versions are generated, and the information corresponding to the four concepts in the CBA method must be collected to support the evaluation and comparison of design solutions.

When the LPS method is used in IPD projects, planners use the PULL method instead of the traditional PUSH method to create plans. That is, planners identify necessary tasks in the reverse manner from the predefined milestones. In addition, planners are concerned about not only what SHOULD be done but also what CAN be done. That is, in the design phase in IPD projects, the completion of prerequisite tasks, the modification proposals and the modification propagation should be considered in plan creation. During the execution of the plan, planners should regularly modify the plan according to the status of the plan execution. Further details about the LPS method can be found in [34]. Due to the use of the LPS method, a plan is no longer created purely subjectively by the planners. Instead, many objective factors must be considered, such as milestones, completion of prerequisite tasks, modification proposals and modification propagation, which makes the plan creation more complex. In addition, creation or modification of the plan is more frequent when the LPS method is used.

Information sharing in IPD projects has its own characteristics due to the adoption of lean methods. First, each participant submits partially rather than fully completed deliverables to other participants to support concurrent engineering. Second, different versions of a deliverable are delivered frequently due to frequent modification. Third, a large number of design iterations and the co-existence of parallel design solutions lead to complex versions. Finally, information is shared mainly among participants instead of within each organization. All these characteristics make information sharing in IPD projects prone to errors and complicate information retrieval and tracking.

2.2. Process model of IPD collaboration

According to the above description, the process of IPD collaboration is composed of a series of "design - evaluate/compare - modify" type of design iteration in the design phase. The corresponding model is established as shown in Fig. 1.

First of all, leaders of all the participants use the PULL method to create the work plan and define milestones in the work plan collaboratively. As a simplified example, a work plan for the preliminary design is created, including the following sequential tasks: create architectural design model (T1), create HVAC system design model (T2), create energy consumption calculation report (T3), create cost estimation report (T4) and create lifecycle cost estimation report (T5). In the work plan, accomplishment of the tasks T1, T2 and T3 is defined as a milestone, considering all the three tasks are compulsory ones.

Then, each participant executes his/her tasks defined in the work plan, i.e., design or conduct analysis and calculation based on the design results. All deliverables such as the architectural design model are thus obtained and they constitute a design solution. The key results of the deliverables obtained from analysis and calculation, for instance, the energy consumption calculation report, are regarded as CBA attributes.

When a predefined milestone in the work plan is reached, the participants are supposed to hold meetings to evaluate the corresponding design solutions based on the CBA attributes and then to submit proposals to optimize the design solution. Continuing the above example, when the tasks "T1", "T2" and "T3" are accomplished, i.e., the milestone is reached, a meeting is held and the participants are supposed to submit their proposals on the design solution directly after the meeting, because there is only one design solution. In case there are parallel design solutions, just as two design solutions generated in the following-mentioned design iterations, they are evaluated according to the corresponding CBA attributes by all the participants to choose some better design solutions for further development. Assuming that, based on the obtained CBA attribute, energy consumption, the HVAC subcontractor and the main contractor put forward the proposals "more energy-efficient air conditioner should be used" (P1) and "thermal insulation of glass curtain wall should be improved" (P2), respectively, to improve the design solution on energy consumption.

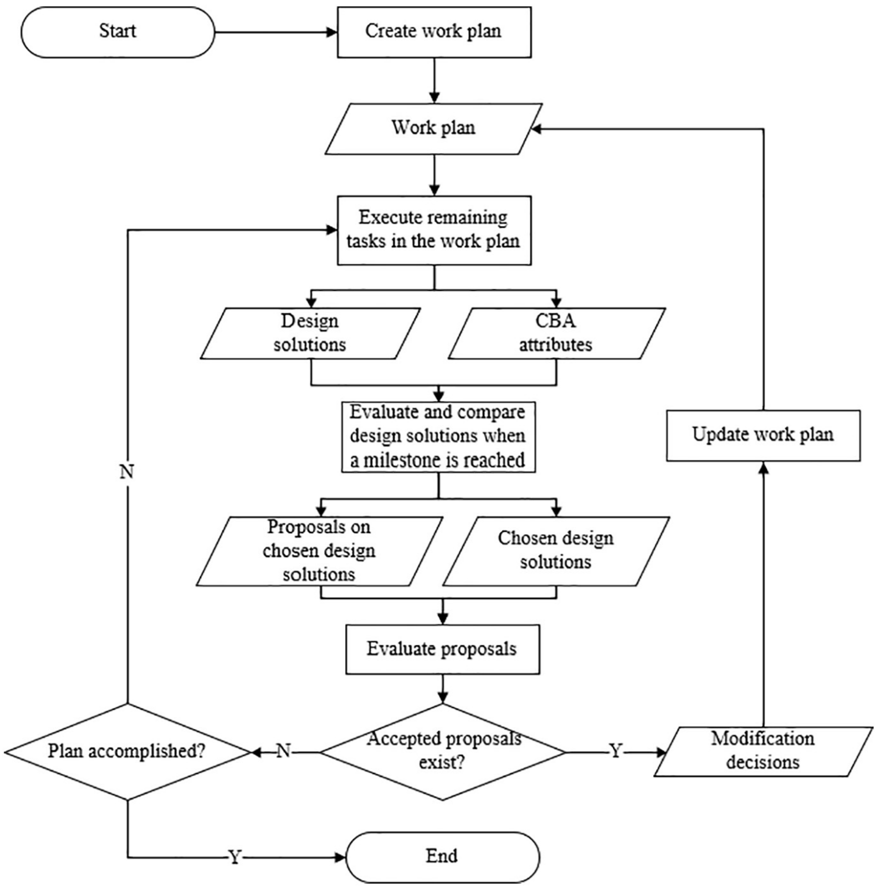


Fig. 1. Process model of IPD collaboration.

The proposals are then evaluated by all the participants to determine which to be accepted and to make the corresponding modification decisions for implementing the next design iteration. For example, assuming that two modification decisions are made corresponding to "only 'P1' is accepted" and "both 'P1' and 'P2' are accepted", respectively. The work plan is then updated to include tasks such as "modify HVAC model according to P1" corresponding to proposals in the modification decisions, and tasks that have not been executed in the previous work plan, such as "T4" and "T5". It deserves to note that two parallel design solutions are now included in the new work plan corresponding to the two modification decisions.

If there are no accepted proposals and the work plan is not accomplished, the remaining tasks in the work plan continue to be executed. For example, if none of "P1" and "P2" is accepted, the remaining tasks "T4" and "T5" continue to be executed. Otherwise, if the work plan is accomplished and there are no accepted proposals, the process ends.

2.3. Major functional requirements

According to the process model, the major functional requirements that specifically serve the IPD collaboration but are not realized by traditional collaboration platforms are identified as follows:

(1) Generate the work plan automatically

To ease the complex and frequent work plan creation/modification caused by the TVD method, LPS method and SBD method, the work plan creation/modification should be automated as much as possible in the new collaboration platform. In addition, according to Section 2.1, the automated plan generation should use the PULL planning method and consider the objective factors, including milestones, completion of prerequisite tasks, modification proposals and modification propagation. Moreover, the work plan should guarantee consistency among the deliverables of different versions that are the outputs of the tasks included in the work plan.

(2) Push information to users automatically

To ease frequent and error-prone information sharing, in the new collaboration platform, necessary information should be pushed automatically in time to users who need it. Users will be able to create, modify or review deliverables or evaluate and compare design solutions easily based on the pushed information.

(3) Show relationships among deliverables

To ease the retrieval and tracking of project information, in the new collaboration platform, relationships among deliverables of different versions should be visible to clarify the evolution process of the design and relationships among deliverables of the same version.

In addition to the above major functional requirements, the functions previously obtained, including those provided by traditional collaboration platforms, are still useful for IPD collaboration.

3. Designing the system architecture

The above-identified major functional requirements show the improvement direction of traditional collaboration platforms. To reuse mature functions provided by traditional platforms to ease the development of the new collaboration platform, it is better to reuse and customize existing collaboration platforms rather than to redevelop a completely new one for research purposes.

The architecture of the new collaboration platform to be developed

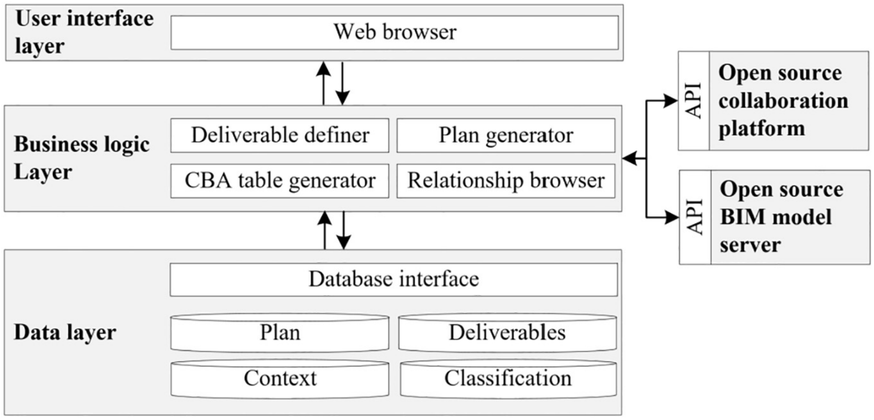


Fig. 2. Architecture of the new collaboration platform.

is designed as shown in Fig. 2. It is developed based on two existing open-source systems: an open-source BIM server, i.e. the BIMserver.org platform [25], and an open-source collaboration platform, i.e. the BEX5 platform [37]. The former provides functions for managing a BIM database, BIM parsing, checking, query and visualization, and corresponding application program interfaces (APIs) that can be invoked by other systems. The latter provides common functions supporting collaboration, such as file check-in/check-out/downloading/uploading, workflow creation/execution, and user management, and the corresponding APIs.

The architecture of the new collaboration platform is a three-tier structure in which the data layer is used to store and manage collaboration data that do not exist in the above open-source systems; the business logic layer is composed of modules that implement the above major functional requirements; and the user interface layer is a web browser. Additional details regarding the data layer and business logic layer will be introduced below.

3.1. Data layer

An information model must be established to specify the structure of the data layer. By extracting elements from the process model as shown in Fig. 1 and clarifying the relationships among the elements, the information model of IPD collaboration is established and represented using the Unified Modeling Language (UML), as shown in Fig. 3. The information model is composed of four parts, i.e., plan, context, deliverable and classification.

In the plan part, the work plan includes sequenced tasks. These tasks are classified into three types, i.e., the tasks to create deliverables, the tasks to modify deliverables that have been created, and the tasks to review deliverables. The output and input of the former two types of tasks are deliverables. The inputs of the last type of tasks are deliverables, and the outputs are proposals.

In the context part, there are two types of proposals, i.e., accepted proposals and rejected proposals. The accepted proposals comprise modification decisions that will be implemented by the work plan of the next design iteration. The CBA factors are related to the calculation or analysis of deliverables whose results are the values of the CBA factors, i.e., the CBA attributes. Based on the design solutions and corresponding design factors, the CBA tables can be generated, which can be used to choose the qualified design solutions by comparing different ones.

In the deliverables part, deliverables that are consistent with each other are included in a design solution. There exist "depend_on" relationships among deliverables. For example, the "structural design model" depends on the "architectural design model." A deliverable may include one or more files that are structured or unstructured (structured or unstructured files hereafter for short). For example, a deliverable "architectural design model" includes the structured files "first floor architectural design model.ifc" and "standard floor architectural design model.ifc".

In the classification part, classes corresponding to elements and work results according to different classification systems are included. Some deliverables, including structured files, may include these classes. For example, as shown in Fig. 4, the deliverable "architectural design model" includes the element classes, such as "exterior walls" and "exterior windows". When a deliverable depends on another that includes classes, the depend_on relationship can be refined to the class level. For example, as shown in Fig. 4, the deliverable "energy consumption calculation report" depends on the element classes, such as "exterior

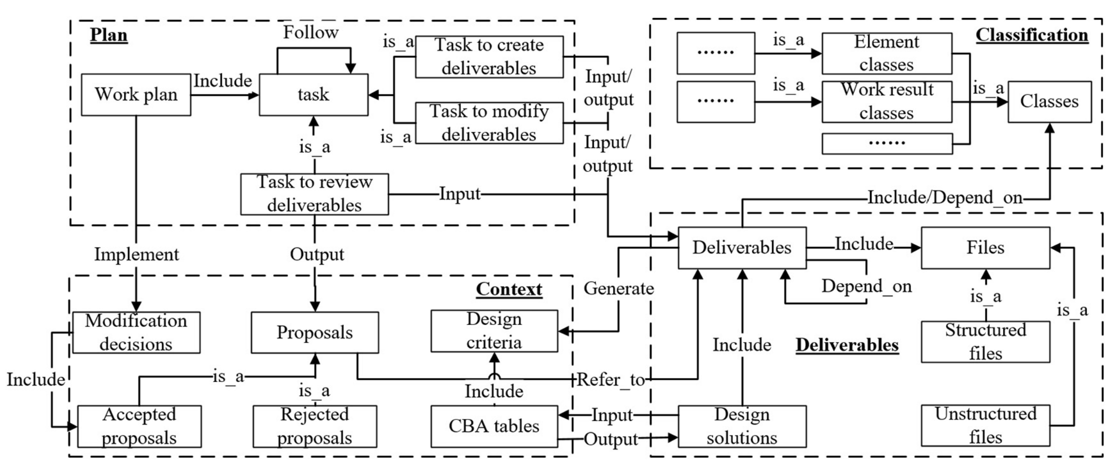


Fig. 3. Information model of IPD collaboration.

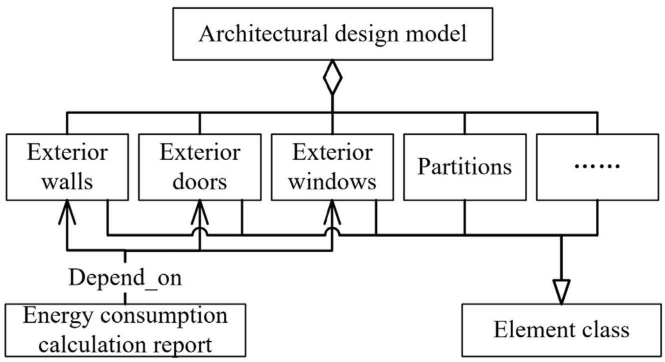


Fig. 4. Example of the classes included in structured files and refinement of depend_on relationships.

walls" and "exterior windows," included in the deliverable "architectural design model."

Beyond the database, whose data structure is specified according to the established information model, a database interface is provided for modules in the business logic layer to access the data in the database.

3.2. Business logic layer

Three major functional requirements have been noted in Section 2.2: "generate work plan automatically", "push information to users automatically" and "show relationships among deliverables". Correspondingly, three modules in the business logic layer are designed: "plan generator", "CBA table generator" and "relationship browser". The module "plan generator" can be used to satisfy the functional requirement "generate work plan automatically". For the requirement "push information to users automatically", the workflow engine provided by the existing open-source collaboration platform can be used to execute the work plan to push information to users who create, modify or review deliverables. Then, the module "CBA table generator" can be used to collect and push information to users who evaluate and compare design solutions using the CBA method. In addition, the module "deliverable definer" can be used to edit the deliverable part of the information model to satisfy special conditions of some IPD projects. The four modules will be introduced in more detail below.

3.2.1. Deliverable definer

In the information model shown in Fig. 2, subclasses of the class "Deliverables" can be defined to represent specific deliverables, such as "architectural design models" and "energy consumption calculation reports", and the "depend_on" relationships among the subclasses are defined as, for example, "energy consumption calculation reports depend on architectural design models". The subclasses and the relationships among them are largely the same in different IPD projects and can be predefined in the new collaboration platform. On this basis, to satisfy the special requirements of some IPD projects, users can use the module "deliverable definer" to create, modify or delete the subclasses representing specific deliverables and the relationships among them.

For deliverables that include structured files, this module can be used to define the classification classes included in the deliverables and refine the "depend_on" relationships to the class level, as shown in Fig. 3. For the calculation or analysis of deliverables, such as "cost estimation for HVAC system", the design factors, such as "cost of HVAC system (RMB)", corresponding to their result should be defined.

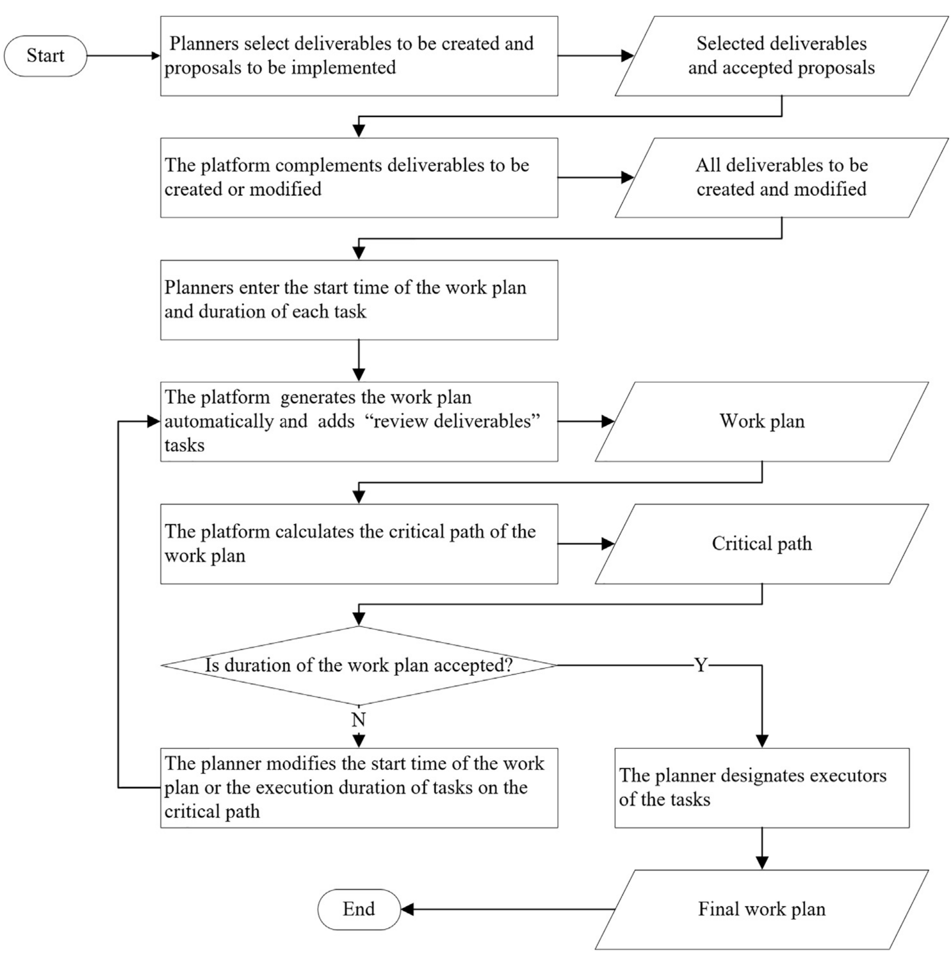


Fig. 5. Process of generating a work plan.

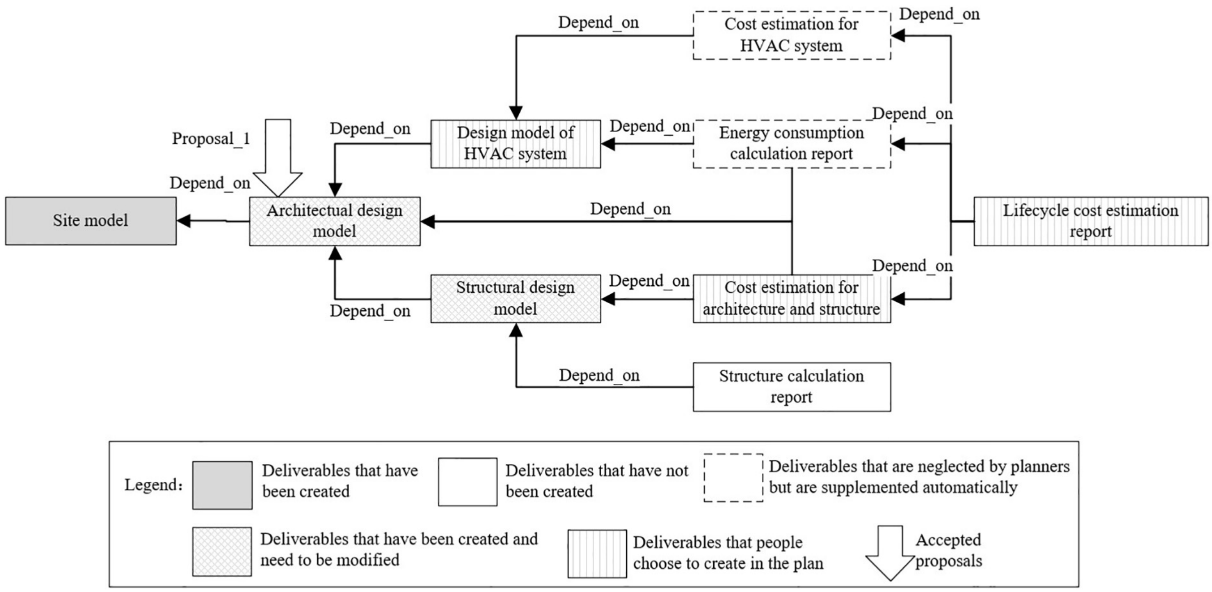


Fig. 6. Example of identifying all deliverables to be created or modified.

In addition, this module is used to designate participants who are authorized to create, modify or review specific deliverables to ease the allocation of tasks when creating a work plan.

3.2.2. Plan generator

As described in the process model in Fig. 1, at the completion of the previous design iteration, proposals raised by participants are filtered, and some are accepted for implementation in the next design iteration. Based on the "depend_on" relationships among the deliverables and the accepted proposals, the work plan of the next design iteration is generated automatically with the help of the "plan generator" module. The process of generating a work plan is shown in Fig. 5.

The planner selects deliverables to be created, as shown in Fig. 6, including "lifecycle cost estimation report", "design model of HVAC system" and "cost estimation for architecture and structure", and confirms the implementation of the accepted proposals, e.g., "proposal_1" associated with the "architectural design model."

The collaboration platform will run the graph search algorithm [35] to supplement deliverables to be created or modified. As shown in Fig. 6, deliverables that the previously selected deliverables depend on, such as "cost estimation for HVAC system" and "energy consumption calculation report", will be supplemented. Then, the deliverables that have been uploaded but are influenced by the modification propagation triggered by the accepted proposal, such as "structural design model", will be supplemented. Next, the planner can enter the start time of the work plan and the duration of each task.

Based on the deliverables to be created or modified, "depend_on" relationships among the deliverables, the start time of the work plan and the duration of each task, the collaboration platform will use the Design Structure Matrix (DSM) algorithm [36] to generate the work plan. The collaboration platform will automatically add a "review deliverables" task after each "create/modify deliverables" task and assign a default execution duration to the task "review deliverables".

The critical path of the initial work plan will be computed. The planner can modify the start time of the work plan or the execution duration of tasks on the critical path to ensure that the work plan ends on time. The planner designates executors of the tasks to finish the final work plan.

After the work plan is generated, it is transformed and imported into the workflow database in the existing open-source collaboration platform and executed by the workflow engine. When a user executes a task, the collaboration platform will push deliverables that are uploaded in the pre-tasks to the user, and the user can download files included in the deliverables. When executing "create/modify deliverables" tasks, users can upload files and enter the modification description corresponding to the accepted proposals. If design factors are defined associated with the output deliverables, the users will need to enter the values of the design factors, i.e., design attributes, according to the result of the output deliverables. When executing the task "review deliverables," users should enter proposals based on the pushed deliverables.

3.2.3. CBA table generator

After a design iteration is completed, the collaboration platform will automatically extract the design solutions and the corresponding design factors, attributes and criteria involved in the design iteration. Then, a CBA table, as shown in Table 1, is generated and acts as the basis for users to compare design solutions.

3.2.4. Relationship browser

To facilitate the tracking of project information, in the new collaboration platform, relationships among deliverables of different versions should be shown to clarify the evolution process of the design, as shown in Fig. 6. Modification decisions that are composed of accepted proposals describe the modification content among design solutions. The CBA tables used for evaluation and comparison follow parallel design solutions. Users can obtain more details by clicking elements in the mapping, such as deliverables, proposals and CBA tables.

In addition, relationships within each version of the design solution are shown to help users obtain a set of consistent information, as shown in Fig. 7. Relationships can be expanded and retracted. Users can

Table 1
Example of a generated CBA table.

Factors [criteria]	Design solution V3	Design solution V4
HVAC cost (RMB) [the lower the better]	10,000,000	13,000,000
Architecture and structure cost (RMB) [the less the better]	30,000,000	30,000,000
Energy assumption cost (RMB/year) [no more than 21,000, the less the better]	20,000	10,000
Lifecycle cost (RMB) [the less the better]	50,000,000	46,000,000

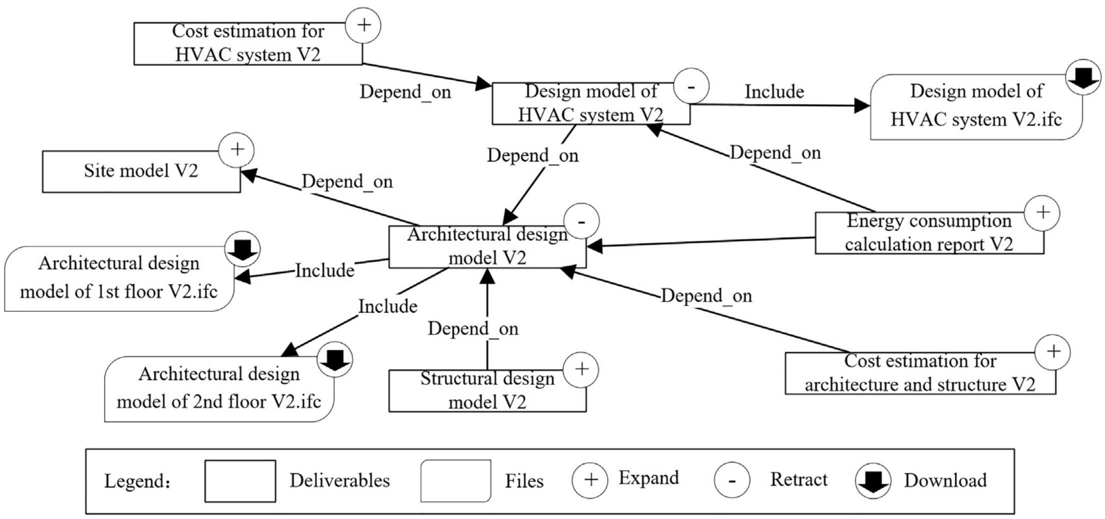


Fig. 7. Example of relationships in a design solution.

extract the relationships to obtain related deliverables and inclusive files that can be downloaded.

4. Developing the prototype system

A prototype system of the new collaboration platform is developed based on the design introduced in Section 3. Some tools and technologies are adopted to realize the components in the system architecture as shown in Fig. 2. For the data layer, a MySQL database is used to store the data according to the information model. For the business logic layer, the Java language is used to realize the function modules as described in Section 3.2. The function modules read/write data in the MySQL database via database interface and invoke functions in the open-source collaboration platform and the open-source BIM server via their application interface. The freeware Apache Tomcat is used to establish the application server and the function modules are packed in the server to provide web service. For the client layer, HTML5, CSS and JavaScript are used to develop the user interface in the web browser to invoke the web service. The open-source collaboration platform, i.e., the BEX5 platform [37], provides basic collaboration functions and stores files and project management data. The open-source BIM server, i.e., the BIMserver.org platform [25], provides functions for the management, parsing, checking, query and visualization of BIM models. Fig. 8 shows typical user interfaces of the prototype system.

5. Validating the prototype system

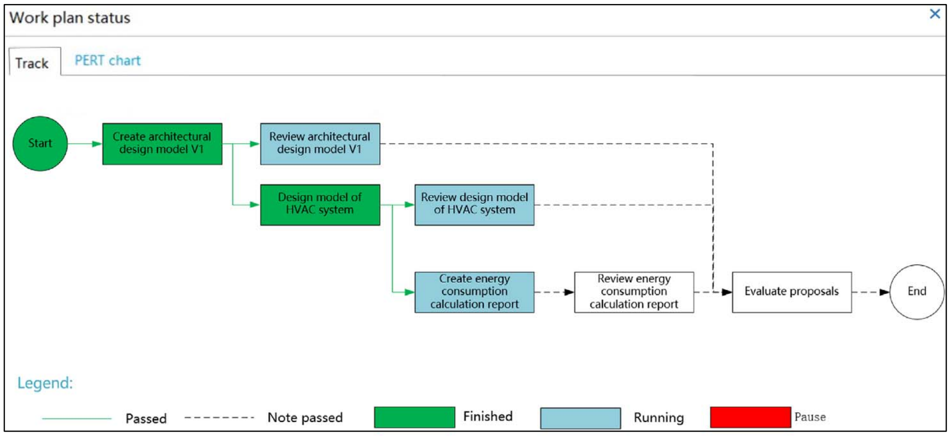
An ideal method to validate the prototype system is to apply the system to an actual IPD project and evaluate the results of the application. However, it is difficult to find an actual IPD project to conduct the validation because such projects remain rare. Hence, in this research, the prototype system is applied to a virtual IPD project originating from a real project.

Supported by Beijing Urban Construction Group (BUCG), we chose a finished building project, i.e., the Beijing Urban Construction Technology Building (BUCTB). BUCTB is an office building located in Beijing with 80,498 sq. m of space comprising fourteen levels on the ground and four levels underground. The contract adopted by the project was a traditional DBB contract. However, because key participants of the project, i.e., the owner, the designer, the main contractor and some sub-contractors, were all from subsidiaries of BUCG and wanted to try the IPD method to maximize the value of the project, some IPD characteristics were applied in the project, such as early involvement of participants, continual "design – evaluate/compare - modify" iterations, etc. Thus, the information generated in the project was applicable to the validation.

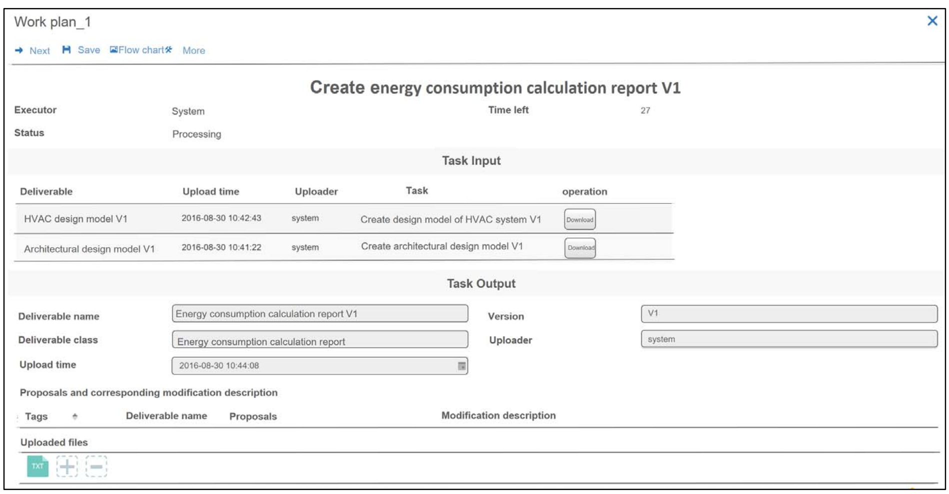
We collected the information on the project as comprehensively as possible, including deliverables of programming, design, calculation and construction, minutes of review meetings, RFIs and change orders (COs). In IPD projects, batches of information in design are smaller and the frequency of information transfer is higher than in traditional projects because of the concurrent nature of the engineering [22]. To simulate an IPD project, with the help of the participants in the project, we broke the collected deliverables into smaller deliverables, as generated by IPD projects, and built "depend_on" relationships among them. In addition, the comments in the minutes, RFIs and COs were all regarded as accepted proposals that triggered modification of the design in the IPD projects.

Based on the collected and adjusted information, we acted in the role of the participants to simulate the implementation of IPD collaboration using the prototype system. The simulation was conducted in typical scenarios, including creating a new work plan, executing the work plan, reviewing deliverables and making proposals, comparing and evaluating various design solutions, modifying a work plan, and tracking and retrieving historical information. Then, we showed the process to the actual participants of the project and collected their comments on the prototype system. 10 people from the owner (2), the designer (3), the main contractor (3), the HVAC sub-contractor (1) and the Plumbing sub-contractor (1), respectively, were involved in the work. All participants had sound specialized abilities and project management experience (8–15 years) and acted as leaders or key staff in the project. The advantages of the prototype system are presented as follows:

- Most of the day-to-day work in IPD collaboration can be conducted online using the collaboration platform, and some simple meetings can be hold online using a video conference system.
- The collaboration platform significantly simplifies the creation and modification of the work plan. The generated work plan is of high quality and considers such factors as the current status of the plan execution and the implementation of proposals.
- The pushing of the information is precise and effective. Participants do not need to look for needed information proactively, and thus, collaboration is facilitated.
- The creation, evaluation and implementation of proposals are under control and can be tracked more clearly.
- Management of design solution versions is more orderly, and inconsistency among deliverables is nearly eliminated. It is more



a. Browse the status of work plan execution



b. Execute a task

Fig. 8. Typical user interfaces of the prototype system.
a. Browse the status of work plan execution.
b. Execute a task.
c. Browse the relationships among design solutions.
d. Browse the relationships in one design solution.

efficient to track and retrieve historical information with the help of the relationship browser.

The drawbacks of the prototype system are presented as follows:

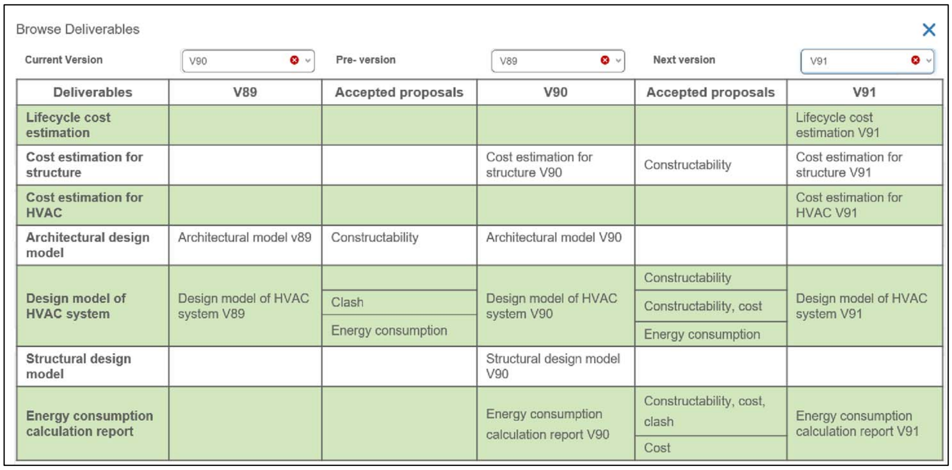
- Synchronous collaboration cannot be conducted by using the system.
- Offline meetings are still needed when complex and important problems are discussed.

In summary, the validation showed that the developed prototype system supported IPD collaboration better than existing collaboration platforms and can replace the "big room" for any project. These improvements are expected to significantly reduce the major difficulty in implementing IPD projects and thus promote the adoption of IPD.

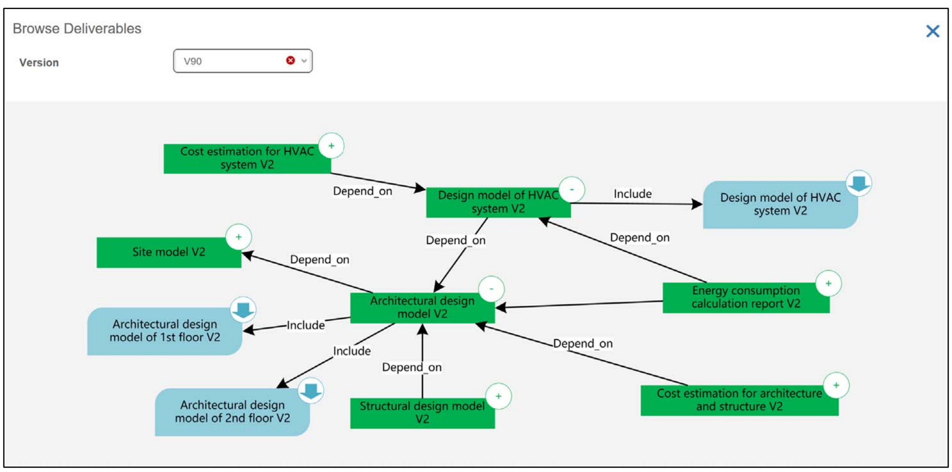
6. Conclusions

This paper clarifies the critical aspects for the development of a dedicated collaboration platform for IPD projects. The major requirements were summarized with the support for lean methods, and a prototype system of the collaboration platform was developed and validated. The new collaboration platform allows the collaborative work plan creation and execution in IPD projects, which were previously performed manually, to be automated. Furthermore, the project information can be managed in an orderly manner and is easy to retrieve online, and the "big room" can be replaced for any project. These improvements can significantly reduce the major difficulties of the implementation of IPD projects and thus promote the adoption of IPD. This paper contributes to the body of knowledge in that it introduces the theory and a corresponding tool to improve IPD collaboration using a dedicated collaboration platform. This knowledge can be used not only to customize the existing collaboration platform but also to develop new collaboration platforms for use in IPD projects.

Our future work will concentrate on additional development of the collaboration platform with the goal of further replacing the offline activities, including meetings. Considerable work is needed to realize this goal, including the development of a powerful virtual meeting room to support discussion among IPD project participants, the establishment of an online social network in IPD projects to provide more flexible communication methods and improve relationships among participants, and the use of more advanced information integration



c. Browse the relationships among design solutions



d. Browse the relationships in one design solution

Fig. 8. (*continued*)

technologies to integrate scattered and heterogeneous information from different participants.

Acknowledgments

This study was supported by the 'National Natural Science Foundation of China' (No. 51078201), the 'Tsinghua University Research Fund' (No. 2011THZ03), the 'Beijing Municipal Science and Technology Project' (No. Z151100002115054), Beijing Urban Construction Group Company Limited and Glodon Software Company Limited.

References

[1] T. Hartmann, M. Fischer, J. Haymaker, Implementing information systems with project teams using ethnographic–action research, Adv. Eng. Inform. 23 (2009) 57–67, http://dx.doi.org/10.1016/j.aei.2008.06.006.
[2] N. Azhar, Y. Kang, I.U. Ahmad, Factors influencing integrated project delivery in publicly owned construction projects: an information modelling perspective, Procedia Eng. 77 (2014) 213–221, http://dx.doi.org/10.1016/j.proeng.2014.07.019.
[3] B. Becerik-Gerber, D. Kent, Implementation of Integrated Project Delivery and Building Information Modeling on a Small Commercial Project, Proceedings of CIB W89 Conference, Wentworth Institute of Technology, Boston, 2010.
[4] D.C. Kent, B. Becerik-Gerber, Understanding construction industry experience and attitudes toward integrated project delivery, J. Constr. Eng. Manag. 136 (2010) 815–825, http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000188.
[5] C. Thomsen, Managing Integrated Project Delivery, Construction Management Association of America (CMAA), McLean, VA, 2009, http://dx.doi.org/10.1016/b978-0-7506-8515-3.x0001-3.
[6] Consensus Docs, Standard multi-party integrated project delivery (IPD) agreement, https://www.consensusdocs.org/Resource/FileManager/300.pdf, (2017) , Accessed date: 12 January 2017.
[7] American Institute of Architects, Standard form multi-party agreement for integrated project delivery document C191-2009, http://nebula.wsimg.com/a466a3e1abf9f4e049e652b36ddda829?AccessKeyId=0D015044C9238FCBF550&disposition=0&alloworigin=1, (2017) , Accessed date: 1 February 2017.
[8] American Institute of Architects, Document C195-2008 C195-2008 standard form single purpose entity agreement IPD, https://www.aiabookstore.com/aia-documents/aia-documents-c-series/c195-2008-standard-form-single-purpose-entity-agreement-ipd.html, (2017) , Accessed date: 12 January 2017.
[9] Lean Leadership Canada, Integrated form of agreement for integrated lean project delivery among owner, architect & CM/GC, http://www.leanleadership.ca/Moose%20Jaw%20IFOA%20IPD%20Agreement%20Public%20copy%20to%20share%20Sept%203%202013.pdf, (2017) , Accessed date: 21 January 2017.
[10] Zhiliang Ma, D. Zhang, J. Ma, BIM-based collaborative work model and information utilization framework for IPD project, Journal of Tongji University (Natural Science) 42 (2014) 1325–1332, http://dx.doi.org/10.3969/j.issn.0253-374x.2014.09.004.
[11] B. Dave, E. Pikas, H. Kerosuo, T. Mäki, ViBR–conceptualising a virtual big room through the framework of people, processes and technology, Procedia Econ. Financ. 21 (2015) 586–593, http://dx.doi.org/10.1016/S2212-5671(15)00216-6.
[12] F. Lanubile, C. Ebert, R. Prikladnicki, A. Vizcaino, Collaboration tools for global software engineering, IEEE Softw. 27 (2010) 52–55, http://dx.doi.org/10.1109/MS.2010.39.
[13] M.A. Rosenman, G. Smith, M.L. Maher, L. Ding, D. Marchant, Multidisciplinary collaborative design in virtual environments, Autom. Constr. 16 (2007) 37–44, http://dx.doi.org/10.1016/j.autcon.2005.10.007.
[14] A.R. Mohamed Eshaq, P. Karboulonis, Design considerations for the design of an advanced VR interface for knowledge management and its relevance to CAD,

Autom. Constr. 12 (2003) 501–507, http://dx.doi.org/10.1016/S0926-5805(03)00036-0.
[15] X. Wang, P.S. Dunston, User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review, Autom. Constr. 17 (2008) 399–412, http://dx.doi.org/10.1016/j.autcon.2007.07.002.
[16] H.-M. Chen, H.-C. Tien, Application of peer-to-peer network for real-time online collaborative computer-aided design, J. Comput. Civ. Eng. 21 (2007) 112–121, http://dx.doi.org/10.1061/(ASCE)0887-3801(2007)21:2(112.
[17] H.-M. Chen, C.-C. Hou, Asynchronous online collaboration in BIM generation using hybrid client-server and P2P network, Autom. Constr. 45 (2014) 72–85, http://dx.doi.org/10.1016/j.autcon.2014.05.007.
[18] H.J. Choo, J. Hammond, I.D. Tommelein, S.A. Austin, G. Ballard, DePlan: a tool for integrated design management, Autom. Constr. 13 (2004) 313–326, http://dx.doi.org/10.1016/j.autcon.2003.09.012.
[19] N. Forcada, M. Casals, X. Roca, M. Gangolells, Adoption of web databases for document management in SMEs of the construction sector in Spain, Autom. Constr. 16 (2007) 411–424, http://dx.doi.org/10.1016/j.autcon.2006.07.011.
[20] W. Mao, Y. Zhu, I. Ahmad, Applying metadata models to unstructured content of construction documents: a view-based approach, Autom. Constr. 16 (2007) 242–252, http://dx.doi.org/10.1016/j.autcon.2006.05.005.
[21] I. Faraj, M. Alshawi, G. Aouad, T. Child, J. Underwood, An industry foundation classes web-based collaborative construction computer environment: WISPER, Autom. Constr. 10 (2000) 79–99, http://dx.doi.org/10.1016/S0926-5805(99)00038-2.
[22] P.H. Chen, L. Cui, C. Wan, Q. Yang, S.K. Ting, R.L.K. Tiong, Implementation of IFC-based web server for collaborative building design between architects and structural engineers, Autom. Constr. 14 (2005) 115–128, http://dx.doi.org/10.1016/j.autcon.2004.08.013.
[23] J. Plume, J. Mitchell, Collaborative design using a shared IFC building model—learning from experience, Autom. Constr. 16 (2007) 28–36, http://dx.doi.org/10.1016/j.autcon.2005.10.003.
[24] V. Singh, N. Gu, X. Wang, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, Autom. Constr. 20 (2011) 134–144, http://dx.doi.org/10.1016/j.autcon.2010.09.011.
[25] BIMserver.org, Open building information model server, http://bimserver.org, (2017) , Accessed date: 25 January 2017.
[26] J. Beetz, L. van Berlo, R. de Laat, P. van den Helm, BIMserver.org—an open source IFC model server, Proceeding of the CIB W78 Conference (2010).
[27] American Institute of Architects California Council, Integrated project delivery, a guide, http://info.aia.org/SiteObjects/files/IPD_Guide_2007.pdf, (2017) , Accessed date: 14 January 2017.
[28] Z. Ma, J. Ma, Formulating the application functional requirements of a BIM-based collaboration platform to support IPD projects, KSCE J. Civ. Eng. (2017) 1–16, http://dx.doi.org/10.1007/s12205-017-0875-4.
[29] American Institute of Architects California Council, IPD an updated working definition, http://www.aiacc.org/new-ipd-pdf-form, (2017) , Accessed date: 3 February 2017.
[30] H.W. Ashcraft, The IPD Framework, Hanson Bridgett, San Francisco, 2012.
[31] K. Yong-Woo, Dossick and Carrie Sturts, what makes the delivery of a project integrated? A case study of children's hospital, Lean Construction Journal (2011) 53–66.
[32] G. Ballard, Should Project Budgets Be Based on Worth or Cost, Proceedings of International Conference of the International Group for Lean Construction, San Diego, CA, 2012.
[33] I.I. Sobek, K. Durward, A.C. Ward, J.K. Liker, Toyota's principles of set-based concurrent engineering, MIT Sloan Manag. Rev. 40 (1999) 67.
[34] A. Mossman, Last Planner: 5 + 1 Crucial & Collaborative Conversations for Predictable Design & Construction Delivery, The Change Business Ltd., UK, 2013.
[35] Computer Science Department of Stanford University, Graph search algorithms, http://cs.stanford.edu/people/abisee/gs.pdf, (2017) , Accessed date: 2 February 2017.
[36] D.V. Steward, The design structure system: a method for managing the design of complex systems, IEEE Trans. Eng. Manag. (3) (1981) 71–74, http://dx.doi.org/10.1109/TEM.1981.6448589.
[37] BeX, Justep, http://www.wex5.com/bex5, (2017) , Accessed date: 19 January 2017.