

Article

Improving Design by Partnering in Engineering–Procurement–Construction (EPC) Hydropower Projects: A Case Study of a Large-Scale Hydropower Project in China

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Abstract: Hydropower, as a renewable energy resource, has become an important way to fit for Chinese long-term energy policy of energy transformation. Engineering–procurement–construction (EPC) has been increasingly adopted for improving hydropower project delivery efficiency in the utilization of water resources and generation of clean energy, where design plays a critical role in project success. Existing studies advocate the need to use partnering for better solutions to designs in EPC hydropower projects. However, there is a lack of a theoretical framework to systematically address design-related issues considering different participants' interactions. This study coherently examined the causal relationships among partnering, design management, design capability, and EPC hydropower project performance by establishing and validating a conceptual model, with the support of data collected from a large-scale EPC hydropower project. Path analysis reveals that partnering can directly promote design management and design capability and exert an effect on design capability through enhancing design management, thereby achieving better hydropower project outcomes. This study's contribution lies in that it theoretically builds the links between intra- and inter-organizational design-related activities by systematically mapping EPC hydropower project performance on partnering, design management, and design capability. These findings also suggest broad practical strategies for participants to optimally integrate their complementary resources into designs to achieve superior hydropower project performance.

Keywords: hydropower development; engineering–procurement–construction (EPC); partnering; design management; design capability; case study



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1. Introduction

The demand for renewable energy in China is growing these years to relieve environmental pressures of CO₂ emissions from fossil fuels [1,2]. The Chinese central government has proposed a long-term energy policy in 2016 to decrease energy consumption per unit of GDP and increase the share of non-fossil fuel energy [3]. Hydropower development is a suitable way to align with the policy for energy transformation based on the abundant hydropower resource in the country [4], and the installed hydropower capacity of China accounts for more than 25% of the world's hydropower resources [5]. Hydropower projects can effectively produce renewable energy, reduce the use of fossil fuels, and bring social and economic benefits with flood control, irrigation, and navigation [6–8]. Normally, hydropower projects are large in scale, with a long implementation period, and project participants are usually confronted with a complex environment and reciprocal interface management among different delivery processes. As a fast-track delivery approach, the

engineering–procurement–construction (EPC) method, with turnkey and design–build contracting methods being its main branches [9], can effectively integrate the management of design, procurement, and construction [10,11]. This method has been increasingly adopted to improve the efficiency of hydropower development in the utilization of water resources and the generation of clean energy worldwide [12–14]. For example, the Yangfanggou project in China, the Coca Codo Sinclair project in Ecuador, the Karuma project in Uganda, the Nadarivatu project in Fiji, and the Karot project in Pakistan are ongoing and completed EPC hydropower projects, which are scattered in Asia, Africa, Latin America, and Oceania.

In EPC projects, the contractor is responsible for design, procurement, and construction tasks [9,13,15–17], in which design plays a critical role in transforming clients' visions into reality and governing procurement and construction activities [18–20]. The designer of an EPC hydropower project needs the competent capability to deal with technical issues and meet significant challenges on social and environmental impacts arising from the diversion of watercourses [21–23]. These require effective design management for incorporating all stakeholders' needs into project designs and appropriately considering the trade-offs among economic, social, and environmental outcomes to align the interests of the stakeholders [24,25]. Due to reciprocal interdependence natures, the lack of synergy among stakeholders has become the main barrier to the efficient delivery of energy projects [26,27]. It is essential for project participants to establish partnering relationships for jointly managing design processes, which facilitates meeting the needs and concerns of stakeholders [28,29]. Partnering is a long-term commitment between organizations for mutual project objectives by maximizing the effectiveness of all participants' resources [30], which is a trust-based relationship that fosters open communication among project participants [31,32]. This can help project participants share their data, information, and knowledge to manage various design processes and enhance designers' capabilities to achieve the EPC project's functional, financial, technical, social, and environmental objectives [25,33].

Although there have been studies into the impact of design management on project outcomes from the perspective of stakeholder collaboration [14,25,34], little research has introduced design capability to coherently demonstrate how designers' capability is affected by partnering approach and design management, as well as their effects on project performance. Thus, the aim of this study is to reveal the causal relationships among partnering, design management, and design capability related to how project performance improvements are created from them, via establishing and validating a conceptual design management model. Understanding the cause–effect relationships will be significant to promote multi-organizational dynamics study to a state of the art and assist project participants in appropriately dealing with designs to improve EPC hydropower project performance [29]. Filling the above research gap can help theoretically understand why real-world EPC hydropower project management activities occur and also practically guide how a designer's resources are organized to achieve the set of project objectives with considering all stakeholders' needs.

The rest of this paper is organized as follows: Section 2 establishes a conceptual model of design management in EPC hydropower projects and presents empirical research questions. Section 3 describes research methods and explains why the case project was selected for in-depth study. Section 4 details the survey results and analysis. Section 5 adopts the path analysis to validate and interpret the relationships among partnering, design management, design capability, and EPC hydropower project performance. Section 6 indicates the contributions of the study and provides strategies for EPC project participants to enhance project performance. The findings with limitations and future work are concluded in Section 7.

2. Conceptual Design Management Model

2.1. Background

Design is crucial to the delivery of an EPC hydropower project, and the designer needs sufficient ability to understand the conceptual design given in bidding documents and fulfill the tasks of preliminary and final designs [14,20]. Designs in EPC projects require reciprocal interactions with procurement and construction [35], and design management involves the designer's work, in addition to inputs from the client, the consulting engineer, the builder, and the suppliers [34,36–38]. These require project participants to partner with each other for collaboratively managing design activities in meeting the required design criteria [39,40]. By maximizing the effectiveness of all project participants' input resources, partnering can enhance the designer's ability in achieving design objectives at the bidding and the implementation stages [29,41]. The above views regard EPC project development as an open system that inputs resources from all participants by partnering, adds values in the resource transformation process with the support of effective design management and competent design capability, and then conveys completed projects with superior performance as output to provide benefits for all stakeholders [42,43]. Accordingly, a conceptual model was established to help understand the causal relationships among partnering, design management, design capability, and hydropower project performance in delivering EPC hydropower projects, as seen in Figure 1.

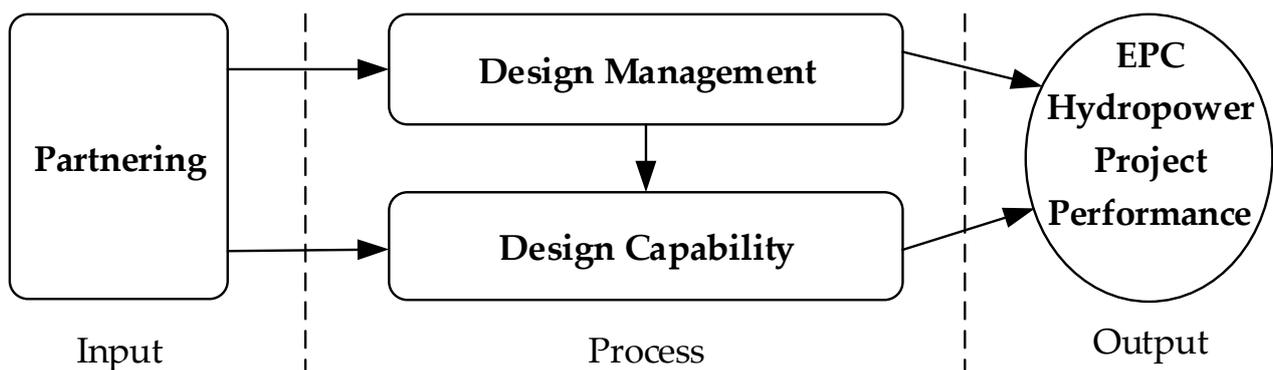


Figure 1. Design management model for delivering EPC hydropower projects.

2.2. Partnering among Project Participants

The partnering strategy has been increasingly popular for the efficiency of the construction industry [30,44,45]. Due to the concurrent nature of EPC projects in conducting design, procurement, and construction activities [20], the use of partnering is indispensable for clients, consulting engineers, builders, designers, and suppliers to cooperatively achieve project objectives [46]. To avoid unsuccessful cooperation caused by problems related to individual and organizational interactions [31], there is a need to identify critical success factors (CSFs) of partnering and understand how the factors are interrelated to facilitate EPC hydropower project performance [32,47]. The identified partnering CSFs include mutual goals, attitude, commitment, equity, trust, openness, team building, effective communication, problem resolution, and timely responsiveness [48–51]. These factors can facilitate participants solving various problems encountered in EPC activities in a timely manner by establishing trust-based relationships, creating openness, and sharing ideas, experiences, and information [41]. The added resources from partnering increase the input of the EPC hydropower development system and help participants to jointly manage design activities and promote innovations in design processes [52].

2.3. Design Management

The EPC contract could not foresee all design conditions in the process of project delivery, and this may cause design-related contract problems, such as unclear design depth and responsibility specification, and claims arising from design changes [28,34,53]. It is necessary to conduct an effective technical audit of designs for controlling design processes, by means of a quality assurance system, design review, and design optimization management [37]. Dealing with these issues involves various project participants, and effective design-related interface management is indispensable to integrate design, procurement, and construction activities simultaneously [54]. There is a need to establish partnering relationships among project participants for proactively seeking optimal design management solutions [25]. Partnering can assist in achieving successful design management to meet all participants' needs and requirements, e.g., designs can be favorable to construction with consideration of resource availability and construction conditions, and design technical specifications can be timely provided for procurement schedule [55,56]. Partnering can also help increase design input by sharing relevant data as well as facilitate design review by incorporating each participant's expertise and experience into the design process, thereby improving design outputs.

2.4. Design Capability

Design capability refers to the degree to which a designer's resources are organized to achieve a set of project objectives that not only meet the needs of the client but sufficiently consider the interests of other stakeholders. Designers of hydropower projects usually face various challenges, such as complex geologic conditions, high dam construction, resettlement plan of affected residents, and ecological environment protection [23,43,57,58]. Specifically, an EPC project designer should have capabilities in clearly understanding the intentions of client/consulting engineer, obtaining sufficient data for design input, meeting technical criteria, selecting financially viable design options, and effectively incorporating the needs of procurement and construction into design processes [25,59,60]. Incompetent design capability may lead to inappropriate design planning, design errors or defects, design rework, poor constructability, high construction cost, and even failing to reach project functional objectives [61–64]. Partnering among project participants can help enhance designers' capability to solve the above design-related problems. Open communication brought forth by partnering can assist designers in thoroughly understanding clients' expectations, and then clearly defining project scopes and functions [65]. Team building between the designer and the builder can help win an EPC project bid, which should be financially viable by choosing the optimal design option, and also helps improve the design's constructability in project implementation [14]. Partnering can help project participants jointly examine the design-related factors within the hydropower projects and in the external environment such as operability, maintainability, occupation health, safety, and impacts on the environment and local communities, thereby meeting the needs and concerns of all stakeholders with win–win philosophy [23].

2.5. Empirical Research Questions

The conceptual model (see Figure 1) demonstrates the cause–effect relationships among partnering, design management, design capability, and how they interact to influence EPC hydropower project performance. To test the model, there is a need to conduct an in-depth survey of EPC hydropower project delivery and answer the following questions about the selected case: (1) To what degree has partnering CSFs been applied among project participants? (2) What is the status of the EPC hydropower project's design management? (3) What are the strengths and weaknesses of the designer's capabilities? (4) What is the performance level of the EPC hydropower project? (5) What are the cause–effect relationships among the above themes?

3. Research Methods

3.1. Choice of the Case of the Yangfanggou Hydropower Project

Hydropower plays an important role in supplying renewable energy for both domestic and international societies by mitigating greenhouse gas emissions [66–69]. The installed hydropower capacity of China reached 352.26 GW in 2018, representing over a quarter of the world's hydropower capacity [70]. The accumulated technological and managerial experience of the Chinese hydropower industry has largely contributed to global hydropower development [4,71,72], and Chinese companies account for over 50% of the global hydropower market, especially in developing countries [73]. Thus, this study focused on the Chinese hydropower industry for empirical data collection. As the Yangfanggou dam is the largest hydropower project that applies the EPC method in China, the project was selected as the case for in-depth study, and all data were collected from this project.

The project plays a key part in utilizing water resources of the midstream of the Yalong River, one of the tributaries of the Yangtze River. The project comprises dams and power plants with a total installed capacity of 1500 MW. The main functions of the project are electricity generation and flood control. The key project participants are the client, the general contractor (the designer–builder alliance consisting of one design company and one construction company), and the consulting engineer.

3.2. Multiple Methods to Collect Data for the Case Study

A case study is an empirical method that investigates contemporary real-life phenomena using multiple sources of evidence [74]. The method can assist to explain how and why real-life things occur [75], which may not be obtained from survey or experimental research [76]. Case studies can be classified into three types—namely, exploratory, descriptive, and explanatory case studies [77]. Explanatory cases, especially complex and multivariate ones, can be deployed for causal studies to test a constructed theory [78]. Due to the sophisticated and reciprocally interacted nature of EPC activities, the Yangfanggou hydropower project was chosen as an explanatory case in this study to test the design management model for delivering EPC hydropower projects (see Figure 1).

Multiple methods for eliciting data in case studies can enhance the reliability of the results [78], as multiple sources of evidence can be validated and complemented with each other. In this study, questionnaires, interviews, direct observation, and project document reviews were used to collect both quantitative and qualitative data, and all data were collected in two field trips to the Yangfanggou hydropower project. The questionnaire was designed based on the above literature review for constructing the conceptual design management model (see Figure 1) and applied a five-point Likert scale to obtain quantifiable data as to partnering, design management, design capability, and EPC hydropower project performance. The respondents were the key management and technical staff from project participants, including the client, the designer–builder alliance, and the consulting engineer. All of them had professional experience involved in the project from different organizations to ensure that the data collected could reliably reflect the status of the project. The fieldwork approach ensured that all sent questionnaires had been collected and the total amount of the received questionnaires is 93 during the two field trips. Excluding invalid questionnaires such as those not completely answered, 83 questionnaires were used for analysis. The distribution of questionnaires is shown in Table 1.

Table 1. The distribution of questionnaires and interviewees.

Role of Respondents	Received Questionnaires	Valid Questionnaires Used for Analysis	Interviewees
The client at the headquarter	10	8	19
The client at the site	34	34	11
The designer–builder alliance	26	22	19
The consulting engineer	23	19	12
Total	93	83	61

Semi-structured interviews were conducted during the field trips, and the themes of the questionnaire were used as interview topics to obtain in-depth qualitative data. A total of 61 technical and managerial experts involved in the project attended the interviews during the field surveys (see Table 1). All interviewed experts were familiar with the case and held important positions in their organizations, such as director, deputy general manager of the company, project manager, department head, and chief engineer. Given the number and profiles of the interviewees (see Table 1), the data collected from interviews can well complement, confirm, and interpret the data extracted from the questionnaire survey [78]. In this study, direct observation was also used to enhance the researchers' understanding of the conditions on design management. Reviewing the collected project documents could help elucidate the project delivery process related to designs. The data collected by the above methods were collectively used to test and explain the design management model for delivering EPC hydropower projects (see Figure 1).

3.3. Data Analysis Techniques

The Statistical Package for Social Science (SPSS 24.0) was used to perform the analysis of questionnaire results. Statistical analysis techniques adopted in this research included consistency test, the sample mean estimation, rank cases, and path analysis.

Cronbach's α is essential to measure the internal consistency reliability [79], and it can be calculated by the following formula [80]:

$$\alpha = \frac{kr}{1 + (k - 1)r} \quad (1)$$

where k is the number of indicators in the scale, and r is the average correlation between pairs of indicators. The selection criteria for Cronbach's α are $0.7 \leq \alpha \leq 0.8$ (acceptable), $0.8 \leq \alpha \leq 0.9$ (good), and $\alpha \geq 0.9$ (excellent) [81].

The mean is the main method used to estimate the value of the population and measure central tendency in behavioral studies [82]. The sample mean of all indicators is reported to estimate ratings and ranked in descending order for the sake of facilitating the understanding of the status of the surveyed themes. The path analysis has been adopted based on linear regression with the results tested using a significance level, which follows the typical level for statistical significance of 0.05, with a level of 0.01 considered highly significant. The data from the interviews and direct observations were used to further confirm and interpret the cause–effect relationships established in Figure 1.

4. Survey Results and Analysis

4.1. Partnering

To investigate the degree to which partnering was applied among project participants, respondents were asked to rate ten CSFs of partnering, where 1 = the lowest degree, and 5 = the highest degree. The results are presented in Table 2.

Table 2. Partnering among project participants.

Factors	Rating	Rank	Cronbach's α
Mutual goals	4.11	1	0.92
Effective communication	4.08	2	
Team building	4.05	3	
Problem resolution	4.02	4	
commitment	4.00	5	
Timely responsiveness	3.99	6	
Equity	3.96	7	
Attitude	3.94	8	
Openness	3.81	9	
Trust	3.80	10	
Average	3.98		

As shown in Table 2, the average rating is 3.98, indicating that partnering is applied to a considerable high level in the Yangfanggou hydropower project. Mutual goals obtain the highest rating (4.11), demonstrating project participants share many common goals and concerns in project delivery. This provides a sound basis for participants to cooperatively fulfill project tasks. Notably, trust has the lowest rating (3.80). This is attributed to that achieving trust is not easy, and the formation of trust requires participants to take satisfactory actions with each other in the whole collaboration period. Interview with managers of client confirms that, due to a low level of trust in the contractor, the client had to increase resources input to monitor the project implementation process, resulting in high transaction costs of project delivery.

4.2. Design Management

Respondents were asked to rate the implementation of design management measures in design-related interface management, technical audit of designs, and design-related contract management. The ratings were on a five-point Likert scale, where 1 = completely not true, and 5 = completely true. The results are shown in Table 3.

Table 3. Design management in the EPC project.

Indicators	Descriptions	Rating	Rank	Cronbach's α
(1) Design-related interface management				
Design constructability	Design options are favorable to construction considering resource availability and site conditions.	4.20	1	0.94
Design documentation	Standardizing the process of managing design documents among project participants.	4.18	3	
Design in meeting procurement requirements	Technical specifications are provided by designers in a timely way for preparing procurement plans, selecting suppliers, equipment manufacturing, and installation.	4.11	6	
Design schedule management	Having made appropriate design plan according to project time objective, and ensuring designs to meet the schedule.	4.08	7	
Management of HSE-related design	Effectively incorporating HSE information into designs to meet the requirements.	3.96	11	
(2) Technical audit of designs				
Internal review	Establishing an internal design review process for quality control, cost assessment, and schedule planning.	4.19	2	0.94
Design quality assurance system	Having a clear quality assurance system for guiding design departments to perform their tasks accordingly.	4.12	4	
External review	Having external expert panels review key design options and give technical suggestions.	4.12	4	
Design optimization	Design optimizations are appropriately proposed and implemented considering site conditions.	4.02	9	

Table 3. Cont.

Indicators	Descriptions	Rating	Rank	Cronbach's α
(3) Design-related contract management				
Design contract management	Design depth and responsibilities are clearly specified in EPC contracts.	4.06	8	
Claim management	Timely process of claims related to design change.	4.01	10	
	Average	4.10		

As shown in Table 3, design constructability obtains the highest rating (4.20), indicating that the designer–builder alliance as the general contractor can effectively integrate design and construction processes. For instance, an interviewed manager of the builder said: “The original design for the width of a working berm could only allow manual operation in construction. After receiving feedback from us, the designer increased one meter wide of the berm to accommodate mechanical operation, saving a lot of construction time and costs”. The other design management measures obtain ratings not lower than 3.96, indicating that design management of the Yangfanggou hydropower project generally performs well in aspects of design-related interface management, technical audit of designs, and design-related contract management.

4.3. Design Capability

To examine the design capability of the general contractor, respondents were asked to score the following design capability indicators in the EPC project on a scale of 1–5, where 1 = completely not true, and 5 = completely true, as shown in Table 4.

Table 4. Design capability of the EPC general contractor.

Indicators	Descriptions	Rating	Rank	Cronbach's α
(1) Preliminary design				
Conceptual design review	Intentions of client/consulting engineers are clearly understood by studying conceptual designs in bidding documents.	4.11	4	0.90
Sufficiency of data	Necessary data for design is obtained.	4.32	1	
Technical feasibility	The preliminary design is technically feasible regarding project objective, scope, and function.	4.20	2	
Financial viability	The design option is financially viable.	4.09	5	
(2) Final design				
Basic design	Major technical solutions are proposed to fulfill basic design tasks and obtain timely approvals from consulting engineers.	4.14	3	
Detailed design	Detailed design calculations, construction drawings, and technical specifications are delivered to fulfill detailed design tasks and obtain timely approvals from consulting engineers.	4.04	7	
Coordination with procurement and construction	Design progress and depth meet the needs of procurement and construction.	4.05	6	
	Average	4.14		

The results in Table 4 reveal that the average rating is 4.14, reflecting the strength of the designer in conceptualizing complex engineering problems and giving appropriate solutions. In the preliminary design, the sufficiency of data ranked first, which is attributed to the fact that the designer has been involved early in the conceptual design and has accumulated adequate data for preliminary design input. With sound data, the uncertainties in the design process can be largely removed, and it is not surprising that the technical feasibility of the preliminary design obtains the second-highest rating. Financial viability has the lowest rating among indicators in the preliminary design stage, showing that financial issues are more challenging than technical concerns for the designer. If provided tender price from the design option is high, the bid of the project may not satisfy the client

and lose competence in bidding. If the quoted building price is low, winning the bid may mean that the contractor loses money.

In the final design, basic design obtains the highest rating (4.14), and this can be attributed to the fact that the technical feasibility of preliminary design provides a sound basis for proposing satisfactory major technical solutions. However, detailed design has the lowest rating of 4.04, and this demonstrates that it is challenging for the designer to meet the requirements of the consulting engineer. To improve the efficiency of the design review process, open communication between the designer and the consulting engineer is needed to better understand each other regarding interpretation of data, design intentions, and theoretical calculation in designs. Coordination with procurement and construction has the second-lowest rating, and this reflects the difficulty in ensuring design progress and depth to meet the needs of procurement and construction due to the specialty complexity of hydropower projects.

4.4. Hydropower Project Performance

To understand the outcomes of the Yangfanggou hydropower project, respondents were asked to rate project performances on a scale of 1–5, where 1 = very poor performance and 5 = very good performance. The results are shown in Table 5.

Table 5. EPC hydropower project performance.

Indicators	Rating	Rank	Cronbach's α
Quality	4.39	1	0.88
Social responsibility	4.33	2	
Safety	4.28	3	
Time	4.26	4	
Health	4.19	5	
Economic benefit	4.17	6	
Environment	4.16	7	
Cost	3.96	8	
Average	4.22		

As seen in Table 5, the average rating is 4.22, showing the project has good performance in general. Quality is rated highest (score = 4.39), demonstrating the effectiveness of executing quality management measures, e.g., a clear quality assurance system has been established for guiding each design department to perform their tasks accordingly (see Table 3). Comparatively, cost performance obtains the lowest rating of 3.96. This is attributed to the EPC hydropower project's unforeseen risks, such as floods, slides of steep slopes, mudflows, and collapses of underground works, making cost control challenging for project participants.

5. Testing the Model

As presented in Tables 2–5, the internal consistency reliability is sufficient for the scale, with the minimum Cronbach's α of 0.88. To further examine the relationships in the conceptual model (see Figure 1), path analysis was conducted in this study. The means of the respective group ratings (including 10 partnering CSFs, 11 design management indicators, 7 design capability indicators, and 7 indicators of EPC hydropower project performance) were used as variables in the path analysis to test the conceptual model. The regression coefficients of each path and the percentage of variance explained are represented by R^2 and summarized in Table 6.

Table 6. Test of mediated relationships among conceptual model components.

Step	Predictors	Criteria	R	R ²	R _a ²	F	β	t
1	P	DM	0.477	0.228	0.218	23.907	0.477 ***	4.890
2	P	DC	0.638	0.407	0.392	27.449	0.363 ***	2.947
3	DM	PP	0.591	0.349	0.333	21.465	0.379 ***	2.960
		DC					0.230 *	2.219
							0.432 ***	3.990

Note: R_a² = adjust R²; β = standardized regression coefficient; P = partnering; DM = design management; DC = design capability; PP = project performance; *** = p < 0.001, ** = p < 0.01, * = p < 0.05.

The results in Table 6 confirm the cause–effect relationships established in the conceptual model, as shown in Figure 2.

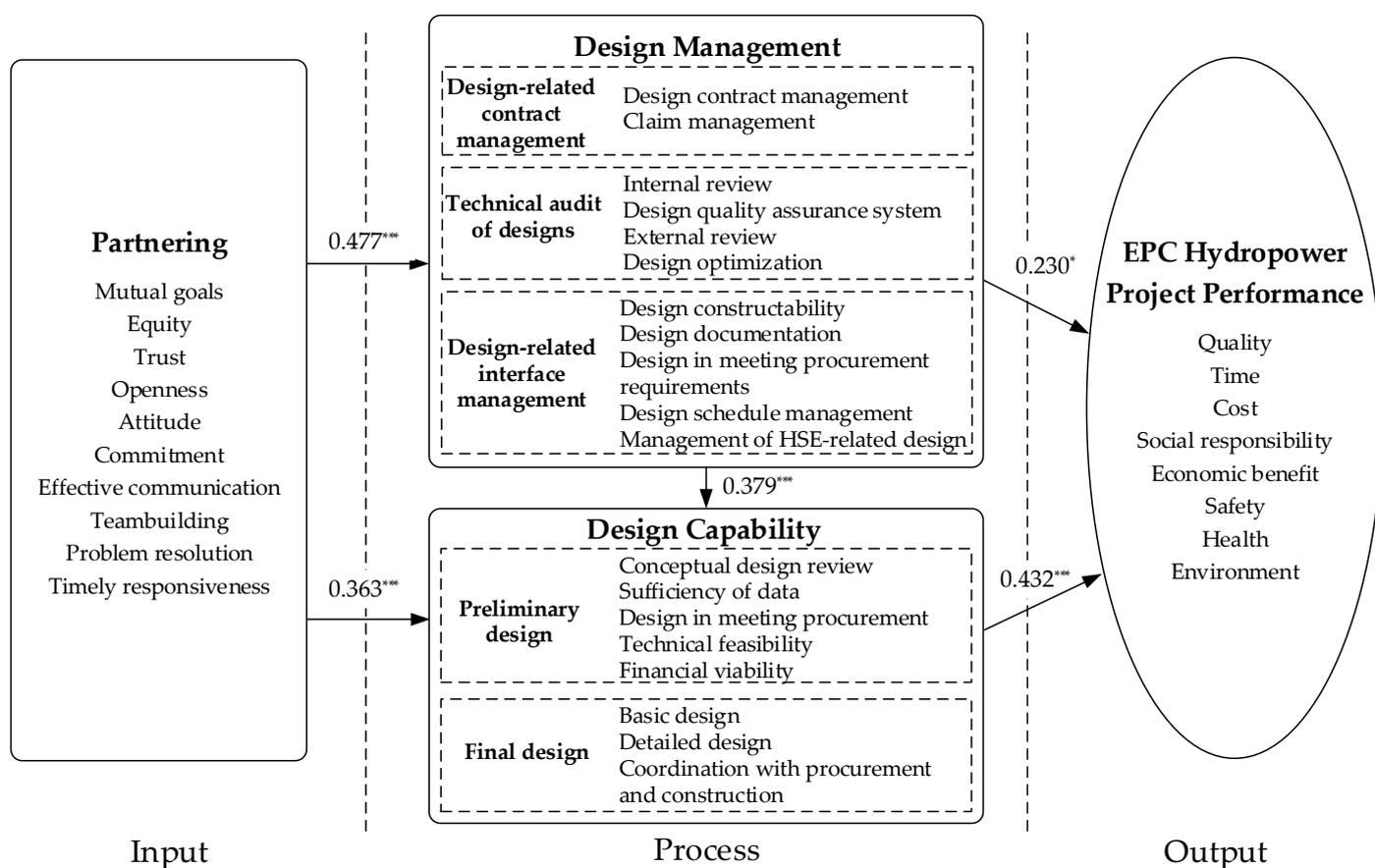


Figure 2. Relationships among partnering, design management, design capability, and hydropower project performance. Note: *** = p < 0.001; ** = p < 0.01; * = p < 0.05.

The path analysis verifies three significant paths from partnering to EPC hydropower project performance (see Figure 2). The first path is partnering → design management → project performance; the second path is partnering → design capability → project performance; the third path is partnering → design management → design capability → project performance. The three paths confirm that partnering among project participants can directly promote design management and design capability and also exert an effect on design capability through enhancing design management, thereby improving project performance, as discussed below.

5.1. Relationship between Partnering and Design Management

As shown in Figure 2, design management is significantly predicted by partnering, with a standardized regression coefficient of 0.477 ($p < 0.001$), showing the strong impact of partnering on design management in the Yangfanggou hydropower project. Interviews with project participants and direct observation during the field trips confirm that partnering can improve design management in aspects of design-related contract management, technical audit of designs, and design-related interface management (see Figure 3).

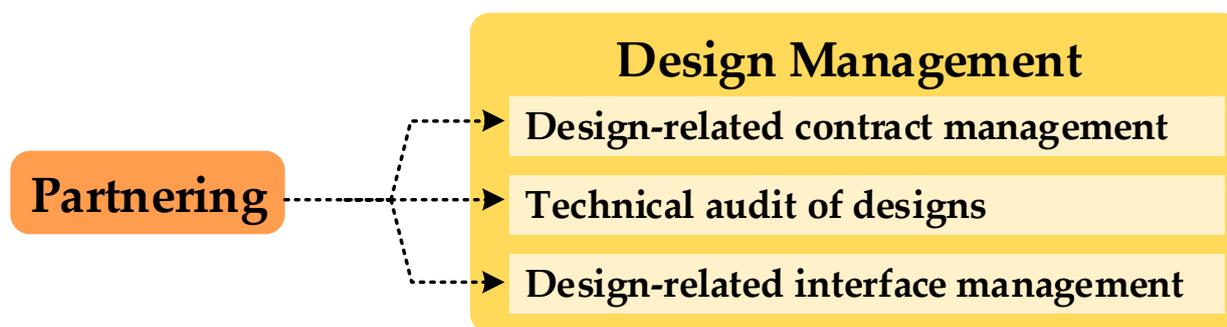


Figure 3. Relationship between partnering and design management.

Firstly, partnering can effectively help project participants deal with design-related contractual issues with a win–win philosophy. On the basis of conceptual design provided by the client/consulting engineer, EPC project design starts with a preliminary design that faces high uncertainties. Although design depth and responsibilities are specified in the EPC contract, the contract clauses cannot foresee all project conditions, and this largely relies on partnering to provide participants with complementary design management support. Interviews confirm that during the Yangfanggou hydropower project, many unforeseen circumstances arose that were not explicitly defined in the contract. All participants need to jointly solve unexpected problems, such as complex geological conditions, unspecified criteria to certain designs and variations. The effect of partnering on design management can be confirmed by very limited resource input in dealing with claims related to design change. A manager from the client contract department indicated that in the Yangfanggou hydropower project, claims and disputes were not a management emphasis because both the client and the contractor focused on an efficient and joint problem resolution and followed the principle of equitably risk allocation without much concern over the other person’s opportunism.

Secondly, partnering can facilitate the technical audit of designs by joint efforts of project participants. Due to mutual goals of partnering, internal and external design review processes were created to ensure all participants effectively contribute their expertise for promoting designs. In the internal review process, a design needs to be reviewed by the builder for construction cost, schedule, and constructability analysis, and then submitted to the consulting engineer for a quality audit. As for key design options, the designer, the consulting engineer, and the client shall organize external expert panels to review the technical reliability of designs, and the feasibility of design optimizations. The interviewed project managers confirm that by sharing participants’ knowledge, experience, and ideas, the partnering attribute of openness can significantly assist in finding solutions to design difficulties.

Thirdly, partnering is essential to improve design-related interface management. Effective communication and timely responsiveness created in partnering can help the designer incorporate technical specifications of equipment and site conditions into designs, thereby appropriately coordinating design, procurement, and construction activities. For instance, the close linkage between the designer and the supplier can ensure progress and depth of the design to reserve the long lead time for manufacturing and installing the

generators in the Yangfanggou hydropower project. The Building Information Management (BIM) system was applied to achieve effective communication and timely responsiveness by exchanging data and information on project activities [83]. With the system, the client and consulting engineer can approve the designs or provide comments, and the builder can conduct constructability analysis for optimizing designs. The BIM system also provides a visual platform for participants to efficiently process and manage design documents in a standardized and reciprocal way.

5.2. Relationship between Partnering and Design Capability

Partnering significantly predicts design capability, with a standardized regression coefficient of 0.363 ($p < 0.001$), confirming the close linkage between partnering and design capability (see Figure 2). The field trip survey shows that the designer established partnering relationships with the client and the builder, respectively, which greatly enhanced the designer's capability in both preliminary and final designs (see Figure 4).

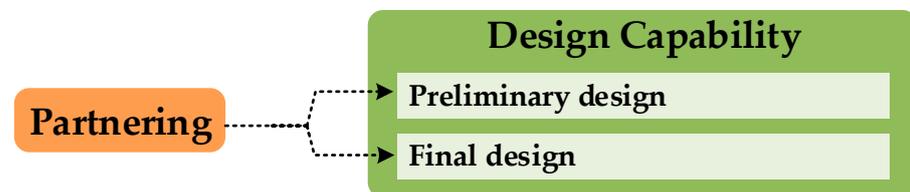


Figure 4. Relationship between partnering and design capability.

Before bidding for the Yangfanggou hydropower project, the designer had successfully designed the client's major hydropower project, the Jinping II project, which has won a significant international engineering award. By winning the trust of the client, the designer obtained the job of conceptual design for the Yangfanggou project from the client. The designer's experience of the conceptual design largely facilitated collecting data and in-depth understanding of the collected data, which can explain the reason why "sufficiency of data" obtains the highest rating of 4.32 (see Table 4). At the bidding stage, the designer and the builder form a close partnering relationship for jointly tendering as an alliancing entity. The designer-builder alliance allows the designer to effectively incorporate the builder's complementary data and information into the preliminary design. Partnering with the client and the builder significantly assists the designer to fulfill the technically and financially feasible preliminary design, thereby helping the designer-builder alliance win the EPC contract.

At the stage of project implementation, the designer's partnering with the client and the builder also greatly improves the final design. To reach the mutual goals of project participants, the designer follows the principles including meeting the functional requirements of the client, complying with design criteria, and controlling construction costs. In dealing with the designer-builder alliance's key concern on construction cost, the client allows the designer to optimize designs for cost reduction by value engineering. If a value engineering proposal presented by the designer can obtain support from both the consulting engineer and external expert panels, the client will approve the optimized design, with all cost savings belonging to the designer-builder alliance. The co-working environment created by the alliance between the designer and the builder facilitates reciprocal design and construction interactions. This effectively assists the designer to integrate the builder's expertise and experience into both basic and detailed designs, making designs favorable for construction with sufficient consideration of resource availability and site conditions.

5.3. Relationship between Design Management and Design Capability

As seen in Figure 2, design management significantly predicts design capability, with a standardized regression coefficient of 0.379 ($p < 0.001$), confirming that design management plays an important role in enhancing design capability in the EPC project. The field trip

investigations reveal that design-related contract management, technical audit of designs, and design-related interface management are all essential to ensure the designer to fulfill tasks for design objectives (see Figure 5).

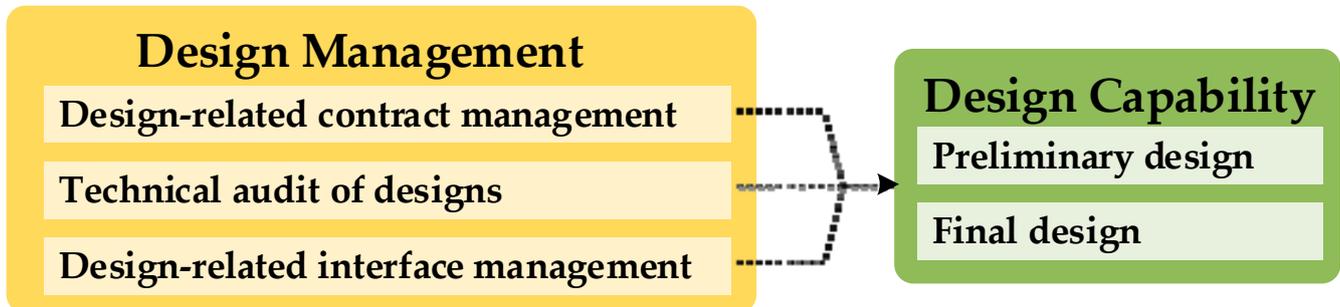


Figure 5. Relationship between design management and design capability.

The EPC contract specifies designers' responsibilities, as well as the design scope and depth in different stages. Design-related contract management largely decides whether designs meet the client's requirements and reach technical standards or not. The design-related contract management is to ensure designs are in line with the contract in the project's functions, scope, and safety reliability. For instance, the client has a considerable concern about the service life of the key equipment such as the generators, and this is the management emphasis of the equipment procurement contract, which can facilitate the designer to choose equipment parameters by mainly considering the operation factor rather than manufacturing costs.

The technical audit of designs is an inter-organizational learning process for the designer, which can effectively promote both basic and detailed designs. In the Yangfanggou hydropower project, the design review processes provide the designer with feedback from the builder, the consulting engineer, the client, and the external experts. This can help find solutions to major technical difficulties, but also reduce design errors and defects such as inappropriate geological treatment and conflicts among civil, mechanical, and electrical drawings. For example, in dealing with the steep slope nearing the dam, all project participants jointly reviewed the design option of the treatment and then changed the original design from reinforcing the whole slope to cutting a large part of the slope and then reinforcing the rest, which is more cost effective.

Design-related interface management is indispensable to integrate procurement and construction needs into designs. In the Yangfanggou hydropower project, a notable measure to integrated management of design and construction is that each design drawing should be reviewed by the builder regarding constructability, construction cost, and schedule before being submitted to the consulting engineer and the client. Interviews indicate that this design management approach can greatly help the designer absorb the builder's technical strength, experience, available resources, and feedback of site conditions, thereby improving design constructability and promoting value engineering for cost saving. As to integrated management of design and procurement, the measure in the Yangfanggou hydropower project is that the designer-builder alliance and the client jointly procure the key equipment. In this process, the feedback from the suppliers can help the designer to prepare the equipment specifications in a timely way to meet the lead time of the equipment's manufacture and installation. The designer's reviewing technical documents from suppliers can ensure the equipment strictly realize the design intentions and meet the needs of the client.

5.4. Impacts of Design Management and Design Capability on EPC Hydropower Project Performance

As shown in Figure 2, design management and design capability significantly predict project performance with standardized regression coefficients of 0.230 ($p < 0.05$) and 0.432 ($p < 0.001$), respectively, verifying that both design management measures and the designer's capability have great impacts on overall hydropower project performance (see Figure 6).

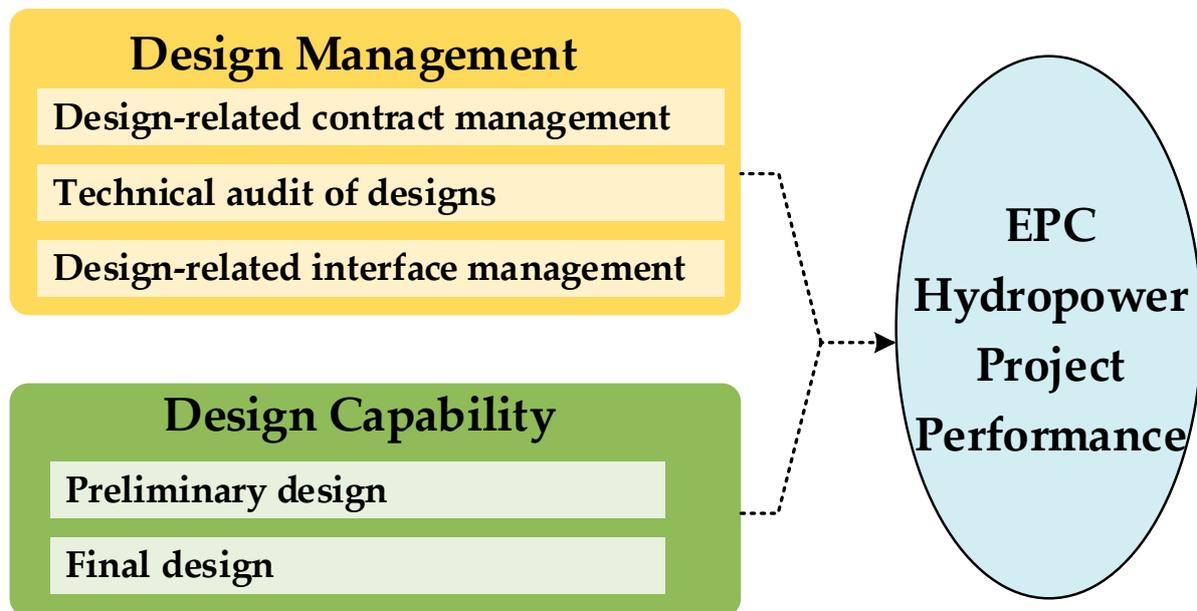


Figure 6. Impacts of design management and design capability on EPC hydropower project performance.

All design management measures are closely related to project outcomes. The project objectives specified in the EPC contract form the basis of the design plan, and design-related contract management, technical audit of designs, and design-related interface management are essential to ensure effective execution of the design plan to achieve project quality, cost, time, and HSE objectives. For instance, internal and external design reviews are indispensable in avoiding design errors and defects to reach high-quality performance.

Design capability's strong influence on hydropower project performance is attributed to the fact that, as design governs the whole project delivery processes, the extent to which the designer is able to achieve the goals of design can largely decide the overall project performance. In the Yangfanggou hydropower project, the designer has the appropriate capability to achieve satisfactory designs, and this can effectively ensure project safety, reduce the build costs by design optimization, and improve delivery efficiency through design with good constructability, thereby achieving superior project performance, as shown in Figure 7. For example, due to the designer's expertise in dealing with the geological conditions of the project, the designed early warnings and response measures for slope treatment (see Figure 7) are effective in improving the HSE performance of the Yangfanggou hydropower project.



Figure 7. The Yangfanggou hydropower project.

6. Discussion

6.1. Contributions to the Body of Knowledge

Design plays a critical role in EPC hydropower project delivery and involves all project stakeholders. Although the impacts of partnering and design management on the international EPC project outcomes have been studied [14,25,34], there is a lack of a theoretical framework that incorporates design capability to systematically address the design-related issues considering different participants' needs with the support of rigorous empirical evidence. This study fills this gap and makes significant theoretical and practical contributions to the body of knowledge, demonstrating how and why real-world EPC hydropower project management activities occur.

Firstly, this study established the design management model for delivering EPC hydropower projects and systematically mapped project performance on partnering, design management, and design capability from a holistic view, which theoretically builds the links between intra- and inter-organizational design-related activities. Secondly, this study validated the causal relationships built in the model and revealed that partnering can directly promote design management and design capability, but also exert an effect on design capability through enhancing design management, thereby improving project performance. Thirdly, the survey results provide both quantitative and qualitative lines of evidence that reflect the status of design-related activities in EPC hydropower project implementation and form a sound basis for participants' management improvement. Fourthly, the above findings suggest broad strategies for participants to optimally integrate their complementary resources to achieve superior EPC hydropower project performance for a more efficient generation of clean energy.

6.2. Strategies for Improving EPC Hydropower Project Development

1. Fostering trust-based relationships among hydropower project stakeholders

Among partnering CSFs, trust obtains the lowest rating (see Table 2), suggesting the need to foster trust-based partnering relationships among project stakeholders in EPC project delivery. The client should follow the principle of equitably allocating the rewards/risks in awarding the contract, and the designer–builder alliance should competently fulfill the tasks as specified in it. In dealing with unforeseen issues not explicitly defined in the contract, both parties need to jointly seek satisfactory solutions rather than take opportunism behaviors by making use of the uncertainties. From a broader view, trust-based relationships among stakeholders should facilitate local communities' participation and understanding of factors of environmental sustainability, and enable designers to

incorporate all stakeholders' needs into designs for jointly seeking Pareto optimal solutions to social, economic, and environmental gains from sustainable hydropower development.

2. Improving design management by utilizing all participants' expertise for audit of designs

Due to the fast-track nature of EPC project delivery, design management is critical to assure design quality. Collaborative design review processes should be established to ensure all participants audit designs for avoiding design defects and errors. Linkages among project participants should be created to facilitate both intra- and inter-organizational review processes in effectively incorporating the expertise of the builder, equipment suppliers, the consulting engineer, external experts, and the client into designs.

3. Enhancing design capability by partnering in EPC project delivery

Design capability reflects the extent to which the designer achieves design goals in EPC project delivery. It is closely related to the cooperation between the designer and the client as well as the builder. Open communication among participants should be created by the partnering approach. This will help the designer clearly understand the client's intentions and sufficiently use the client's accumulated data to provide technically and financially feasible designs. The designer and the builder can form an alliance such as in the Yangfanggou hydropower project, in which both parties share rewards/risks and work as a team, thereby helping the designer to fit in the builder's expertise and feedback for improving design constructability and reducing build cost.

4. Improving interface management with technical support of the BIM system

Interface management is essential to integrate diverse design, procurement, and construction processes. Dealing with the data contributed by all project stakeholders requires the technical support of information management. The BIM system should be appropriately developed to fit the nature of hydropower projects and support EPC project participants' reciprocal interactions. It should incorporate the data on the natural environment (e.g., geological conditions, hydrology, aquatic and terrestrial biota, water quality, sediments, and local climate) and local society (e.g., area of inundation land, affected communities, livelihoods of local residents, and infrastructures). The BIM system should visualize the designs of the dam, underground works, and power plants, and can be a co-working platform that assists the designer, the builder, equipment manufacturer, the consulting engineer, and the client to efficiently mine and exchange data for fast processing, optimal decision making, and more innovation in hydropower development activities.

7. Conclusions

7.1. Findings

In general, the relationships demonstrated in the design management model were tested and confirmed (see Figure 2), and the major findings are as follows: Path analysis validated the design management model and illustrated three significant paths from partnering to EPC hydropower project performance: (1) partnering → design management → project performance; (2) partnering → design capability → project performance; (3) partnering → design management → design capability → project performance (see Figure 2). The first path is in line with the finding of Wang et al. [25], and the second and third paths fill the gap of the absence of a coherent framework demonstrating how designers' capability is associated with partnering, design management, and project performance.

Partnering can effectively facilitate participants' design-related contract management with a win-win philosophy and assist technical audit of designs by contributing their expertise to promote designs. Partnering is also essential to improve design-related interface management by helping the designer incorporate equipment specifications and construction conditions into design processes, thereby appropriately coordinating design, procurement, and construction activities. Cooperation between the designer and the client can help the designer clearly understand the client's intentions and sufficiently utilize the

client's accumulated data to fulfill technically and financially feasible designs. The alliance formed by the designer and the builder can help combine both parties' complementary capabilities to win the EPC contract in bidding and assist the designer to integrate the builder's expertise and feedback into final designs in the project implementation for facilitating design options' constructability and build costs. Both design management measures and the designer's capability have great impacts on project outcomes. This is because design governs the whole process of EPC project delivery, and participants' joint efforts in achieving the goals of design can largely decide the overall project performance.

The survey results outline the status of partnering, design management, design capability, and project performance in the Yangfanggou hydropower project. The average rating of 10 partnering CSFs is 3.98, indicating that partnering is applied to a considerable high level in the Yangfanggou hydropower project. Design management performs well, in general, and mainly involves design-related contract management, technical audit of designs, and design-related interface management. The average rating of design capability indicators is 4.14, reflecting the strength of the designer in conceptualizing complex engineering problems and providing appropriate solutions. Notably, financial viability has the lowest rating of 4.09 among indicators in the preliminary design, and this indicates that financial issues are more challenging than technical concerns for the designer in preparing bidding documents.

The above insights have significant theoretical and practical implications, suggesting the following strategies for improving EPC hydropower project delivery: (1) fostering trust-based relationships among project stakeholders for jointly seeking Pareto optimal solutions to social, economic, and environmental gains from sustainable hydropower development; (2) improving design management by utilizing all participants' expertise for audit of designs; (3) enhancing designer's capability by partnering with the client and forming an alliance with the builder for incorporating complementary data and information into designs; (4) improving interface management of design, procurement, and construction with technical support of BIM system that incorporates the data from project participants, local society, and natural environment.

7.2. Limitations and Future Research Directions

The collective insights of this research were derived from the perspective of the Chinese hydropower project participants in EPC hydropower project delivery, and the results are based on the data only collected from the Yangfanggou hydropower project. Nevertheless, the insights of the study established global experience via the literature and are expected to be transferable to both domestic and international EPC hydropower projects. Future studies are needed to test them by the data collected from other EPC hydropower projects worldwide.

The insights of this study suggest future research emphasis on design management in delivering EPC hydropower projects, including (1) how to incorporate all stakeholders' needs into designs to align the objectives of hydropower development associated with economic, social, and environmental sustainability; (2) how to establish partnering relationships among different project participants for utilizing all expertise to improve the design of EPC hydropower projects; (3) how to improve integrated management of design, procurement, and construction with the support of information technology; (4) how a designer and a builder form an alliance in achieving superior project performance and establish a long-term strategic partnership in expanding share of the market.

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