

Article

A Framework for Selecting Construction Project Delivery Method Using Design Structure Matrix

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Abstract: Determining a project delivery method that matches the characteristics of a construction project is a critical step that affects the success or failure of a project. The Project Delivery Method (PDM) should be adapted to the activities and processes of project implementation. However, the traditional selection method does not come from the internal process of the project which may lead to the delivery method not being able to meet the actual project requirements. This research proposes a DSM-based PDM selection framework model that regroups activities and identifies appropriate PDMs by revealing the dependencies and intensities between activities. The research uses a case to demonstrate the feasibility of the framework. After considering specific project requirements and goals, the framework model can be used as a basis for choosing specific project delivery methods, or as a visualization tool to help owners schedule activities.



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Keywords: project delivery method; PDM; procurement selection; delivery selection; design structure matrix; DSM

1. Introduction

The selection of a project delivery method (PDM) is a crucial step in impacting project success [1,2]. A PDM describes the relationship and working methods among project participants in the process of transforming the owner's goal into the completed facilities [3]. It directly affects construction performance including schedule, cost, quality, and efficiency [4–6]. The PDM can be viewed as both a contractual structure and compensation arrangement through which project owners obtain a completed facility that meets their needs [7]. The PDMs in practice are design-bid-build (DBB), design-build (DB), construction management at risk (CMR), engineering-procurement-construction (EPC), and integrated project delivery (IPD) [8,9]. However, the most common approaches are the first three, and the limitations of design-bid-build and the complexity of project features and requirements lead to a greater willingness to use design-build and other delivery methods [10].

In order to select the appropriate project delivery method, researchers have developed many methods based on case performance [11,12] and mathematical models [2–4,13–16]. These models and methods rely more on subjective expert opinions which are interfered with by the preferences, expertise, and abilities of the evaluators and are not very adaptable to constantly changing projects.

The project delivery method reflects the task, organizational, and contractual relationship of the project. Under the requirements of specific goals, new organizational and contractual relationships are created immediately after the tasks are rescheduled, and the corresponding delivery methods are also generated. However, few studies consider the feasibility of this delivery method from the perspective of the internal development process and working relationship.

This paper attempts to develop a framework model for selecting project delivery methods. The framework uses the design structure matrix (DSM) method to analyze the relationship between the activities in the system and optimizes activities through merging, deleting, and changing locations. The appropriate implementer is selected according to the closeness between the activities and, finally, the project delivery method is formed. This study expands the path and perspective of project delivery method selection, reveals the connection between project activities and project delivery methods, and reduces the instability of selecting project delivery methods.

2. Literature Review

2.1. Major Delivery Methods in Practice

Design-Bid-Build (DBB) refers to the sequential and phased project delivery method involving three key players: the owner, the designer (architect), and the general contractor (builder). In this contractual structure, the owner contracts with the designer and the contractor, respectively, monitoring the activities of the designer and the contractor to ensure compliance with the contract requirements [13,17]. The owner signs a contract with the designer first and then signs an agreement with the contractor through bidding after the design contract is completed. There is no direct connection between the designer and the contractor and all information needs to be transmitted after the owner's decision.

Construction management at risk (CMR) might be the preferred project delivery method when owners need a defined completion date and price. The CMR manager is responsible for providing consultation on architectural services in evaluating costs, schedule, materials, and the like, and advising on optimizations and design alternatives, playing the role of a general contractor during the construction phase. A CMR manager is also responsible for monitoring and controlling the construction process in terms of costs, time, and other requirements to ensure a guaranteed maximum price (GMP) for the project [7,17]. Similar to DBB, the owner contracts with both the designer and the CMR manager.

In the design-build (DB) method, the design and construction are carried out by one entity. The owner only needs to sign one contract covering architecture, engineering, and construction and contracts with a single enterprise responsible for design and construction [6]. The owner will give priority to the DB method when he cannot bear too much risk and responsibility. Because it is a single entity responsible for design and construction, it avoids the possible opposition in DBB [7]. Since the contractor is liable for all coordination efforts, the owner's contract administration and site representative risks and costs are reduced.

Integrated Project Delivery (IPD) is defined as "a method of project delivery characterized by a contractual arrangement among a minimum of the owner, constructor, and designer that aligns the commercial interests of all participants" [18]. IPD integrates all elements of the system into a single process that synergistically utilizes the talents and abilities of all participants through all stages of design, fabrication, and construction to optimize project outcomes, increase value, reduce waste, and maximize efficiency [19]. IPD method includes some contract principles and behavior principles that promote participants' early cooperation, increase mutual trust, and integrate multiple participants under one contract.

2.2. Selection of Major Delivery Methods

Project delivery methods have evolved from traditional DBB to IPD, but not all projects are suitable for newly developed delivery methods. The same type of project even may be suitable for different delivery methods. Each project should develop a project delivery method adapted to its characteristics. It is not so much that the project delivery is selected, it is better designed [20,21]. Some researchers hope to summarize the experience of selecting project delivery methods through existing project cases. Alleman et al. [21] investigated 291 US highway projects and believed that the alternative contracting methods (DB and CM) have better cost and schedule benefits and are therefore more suitable for

highway construction. Demetracopoulou et al. [11] tested 57 lessons learned from Texas highway projects to help clarify the difficulty of choosing PDM. Franz et al. [22] verified the data of 212 projects to compare the cost and schedule performance of different delivery methods. Performance-based research also includes that these provide useful references for encouraging researchers to fully understand PDM and choices [23–25].

Another part of the researchers' hope is to develop a model of delivery method selection based on summarizing the selection criteria. This in turn includes appropriate determination of selection factors or criteria and reasonable methods. The factors for choosing a PDM are constantly enriched [26]. Decision makers focus early on the specific goals of the project [27,28], and as project complexity increases, factors expand to collaboration, integration, sustainability, corruption prevention, etc., [19,29,30]. The corresponding selection methods and models become more and more complex. By calculating the relative importance of different factors in the project goal hierarchy to choose the most appropriate delivery method, the AHP method has become the most commonly used method [4,13]. The artificial neural network method developed by Chen et al. identified similar projects between the target projects in the database and reduced the dependence on an expert's judgment [3]. Many researchers have to work on fuzzy methods in choosing the appropriate PDM to improve the reliability of decision making [2,14,15,31,32]. Additionally, many researchers developed multi-attribute decision making support tools [16,33–37].

However, these efforts may face some difficulties. The complexity of the project makes the choice of delivery method often inconsistent. When researchers try to use project performance indicators (such as cost, schedule, production efficiency, etc.) to select delivery methods, they often draw inconsistent conclusions. Feghaly et al. [38] concluded that DB was statistically superior to DBB in terms of project speed and intensity. Carpenter and Bausman [39] compared the performance of DBB and CM at Risk in public school construction, but the results showed that no one delivery method could meet all performance requirements. Project delivery methods should meet the requirements of the project characteristics. However, the evolution of projects and environmental changes constantly create new features and requirements which weaken the effectiveness of the model.

2.3. Design Structure Matrix

The design structure matrix (DSM), also known as the dependency structure matrix, has become a widely used modeling framework in research and practice. The DSM is a network modeling tool that reflects the interaction of the system's elements, thereby highlighting the system's architecture (or designed structure) [40]. According to the type of system being modeled, DSM can represent various types of architectures. For example, to model a process architecture, the DSM elements would be the activities in the process, and the interactions would be the flow of information and/or materials between them [41]. The DSM approach allows the project or engineering manager to represent meaningful task relationships to determine a reasonable sequence for the modeled activities [42]. The DSM has been identified as a potential tool to simulate interdependent activities, identify suitable assumptions, and formulate and evaluate the result [43].

The activity-based DSM is basically an N-square matrix that contains an activity list of rows and columns arranged in the same order. The order of activities in a row or column indicates the order of execution. In DSM, the relationship between activities is represented by the "X" mark in off-diagonal cells, which reflects the information flow between activities. The "X" mark above the diagonal indicates the information assumption or premise needed to start an activity. DSM is an N-square graph matrix representation of a process that is especially suitable for modeling the sequence and iterative information relationship between activities in the product development process [44–46].

Three possible relationship types between activities and corresponding DSM expressions are shown in Figure 1.

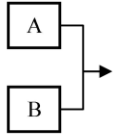
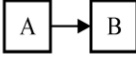
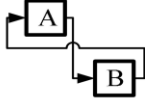
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Figure 1. Three Configurations in DSM Analysis.

The DSM can be divided into four categories: component-based DSM, team-based DSM, activity-based DSM, and parameter-based DSM. The former two DSMs can also be called static DSM, and the last two can be called time-based DSM [47]. They correspond to the four DSM structural directions, as suggested by Yassine, and demonstrate the corresponding analysis methods as shown in Table 1.

Table 1. Four Different Types of Data in DSM (adapted from Yassine 2004).

DSM Types	Representation	Application	Analysis Method
Activity-based DSM	Activities in a process and their input and output	Project scheduling, activity sequencing, and cycle time reduction	Partitioning/Tearing/Banding/Simulation and Eigenvalue Analysis
Parameter-based DSM	Parameters to determine a design and their relationship	Low level activity sequencing and process construction	
Team-based DSM	Teams in an organization and their relationships	Organizational design, interface management, and team integration	Clustering
Component-based DSM	Components in a product and their relationship	System architecting, Engineering, and design	

Partitioning eliminates or reduces feedback marks [46]. This process reorders activities so that dependencies are below or close to diagonals. When this is completed, we can see which activities are sequential, which can be completed in parallel, and which are coupled or iterative [48].

Tearing is the process of selecting the set of feedback marks that, if removed from the matrix (and then the matrix is re-partitioned), it will make the matrix a lower triangle [48]. Once the hypothesis is made through tearing, the matrix is subdivided to determine the preferred execution sequence [42].

Banding is to add alternating light and dark bands in DSM to show independent (i.e., parallel or concurrent) activities (or system elements) [49]. The collection of bands or levels constitutes the critical path of the system/project [48].

Although DSM is considered an effective tool for planning and sequencing, it is rarely used in construction projects. DSM is mostly used for optimizing activities during the planning and design phases [50–55]. These studies have improved the integration of activities in planning and design, helping engineers and managers to control work more

precisely and improve work efficiency. However, research on project delivery method selection based on activity optimization has not been seen.

3. Research Methodology

3.1. The Primary thought of the Study

This study aimed to establish a framework model and method based on the interaction between activities for selecting a project delivery method for construction projects. Therefore, the activity-based DSMs are selected to identify the order and correlation of execution of the main activities and to analyze the likelihood and feasibility of their portfolios to optimize the project delivery process. At the same time, partitioning is chosen as an optimization and analysis tool because it needs to consider the combination of activities.

An example is taken from literature by [48] to explain the basic idea of the framework and then propose the specific steps of the framework in Figure 2. Firstly, the system activities are decomposed, and the spaghetti graph is drawn in Figure 2a. The arrow represents the information relationship between the activities; for example, the arrow B to C means C needs to receive output information from B before it can start. The original DSM is drawn in Figure 2b, and finally, the partitioned DSM is shown in Figure 2c.

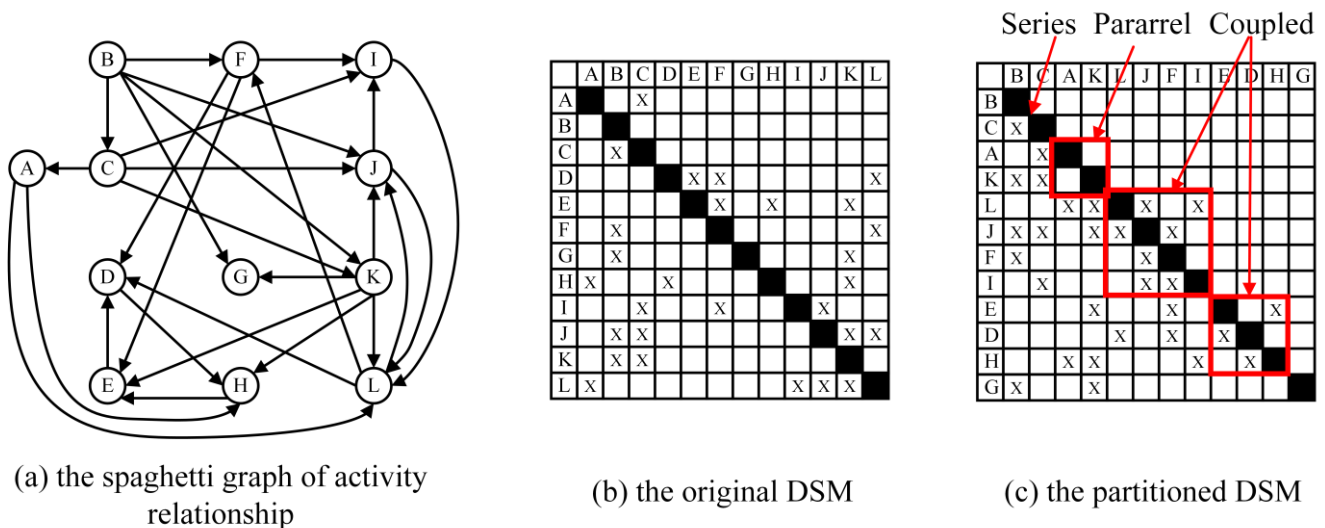


Figure 2. The DSM Method Framework.

Based on the representation of the DSM activity relationship, we can sort out this study's basic ideas and work. The project delivery method can be associated with the representation of three activity relationships in partitioned DSM.

- (1) Once the DSM is partitioned, a series of activities are identified and executed in sequence, such as how B and C are sequential in Figure 2. The owner can determine an integrated contract or decentralized contract based on factors such as the closeness between the activities. If the activities are closely linked, they should be managed by one contractor. However, the owner can award contracts to different contractors, and the owner is responsible for the coordination of the activities.
- (2) Activity A and K are independent or paralleled, and they can be executed concurrently without information exchange with each other. The two activities only need to start after receiving the information of their respective previous work without considering the status of each two of them. So, it is suitable for the owner to entrust them to two contractors independently.
- (3) In Figure 2c, a loop is formed in blocks E-D-H: task E first needs to estimate or assume the output of task H, the outcome of E is transmitted to task D, then the output of D flow to task H, and finally, the output of H is fed to task E. At this point, task E starts in a state of uncertainty and incomplete information. Many times can this

uncertainty gradually decrease or converge only after E-D-H iterations occur. If multiple contractors perform separately, this iteration will not be accurately predicted and adequately controlled. There are similar but more complicated relationships among I, L, J, and F, and more upfront planning is required. It is difficult for owners to coordinate different contractors effectively, so they are more suitable for one contractor to conduct integrated management.

3.2. The Procedure of the Selection Model

The selection model for PDM using DSM includes four steps: Identify Requirements or Objectives, Building/Creating the Design Structure Matrix, Project Redesign/Optimization, and Design/Select Project Delivery Method. The model is shown in Figure 3.

Step 1. Identify requirements or objectives. This step consists of three main tasks, including asking the owner and environmental requirements or limitations, identifying project characteristics, and determining project goals. Identifying the environment of the project and clarifying the project owner's needs is the primary task of choosing a suitable project delivery method [4,56,57]. The sequence of activities, the responsibilities of the organization, and the corresponding contract structure are all based on meeting the owner's needs. Project characteristics define the technical nature of the work [58] which will affect the rationality and feasibility of redesigning the process. Project objectives need to be defined broadly in terms of scope, schedule, budget, and project complexity [4].

Step 2. Building/Creating the Design Structure Matrix. Appropriate structural decomposition and accuracy of activity dependencies determine the effectiveness of the DSM approach [48]. This step, therefore, consists of four activities. First, the project manager should fully decompose the project and forms a list of activities whose outputs constitute the entirety of the project entity. The list of activities can be determined by converting existing documents or structured expert interviews [48]. Second, the inputs and outputs of each activity should be determined, which reflect the dependencies between the activities. After the activities and their dependencies are entered into the matrix, an activity-based DSM can be formed. Finally, the marks in the DSM should be checked to confirm whether the relationships between the activities are correct and whether there are activity conflicts. It is worth noting that even if the activities are decomposed the same in different projects, the relationship between activities may still change with the owner's goals and requirements. When schedules are tight, identifying requirements may no longer be an absolute priority activity, but instead needs to be developed gradually through constant feedback during design and construction.

Step 3. Project Redesign/Optimization. After representing the process in the matrix, the project can be redesigned using partitioning, tearing, banding, and clustering. As mentioned previously, this framework focuses on the relationship and regrouping of activities, so partitioning is the main analysis tool.

Step 4. Design/Select Project Delivery Method. In this step, the strength of the relationship and the sequence of activities in the same partition should be checked first from a technical, regulatory, or management perspective. A partition represents the least amount of feedback between activities within it but may be technical, regulatory, or have weak dependencies that are not worth management action. Once it is confirmed that there is no unreasonableness or error, the activities in the partition can be packaged as a basis for assigning responsible persons. Likewise, relationships between activity packages should be examined and combined where feasible. Team activities can be assigned when all activities and activity packages have no relationship conflicts. Finally, a suitable PDM is selected or designed.

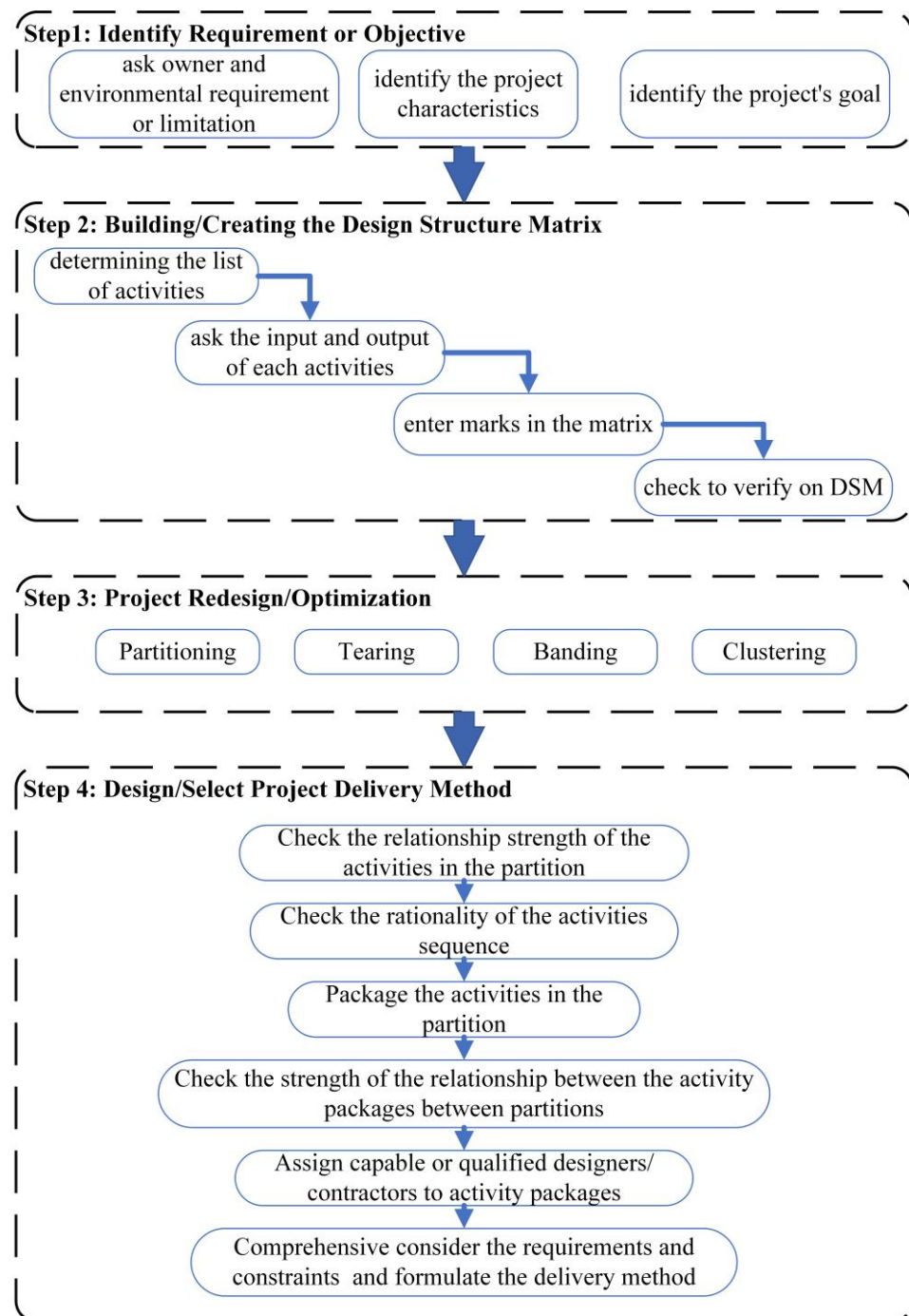


Figure 3. The Framework Model Using DSM to Select the PDM.

4. Case Study

This article uses a case study to describe the feasibility of this method in actual project implementation and uses surveys for verification. The survey asks practitioners their views on the project's activity relationship and inputs the feedback into the model to obtain the simulation results. The feasibility of the method is verified by comparing the simulation results with the actual delivery method.

4.1. Background of the Project

The project is a post-earthquake hospital reconstruction project in China with a total investment of 73.55 million yuan (US\$11.37 million) and a total construction area of

13,918 m². The project was publicly tendered on 16 January 2018. The winning bidder was determined on 14 February 2018 and the construction of the project began in April 2018 and was finally finished on 7 August 2019. The funding for the project is fiscal funds, which can remain stable and sufficient.

4.2. Identify the Owner's Requirements and Analyze the Working Conditions

According to the central and provincial government's overall plan, the project needed to be delivered before the end of August 2019. The project construction period included design and construction for a total of about 500 days. In order of decreasing importance, the owner put forward the following requirements: to be completed on time or in advance, without quality and safety accidents, reducing environmental damage, improving the ability of the project to resist potential disasters, and improving the local medical level.

The historical weather statistics show that the local area faces regular heavy rains in July, and low temperatures in November, December, January, and February. For about five months of each year, normal construction cannot be carried out and may even be completely shut down. Therefore, the actual available time of the project was about 350 days, which is only 70% of the average time. The owner of this project did not have any management capabilities or experience in similar projects. Moreover, when the project was bidding, the project's detailed design was not completed, and only the plan was made. The final needs of the owner for the project were not precise, and there was the possibility of new requirements midway. The project site was small and challenging to construct. It was close to the river, and the groundwater level was high. The environmental carrying capacity of the project site was fragile, and it was close to a natural heritage protection area, so environmental pollution needed to be minimized as much as possible.

4.3. The Survey and Implementation

The survey was sent out in May 2021. The interviewees were the owner, on-site representative of the owner, designer, contractor enterprise manager, contractor project manager, project production manager, and project supervisor who had participated in the project. The questionnaire asked respondents to review the project implementation process and propose adjustments based on their practical experience.

The basic information of the interviewees and the projects they participated in are shown in Table 2.

Table 2. Respondent Details in Survey.

Respondent Details		Quantity	Total (%)
By respondent's occupation			
Contractor	Project manager	1	11.1
	Designer	2	22.2
	Production manager	2	22.2
	Enterprise manager	1	11.1
Project Supervisor		1	11.1
Owner		2	22.2
By respondent's working year		Quantity	Total (%)
≥15		2	22.2
≥10, <15		4	44.4
≥5, <10		3	33.3
<5		0	0

The contents of the survey mainly include:

- (1) Under the circumstance that the constraints cannot change, how can the project activities be adjusted to achieve the owner's goal of 30% ahead of schedule (including deletion, merger, location change, activity association change, etc.)?
- (2) If the activity changes, mark the adjusted relationship and location.

- (3) Which current project delivery method is suitable for the adjusted activities?

4.4. Identify Project Activities and Establish the Activity Decomposition Diagram

The project construction process can be decomposed into three major functions or processes: design, preparation, and production. Each can be further divided into more works and activities, and then a node tree can be established. The activities at the bottom of the figure can still be decomposed. For example, 'make detailed design' can still be decomposed into 'design spaces and facades', 'assist in the design of external structures and foundations', 'design frame and roof structures', 'design the complementary structures, surfaces, fittings, and courtyard', and 'prepare a construction specification' [59]. However, these activities are generally completed by different designers within a team. As far as the project delivery method is concerned, the work breakdown below the project work team is no longer necessary. The works and activities are decomposed in Figure 4, and their explanations are below:

- (1) Draw up brief. It is a process to collect the basic information provided by the owner concerning space requirements. The information consists of needs and requirements about the economy, dimension, quality, scheduling, function, etc. Additionally, the possibilities of site situation and availability of resources should be collected. This work is denoted by "A" and can be composed of four activities represented by A1~A4, respectively.
 - Identify requirements (A1). The needs of the owner and requirements from outside involve many aspects, including financial requirements, space scale requirements, quality and function requirements, schedule requirements, alternative technical solutions, etc.
 - Survey and analyze site information (A2). Analysis of the present situation includes the availability of existing conditions and the possibility of change. Designers and contractors need to analyze the geotechnical condition, city plan, local planning, availability of resources and management systems, etc.
 - Establish objectives (A3). This activity formulates and establishes the overall goals of the project. Goals may include establishing the desired attributes and functions developed by the owner, determining regulating requirements, and clarifying the design scope.
 - Establish design parameters (A4). Establish design limits, guidelines, and project requirements such as budget, cost, scheduling, quality, constructability, and environmental effects.
- (2) Make conceptual design. Concept design is the forming of abstract concepts using approximate concrete expressions [60]. General concepts such as site use and boundary, architectural consideration, major system types, and materials are explored. Conceptual cost estimates and budgets may also be developed. This work is denoted by "B" and can be composed of four activities represented by B1~B3, respectively.
 - Develop preliminary design (B1). This process will determine the project program and terms to define the function. Some drawings, including the basic dimensions of the project, the major architectural components, and structural systems, are developed to illustrate the concept of design and the project scope.
 - Coordinate and find compatibility (B2). System schemes between disciplines need to be coordinated for integration. Some checks such as function compatible checks, quality reviews, and standard/code coordination checks should be performed from the macro-level.
 - Evaluate and review the preliminary design (B3). The owner reviews the preliminary design from multiple perspectives, including meeting requirements, function, economy, feasibility, legal and government permits, etc., to determine whether the scheme can achieve the expected effect and whether the detailed design can be carried out.

- (3) Make detailed design. This process starts with the evaluation of the scheme. The detailed design needs to be elaborated on until the contractor can choose the construction method and purchase materials accordingly. The design process needs to integrate the design process of all disciplines. This work is denoted by “C” and can be composed of three activities represented by C1–C3, respectively.
 - Make a detailed design (C1). The detailed design includes activities such as facade design, internal space design, decoration design, structural design, ventilation system design, pipe design, fire protection design, landscape design, etc.
 - Check the compatibility of detailed design (C2). The design documents for all disciplines should be checked to ensure compatibility between various professional designs and reduce or eliminate rework due to design conflicts.
 - Make the resource checklist (C3). The resource list includes raw materials and equipment. It should list the types, quantities, specifications, models, etc. so that the contractor can purchase resources and arrange the arrival time reasonably.
- (4) Acquire contractors. This process includes all activities concerning bidding and tendering. This work is denoted by “D” and can be composed of four activities represented by D1–D4.
 - Issue bidding documents (D1). The owner puts forward technical and management capability requirements to the contractor.
 - Tendering (D2). The contractor submits documents to the owner to prove that it is suitable for undertaking the project.
 - Review and select contractor (D3). The owner reviews the contractor’s tender documents, and judges and selects the most suitable contractor.
 - Sign contract (D4). The owner and the contractor sign the contract after reaching an agreement through negotiation.
- (5) Prepare for construction. The preparation mainly refers to the workforce and material preparation made by the contractor for the construction, including the project team, equipment, materials, etc. This work is denoted by “E” and can be composed of four activities represented by E1–E4, respectively.
 - Organize project team (E1). The contractor needs to select a qualified project manager and teams to construct the project.
 - Make a construction plan (E2). This plan is about construction scheduling, quality assurance, cost control, and environmental protection.
 - Prepare and implement procurement (E3). The contractor needs to make an accurate equipment and material procurement plan and carry out an inquiry, procurement, and storage as planned.
 - Prepare site (E4). The construction site must have no legal issues and have the appropriate condition for construction.
- (6) Construct project. Implement concrete activities to complete the tasks and objectives specified in the project plan. This work is denoted by “F” and can be composed of four activities represented by F1–F4.
 - Plan the daily work (F1). Decompose the overall construction plan to the work to be completed every day according to the schedule, and formulate the personnel and resource allocation plan, quality control measures, and inspection plan.
 - Allocate the resources (F2). Allocate sufficient quantity and quality resources to daily work.
 - Do the physical work (F3). Arrange appropriate workers and tools to complete daily work and gradually form products.
 - Inspect and approve the work (F4). The contractor needs to evaluate the quality and progress of phased products through regular inspection to ensure the project is completed on time and reduce rework.

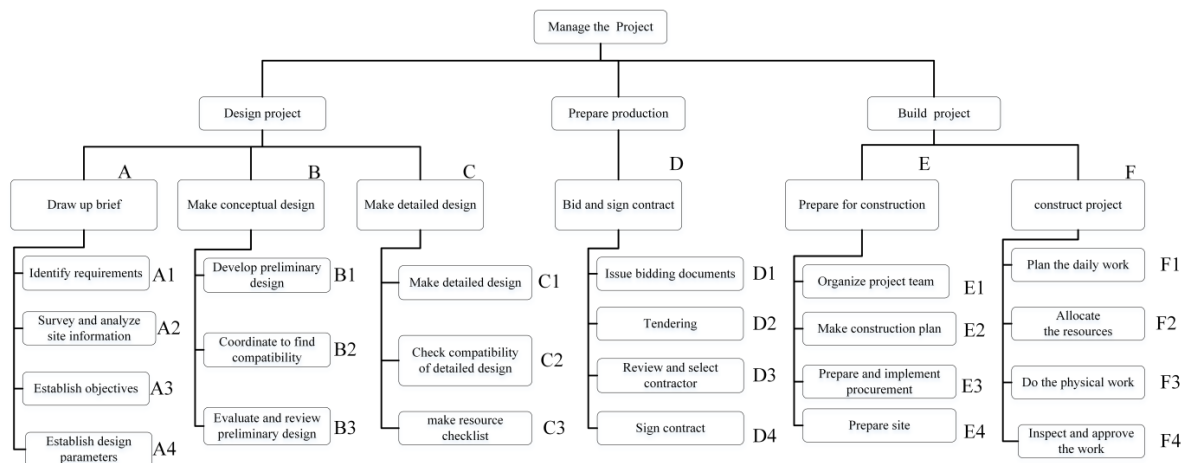


Figure 4. The node tree of the construction project.

4.5. Identify the Relationship between Activities and Establish an Original DSM

It should be noted that there are not only the feedforward and feedback relationships between the internal activities of each stage but also feedforward and feedback relationships between the cross-stage activities. There are three main stages of design, preparation, and construction in the basic model, and there are feedforward and feedback information flows between multiple cross-stage activities. Since the construction stage may encounter different assumptions from the design, the construction activities need feedback information from the initial design to guide the modification, so the possible process cycles appear within the stages and appear between stages. The dependence between activities lists in Table 3. The original DSM is shown in Figure 5.

		A1	A2	A3	A4	B1	B2	B3	C1	C2	C3	D1	D2	D3	D4	E1	E2	E3	E4	F1	F2	F3	F4
	A1	1																					
	A2	2	2																				
	A3	3	X	X	3	X																	
	A4	4			X	4																	
	B1	5			X	5	X	X															
	B2	6			X	6																	
	B3	7				X	7																
	C1	8	X						8	X					X	X							X
	C2	9							X	9						X							
	C3	10							X		10												
	D1	11		X			X					11											
	D2	12										X	12			X							
	D3	13	X											13									
	D4	14											X		14	X							
	E1	15												X		15							
	E2	16							X						X	16	X	X					X
	E3	17									X					X	17						
	E4	18													X		18						
	F1	19															X			19	X	X	
	F2	20															X	X		X	20		
	F3	21																		X	X	21	
	F4	22																				X	22

Figure 5. The original activity-based DSM of the project.

4.6. The Original DSM Is Manipulated to Eliminate or Reduce the Feedback Marks

For the activity-based DSM, partitioning is the primary method to help a transparent structure emerge. Using this method, sequential, parallel completion, coupled or iterative activities are clearly displayed. The DSM tool is DSM_Program-V2.1 [61]. The partitioned DSM is shown in Figure 6.

Table 3. The Dependence of the activities.

Activity	Depends on
Identify requirements (A1)	—
Survey and analyze site information (A2)	—
Establish objectives (A3)	Identifying requirements (A1), surveying and analyzing site information (A2), and developing a preliminary design (B1)
Establish design parameters (A4)	Establishing objectives (A3)
Develop a preliminary design (B1)	Establishing design parameters (A4), coordinating to find compatibilities of preliminary design (B2), and evaluating and reviewing the preliminary design (B3)
Coordinate to find compatibilities of preliminary design (B2)	Developing a preliminary design (B1)
Evaluate and review the preliminary design (B3)	Coordinating to find compatibilities of preliminary design (B2)
Make the detailed design (C1)	Identifying requirements (A1), checking compatibilities of detailed design (C2), signing the contract (D4), organizing the project team (E1), and doing the physical work (F3)
Check compatibilities of the detailed design (C2)	Making the detailed design (C1) and organizing the project team (E1)
Make a resource checklist (C3)	Making the detailed design (C1)
Issue bidding documents (D1)	Establishing objectives (A3) and evaluating and reviewing the preliminary design (B3)
Tendering (D2)	Issuing bidding documents (D1) and organizing the project team (E1)
Review and select contractor (D3)	Identifying requirements (A1)
Sign contract (D4)	Tendering(D2) and organizing the project team (E1)
Organize project team (E1)	Reviewing and selecting the contractor (D3)
Make a construction plan (E2)	Making the detailed design (C1), organizing the project team (E1), preparing and implementing procurement (E3), preparing the site (E4), and inspecting and approving the work (F4)
Prepare and implement procurement (E3)	Making a resource checklist (C3) and making a construction plan (E2)
Prepare site (E4)	Organizing a project team (E1)
Plan the daily work (F1)	Making a construction plan (E2), allocating the resources (F2), and doing the physical work (F3)
Allocate resources (F2)	Making construction plan (E2), preparing and implementing procurement (E3), and planning the daily work (F1)
Do the physical work (F3)	Planning the daily work (F1) and allocating the resources (F2)
Inspect and approve the work (F4)	Doing the physical work (F3)

4.7. Highlight the Partitioned DSM and Explanations

The partitioned DSM highlights two blocks. The first block includes seven activities such as A3, B1, A4, B2, and B3 which start from the ‘establish objective’ to the ‘evaluate and review preliminary design’. This block represents the main process of the preliminary design. Preliminary design stipulates some design features that cannot be broken through in the detailed design and construction, such as each system’s, subsystem’s, and component’s requirements and functions, a high-level outline of design features that meet each of these requirements, and cost estimates. In many reconstruction projects, determining the project goals clearly and making an acceptable design is not a one-time task. In repeated communication between the designer and the project owner; the project owner can gradually clarify his goals, and the designer can compile satisfactory deliverables.

The second block includes nine activities as E2, C1, C2, E3, C3, F3, F1, F2, and F4 which span broadly from ‘make detailed design’ to ‘inspect and approve the work’. It spans from design to procurement and build and spans from design to procurement and construction. In the reconstruction environment, the interviewees think it is tough for the designer to complete the perfect design alone and deliver it to the purchaser and contractor. More improvement work in practice requires feedback from the contractor during construction. This process must be speedy and smooth. Construction control must be transformed into

active control, so it is necessary to monitor the progress every day and revise the plan and resource allocation for the next day in real-time. These feedbacks are all divided into the same block, indicating that they are closely connected and suitable for integration consideration in organizational arrangements.

PARTITIONED DSM		A1	A2	A3	B1	A4	B2	B3	D1	D3	E1	E4	D2	D4	E2	C1	C2	E3	C3	E3	F1	F2	F4
		1	2	3	5	4	6	7	11	13	15	18	12	14	16	8	9	17	10	21	19	20	22
identify requirements	A1	1																					
survey and analyse site information	A2	2	2																				
establish objectives	A3	3	X	3	X																		
develop preliminary design	B1	5			5	X	X	X															
establish design parameters	A4	4		X		4																	
coordinate to find compatibilities of	B2	6			X		6																
evaluate and review preliminary design	B3	7					X	7															
issue bidding documents	D1	11		X				X	11														
review and select contractor	D3	13	X							13													
organize project team	E1	15							X		15												
prepare site	E4	18								X		18											
tendering	D2	12							X		X		12										
sign contract	D4	14								X		X		14									
make construction plan	E2	16								X	X				16	X	X	X					X
make detailed design	C1	8	X							X			X			8	X			X			
check compatibilities of detailed design	C2	9								X						X	9						
prepare and implement procurement	E3	17													X			17	X				
make resource checklist	C3	10													X				10				
do the physical work	F3	21																		21	X	X	
plan the daily work	F1	19													X					X	19	X	
allocate the resources	F2	20													X		X			X		20	
inspect and approve the work	F4	22																		X			22

Figure 6. The partitioned DSM of the project.

Some activities after partitioning have changed in order, D3 (evaluating contractor), E1 (building a project team), and E4 (preparing site) before D2 (tendering) and C1 (detailed design). Bidding is a test of the contractor’s capability. However, the construction period will be greatly extended if the contractor and bidding are inspected after the detailed design is completed, as in the traditional delivery method. The reconstruction environment is complex and changeable. Contractors need not only sufficient technical force but also strong comprehensive management and coordination capabilities. Therefore, in order to speed up the development of the project, more capable contractors should be evaluated in advance and the contractors should get to know the conditions of the scene earlier in order to make full preparations. The bidding documents submitted by the contractor should show the organization’s comprehensive capabilities for the future implementation of the project, such as the organization’s ideas and technical arrangements, the handling of emergencies, and the procurement and deployment of resources.

4.8. The Selection of PDM

According to the activity relationship in DSM, we can not only understand the current delivery method but also design a delivery method that is more suitable for project requirements based on the activity relationship. As mentioned previously, selecting PDM also needs to consider requirements and scenarios. Therefore, after considering the owner’s requirements, appropriate PDM decisions can be made from the DSM.

The characteristics of the case project include many participants, but the owner was incapable of fully managing and has strong time constraints. The partitioned DSM shows that it could be integrated into one block from detailed design to construction completion which means that it can be implemented by one party. The tasks that needed to be transferred and coordinated by the owner were all completed by the contractor when the contractor carried out multi-stage work. The interaction between activities becomes the internal staff’s work with the contractor which will greatly shorten the time and cost of coordination [62]. When the acceleration techniques are adopted, information exchange between personnel

and between subcontractors will become more frequent, and the advantages of integrated delivery methods will become more prominent.

Other goals of the owner included controlling investment and improving medical standards. This determines that control cannot be completely abandoned. Early evaluation of the contractor's ability and deep participation in preliminary design could achieve the owner's goal, and at the same time, it could strengthen the owner's control over the main subsystems and avoid large investment deviation and function deviation.

Therefore, according to the partitioned DSM and opinions of interviewees, this project was suitable for delivery with higher integration such as BD or CM or its variation. The project process of partitioned DSM is shown in Figure 7.

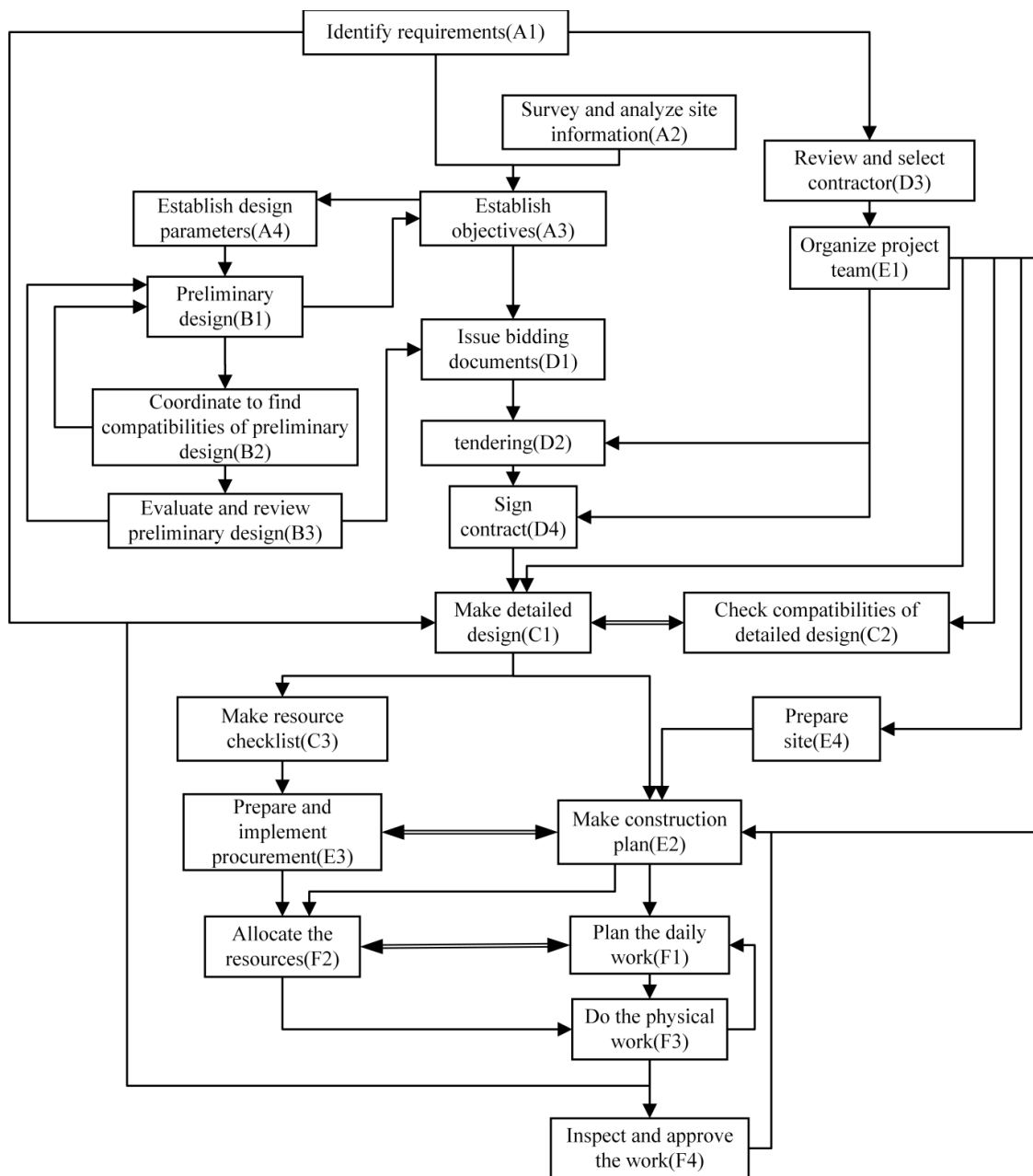


Figure 7. The Project Process based on the partitioned DSM.

This project adopted the EPC delivery method, which is very close to the conclusion obtained by the DSM method. The general contractor was a consortium composed of a design enterprise and a construction enterprise. Both parties participated in the bidding

according to the preliminary design completed by the design enterprise entrusted by the owner, and finally won the bid and undertook the detailed design, raw material procurement, and construction. The professionals dispatched by both parties worked together on-site, which reduced the information transmission path, carried out simulation and error correction in advance, and reduced rework.

5. Discussion

5.1. *The Type of DSM to Be Used*

Successful project implementation needs to understand the project structure and develop and manage a strategy [63]. The selection framework proposed in this study establishes a process model from the relationship between each activity in the construction process and selects the appropriate or optimal delivery method by identifying the relationship between the activities and rearranging the sequence of activities. The framework can also prove the rationality of the selected delivery method or optimize the order of activities in the delivery method.

DSM can be divided into four systems that are interrelated [47]. Which type of DSM to use should depend on the purpose. When only process analysis and optimization are performed, activity-based DSM is used more [64–66]. The parameter-based DSM can better analyze the probability of repetition, the variability of exchanged information, and the impact of iteration [67]. A team-based DSM can clarify how the implementers of various activities communicate and connect with each other. As mentioned earlier, the project delivery method ultimately determines the scope, time, and division of responsibilities of the organization's activities, and limits an organization or group to undertake a single task or multiple related activities. Through appropriate calculations such as partitions and clusters, participants can be combined and divided to achieve the purpose of optimizing the organization. The choice of project delivery method is always a multi-objective optimization problem that needs to be weighed in terms of objectives, management capabilities, and management methods. Constructing a combination of activity-based DSM and team-based DSM under specific target requirements can help decision makers to allocate personnel and responsibilities reasonably.

5.2. *Establishing the DSM under the Requirements of a Particular Project*

Analysis and examples show that the proposed framework helps to select the most objective delivery method or verify the rationality of the delivery method and optimize activities. However, it should be noted that the needs of the owner always have an important influence on the selection process, and even the relationship between the same type of project activities under the different needs of the owner may be different. Therefore, determining the owner's needs is the fundamental requirement for applying this method.

When the project is under high time pressure, finding connections between activities and their intensity to increase activity overlap and reduce rework becomes the main response method. As time becomes the highest priority goal, the division of design phases will be simplified, design and construction need to be partially paralleled, and the information feedback path of activities needs to be redesigned. Based on the relationship between these activities, one can choose the delivery method that can best achieve time compression. When quality becomes the main goal, due to the uniqueness of construction products, more small-scale coupling activity packages need to appear in the delivery method to ensure that product quality is always controllable and form a final product with satisfactory quality.

5.3. *Decomposing the Activities*

This case study only carried out a three-level decomposition because the hospital project was only 13,918 m² and the scale of the project was not large. In order to ensure that it was completed on time, the owners and contractors were willing to use traditional construction technology rather than innovative technology. The workflow was not much

different from regular projects. Project delivery methods vary depending on the scale and technical complexity of the project and will also change during hierarchical decomposition.

Proper decomposition is the key to effectively solving big and difficult problems, which can minimize the interaction between sub-problems [68]. Finding the right level of abstraction to formulate a DSM is not easy since activities can be defined at multiple levels, from very detailed to high-level abstraction [69]. Too much or insufficient task decomposition may lead to management failure. The more decomposition levels, the more specific the underlying activities performed by individuals or small teams. Through continuous decomposition levels, the size of the model increases exponentially, the management organization will increase, and the efficiency will decrease. Too few decomposition levels will result in blurred relationships between activities and unclear division of the management interface. The general rule is to model the process to the level of detail that people want to understand and be able to control the process [47]. The delivery method is expressed as a contract, so it usually only involves the enterprise (sub-enterprise) level and does not need to target individuals or small teams.

5.4. The Expression and Use of Activity Relations

DSM has developed many ways to express the relationship between tasks such as marks, numbers, colors, shadows, etc. This research only uses the most basic markup methods. This expression simply indicates whether there is an interconnection between activities [70]. Other expressions can express more information, such as the probability of overlap or rework between activities [71], interaction strength [72,73], and the duration of the activity [74,75].

In the above information, the connection strength of activities is an important criterion in the choice of project delivery method, especially the delivery method that needs to shorten the project duration. Stronger connections mean that activities can receive more complete information before they can be implemented. Therefore, more effective measures and organizational methods need to be used to ensure the efficiency of information transmission. However, taking additional measures at the same time may bring additional costs. Only when the benefits of relatively strong activity adjustments are greater than the increased costs are adjustments worthwhile, while weak links can be used to diversify risks through contracts and other means. Therefore, follow-up research should deeply analyze the relationship between activity intensity and activity combination from activity intensity.

6. Conclusions

Relationships between activities will become more complicated as building technologies evolve, requiring more flexible delivery methods. A proper PDM will directly affect the effectiveness of the owner's and contractor's organizational arrangements and resource allocation, which will affect the project's success. Therefore, it is necessary to carefully select/design the appropriate PDM at the beginning of the project. Different delivery methods adapt to other activity processes and therefore require different organizational approaches. The delivery method is determined according to the process to maximize the satisfaction of the project requirements. Activity-based DSM can show feedforward and feedback between activities. Operation methods such as partition can optimize and reduce rework caused by information feedback, shorten project duration, and save cost. Depending on the relationship between the activities, the decision maker can choose to delegate certain activities to the appropriate contractor and determine the proper PDM. At the same time, the selected PDM can also be optimized through this framework.

The goal of this paper is to develop an analytical framework that can be used in the early stages of project contracting to demonstrate to participants project activities and the relationships among participants and to support participants' effective allocation and coordination of work. The framework shows the whole process of the project and its activities in a visual way. When decision-makers are faced with specific goals, such as shorter time frames, cost savings, and better organization, this framework can assist

decision-makers in comprehensively reviewing the project and making quick judgments to design the appropriate PDM. The difference between the study and previous studies is that the characteristics of the delivery method are designed from the internal process of the project, rather than extracted from the completed project, which is universal and stable and will not be invalid due to the changes in the project.

In summary, the following managerial insights can be helpful for PDM selection.

Process-based PDM selection can reduce decision-making difficulties caused by changes in project characteristics and complexity and improve the pertinence and universality of PDM.

Applying this method to select an appropriate PDM with an organized structure reduces the subjectivity of decision makers.

The framework visualizes the entire process of the project, helping decision makers comprehensively review the project and make quick decisions.

In the absence of experienced decision makers, or the absence of consensus among decision makers, this research will provide good insights to support the final decision.

This research is associated with the following limitations:

- The research did not consider the intensity of the relationship between activities which directly affects the trade-off between the costs and benefits of activity adjustment and then affects the decision results. The empowerment of association strength should be a direction of further research in the future.
- This research only considered the activity-based DSM; the project team staffing and responsibility assignment should be considered in combination with the organization-based DSM in the future.

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