International Journal of Strategic Property Management
ISSN: 1648-715X / eISSN: 1648-9179
2023 Volume 27 Issue 2: 133–145
https://doi.org/10.3846/ijspm.2023.19180

# PERFORMANCE-BASED PAYMENT STRUCTURAL DESIGN FOR INFRASTRUCTURE PPP PROJECTS

Limin SU [1], Yongchao CAO [2,*], Huimin LI [3]

[1] *School of Mathematics and Statistics, North China University of Water Resources and Electric Power, Zhengzhou, PR China*
[2] *School of Management and Economics, North China University of Water Resources and Electric Power, Zhengzhou, PR China*
[3] *Department of Construction Engineering and Management, North China University of Water Resources and Electric Power, Zhengzhou, PR China*

Received 19 October 2022; accepted 27 April 2023

**Abstract.** The performance-based payment structure has been widely used in infrastructure PPP projects. However, existing research has been absent on the structural unbalance problem of performance-based payment in the current infrastructure PPP projects. This study aims to construct an optimal proportion of the performance-based payment in the total payment, and then design a performance-based payment structure for infrastructure PPP projects. Firstly, the definition of the performance-linked rate is introduced to characterize the proportion of the performance-based payment. Secondly, based on the different objectives of the maximum social benefit and the minimum cost for the public and private sectors, a multi-objective optimization model is constructed to obtain a reasonable value range of the performance-linked rate. Thirdly, the impacts on different parameters in the performance-linked rate are revealed using simulation methods. Finally, the numerical and simulation results show that, for the weak social average ability, the social cost is also high, and a large performance-linked rate should be set. Conversely, when the social average ability is strong, the social average cost is relatively reduced, and a relatively low performance-linked rate should be set. Consequently, the results can guide the contract design in PPP projects.

**Keywords:** payment structure, performance-linked rate, infrastructure PPP projects, social average cost, social average ability.

## Introduction

PPP (Public-Private-Partnership) is a way of cooperation between the public and private sectors (Chan et al., 2018; Cui et al., 2018), which is a long-term contractual relationship between them for construction and operation infrastructures and utilities (Yescombe, 2007). And the participation of the private sector can not only ease the financial pressure from government but also solve the problems of professional service (Engel et al., 2013; Feng et al., 2016; Niu & Zhang, 2013). The PPP model can give full play to the functional advantages of the public and the private sectors and promotes the continuous improvement of the supply quality and service efficiency of infrastructure through introducing the experience and advanced technology management of the private sector (Li et al., 2022). Thus, the private sector's participation in process of the operation and maintenance is of great significance to the sustainable development of infrastructure projects (Shang & Abdel Aziz, 2020).

In the initial stage of PPP projects, the transportation PPP projects in the USA mainly relied on the investment from the private sector, and the private sector's certain return is obtained through user payment (Shi et al., 2020), and then more and more attention are paid to improve the operation efficiency of projects through introducing funds, advanced technologies, and management experiences from the private sector (Li et al., 2022). The development trend of demand-based PPP projects has changed to performance-based payment in many fields (Shang & Abdel Aziz, 2018), and it is also called availability payment. In the performance-based PPP modes, the availability payment is a classical performance-based way (Shang & Abdel Aziz, 2020). According to the

*Corresponding author. E-mail: *18638188626@163.com*

performance-based PPP agreement, the private sector can obtain a certain proportion of payment by paying more effort to improve the requirements of performance evaluation in a franchise agreement. In other words, the amount of performance-based payment mainly depends on the corresponding performance evaluation objectives in the PPP franchise agreement. In essence, it is a core work of the PPP franchise agreement (HM Treasury, 2007). Therefore, the private sector would pay more effort into improve the service qualities, to obtain more performance income in the operation and maintenance process and more subsidy income from the public sector.

The payment structure is commonly composed of the fixed payment and the performance payment in the infrastructure PPP projects, where the fixed payment is the unconditional paid periodically from the public sector once the construction works are completed, and the performance payment is paid to the private sector according to the performance evaluation results in the performance appraisal stage (Higuchi, 2019; Soliño & Albornoz, 2021; Yescombe, 2007). A large number of practices show that an appropriate payment structure can enable the private sector to get reasonable subsidies (Shi et al., 2020; Soliño & Albornoz, 2021; Zhang et al., 2022). Meanwhile, the social utility of PPP projects can be improved, and then the sustainable and healthy development of infrastructure PPP projects can also be achieved (Soliño & Albornoz, 2021; Zhang et al., 2022). Moreover, the payment structure with performance payment is called the performance-based structure, where the proportion of the performance payment in the total payment is called the performance-linked rate in this study. In fact, the performance-linked rate is the risk allocation between the public and private sectors in the operation and maintenance period of the projects. Specifically, if the performance-linked rate is too large, then the proportion of the performance payment in the total payment is too high, and the private sector's risk from the subsidy income increases since the performance evaluation results are uncertain. Conversely, for a low performance-linked rate, it will mean that the private sector's fixed income is too large, which would decrease the private sector's enthusiasm to improve the performance level, and even cause the output target cannot reach and lead to the loss of social welfare. That is, the low performance-linked rate makes the public sector take excessive risks.

So a problem naturally comes up, how to set up the ratio of the performance payment to the total payment to obtain a reasonable way of risk allocation between the public sector and the private sector. In current infrastructure PPP projects, there is performance insufficient or arbitrary phenomenon in the setting performance-linked rate. Particularly, in most cases, the performance-linked rate is determined even mainly based only on the experience of managers in the practical operation and maintenance process of infrastructure PPP projects. Based on the principal-agent theory, Soliño and Albornoz (2021) studied the transfer of risks by combining a fixed payment to the contractor, a payment based on service quality, and a payment relating to the number of users in a transport PPP project. Shang and Abdel Aziz (2020) proposed a Stackelberg game theory-based model to consider the owner's goals in the project, allocate risks appropriately to stakeholders, and assure satisfactory performance by providing reasonable compensation to the private developer in transportation PPP projects. The existing research to date have focused on the constructed payment structure, while the research on the performance-linked rate is nearly blank in the design of the performance-based payment structure, and its calculate method is even rarely studied.

Based on the above analyses, this study will design the performance-linked rate from a theoretical perspective, which mainly provide an appropriate method of risk sharing between the public sector and the private sector. To achieve this aim, this study will carried out from the following three procedures: (1) The definition is introduced. A new definition of the performance-linked rate is introduced, which characterizes the performance proportion between the public sector's performance payment and the private sector's performance appraisal result. It will balance the public sector's demand objective and the private sector's investment risk. (2) The model to obtain the performance-linked rate is developed. To obtain a reasonable performance-linked rate, a multi-objective optimization model is constructed, which can meet the needs of both the public and private sectors, that is, the public sector hope the maximum social benefits and the private sector hope the minimum total cost. (3) The constructed model is solved. The extremum method is used to solve the multi-objective optimization model, and the results is analyzed by simulation methods. Finally, the conclusions are given and the further research of this study are discussed. The main contributions of this study is as follows: (1) A calculate method for the performance-linked rate is proposed, which provide an optimization method for the risk allocation between the public and private sectors from the theoretical level, and (2) theoretically, it enriches the performance-based payment mechanism of PPP projects. A reasonable performance-linked rate can determine the fixed payment and the ratio of the performance payment in total payment, and it will prompt the private sector pay more effort to obtain more performance income, and then realize the rational risk allocation between the public sector and the private sector.

The structure of this study is organized as follows. Section 1 gives literature reviews recalling the status of domestic and foreign research of the performance-based payment for infrastructure PPP projects. The performance-based payment structure is designed including the definition of performance-linked rate, the principle of payment structure and the construction payment structure model solving the performance-linked rate in Section 2. Section 3 gives a numerical simulation to verify the science and reasonable of the constructed. The discussions and implications, conclusions are presented in Section 4 and the last section, respectively.

## 1. Literature reviews

### 1.1. Performance-based payment structure in PPP projects

In general, a successful payment mechanism is closely related to performance appraisal objectives, performance appraisal proportion, key performance indicators and performance evaluation results, and so on. From the existing research, the performance evaluation of PPP projects is not only the basis of performance-based payment for the government to the private sector, but also the key to realizing the "initial intention" of PPP projects to increase the effective supply of public services. In the implementation process of PPP projects, the key to successful implementation lies in effective performance evaluation and supervision of the projects (Beatham et al., 2004; Liu et al., 2015; Martinez & Rodriguez, 2016; Narbaev, 2022). Yu et al. (2007) emphasized the key role of the index system and evaluation model in PPP projects performance evaluation, which directly reflect the real evaluation results of projects. Yuan et al. (2012) pointed out that key performance indicators are the core elements of performance management, which is regarded as a scientific and effective method to realize the value for money of PPP projects. However, PPP projects often lack effective performance evaluation (Xu et al., 2020). Salimian et al. (2022) presented an interval-valued intuitionistic fuzzy multi-criteria decision-making to evaluate and select the suitable alternative in Infrastructure projects.

Wang and Zhao (2018) studied the impact of performance on contractual arrangements of PPP projects, and further concluded that policy change is also a factor affecting PPP project performance. Through semi-structured interviews and multi-case comparisons, Lawther and Martin (2014) found that insufficient performance supervision resources and inconsistent interpretation of output standards of projects may lead to unreasonable payment in PFI projects.

Obviously, the payment from the government depends on the corresponding performance level, and the effective payment mechanism lies in whether the design of the performance linkage rate is scientific, reasonable, and easy to implement. It is reasonable to reduce the payment proportion due to insufficient performance levels in infrastructure PPP projects. Ng and Wong (2007) proved it by a case study in the operation and maintenance process of PPP projects. Through an experiment, Liang et al. (2020) discussed the impacts of the relationship between compensation and performance on the degree of shareholders' support for compensation schemes. It is found that shareholders preferred the compensation schemes with the close relationship between compensation and performance. Additionally, the supervision strength from the government has a great impact on performance. The government monitors the operation and maintenance service quality of the private sector in real time, and adjusts its payment amount to the private sector according to the performance-linked proportion in the PPP contract. Especially, the government will take penalty measures if the performance level fails to meet the requirements of the performance standard.

Different from traditional infrastructure projects, the essence of PPP projects is to improve the quality and quantity of public services and public goods by introducing the funds and management technology of private sectors, and paying more attention to the risk allocation between government and private sectors (Cheung et al., 2010). And the payment mainly depends on the output of performance. Actually, the availability payment is the most frequently used model for performance-based payment (Shang & Abdel Aziz, 2020; Soliño & Albornoz, 2021), which is more applicable to public infrastructure projects.

The payment structure of DBFO (Design Build Finance Operate) transportation projects with performance-based payment mainly includes capital-based payment (with payment or without payment during the construction period) and service-based payment (including availability, operation and maintenance services, traffic management, safety, and user satisfaction) (Aziz & Abdelhalim, 2017; Abdel Aziz, 2007). Additionally, for user paid projects, the payment mechanism of PPP projects with performance-based can also be included to improve the expected objectives of the projects. The government expects to improve social benefits through projects, and the private sector expects to obtain greater benefits in market competition (Yuan et al., 2021), and the benefit is obtained through the public budget composed of the tax from taxpayers and the payment from users.

Obviously, the existing research has provided a large amount of theoretical support for the performance-based payment structure. However, few research focuses on the performance-linked rate in the design process of the payment structure. That is, the proportion allocation between the fixed payment and the performance payment has not yet been fully considered. Therefore, it is necessary to improve the research on payment structure in infrastructure PPP projects, which will mainly be carried out on the performance-linked rate for the performance payment and the performance appraisal results.

### 1.2. Risk allocation in PPP projects

Risk allocation among the contracting parties is implied in any contract with public services (Wang et al., 2018; Ding & Li, 2022). The risks in projects mainly include two kinds: demand risk and performance risk (George & Matt, 2019), where the characterization and management of the demand risk had been studied (Eliasson & Fosgerau, 2013; Flyvbjerg et al., 2005; Roumboutsos & Pantelias, 2015). Generally, most of the technical and economic risks, such as the construction risks during the initial stages of the contract or variation risks of the operating costs, will be borne by the contractors, and the public sector should take the political risks or other situations because of natural disasters and other force majeure (Yescombe, 2007).

In recent decades, many studies on risk allocation between the public and private sectors have appeared. Ng and Loosemore (2007), and Chung and Hensher (2015) studied the risk sharing between the government and the private sector in the Australian highway PPP project, and put forward that a reasonable risk sharing scheme plays a positive role in project risk management. Carbonara et al. (2014) developed a real option-based model to balance the private sector's profitability needs and the public sector's fiscal management interests. To better ensure the achievement of a win–win condition, Pellegrino (2021) proposed a structured model for assessing and benchmarking the impact of different public supports, which releases to mitigate revenue risk in PPP projects from the standpoints of the private and public sectors. Iyer and Sagheer (2011) studied the relationship between traffic volume and concession period of Indian highway BOT projects, and analyzed the risk sharing to protect the interests of all participants by constructing a concession agreement model. Taking the PPP model of 11 kindergartens in Kazakhstan as the survey object, Mouraviev and Kakabadse (2014) found that the government paid a large transfer cost and handed most of the risks to the private sector. By introducing the reciprocal preference theory, Wang et al. (2018) established an optimal incentive mechanism to analyze the risk-sharing ratio. Through investigating the 4,484 PPP projects across 130 developing countries, Wang et al. (2019) also studied whether and how distinct types of the government support can attract more investment from the private sector, in which the results showed that risk allocation plays an important role between the government supports and the investment from the private sector. Also, by establishing a risk-sharing game model for the sewage treatment PPP project, Song et al. (2020) constructed a risk-sharing scheme among the government, contractors, and financial institutions. Additionally, some research found that risks should be shared between the government and the private sector, rather than transferred to one party (Ameyaw & Chan, 2016).

To be sure, in the process of PPP project negotiation, the right inducement and information asymmetry are easy to affect risk sharing, and fair risk sharing depends on many factors, such as the ability of risk management and the attitude of stakeholders towards risk. Therefore, it should effectively control the project risk through risk sharing and realize value for money, and allocate the risk to the party with the strongest risk control ability and the lowest control cost (Tao & Zhao, 2011).

An effective risk allocation between the public and private sectors has been paid more and more attention in PPP projects. Ng and Loosemore (2007) analyzed the rationale behind decisions about risk distributions between the public and private sectors and their consequences. The greatest difficulty of risk sharing is the risks arising from the service demand that are significantly different from the originally predicted service demand (demand risk) and should be transformed to one of the parties whether in full or shared (Soliño & Albornoz, 2021). Another risk is performance risk transferred to the private sector, which mainly depended on the performance evaluation standard in the contract and the performance level of the private sector. The transfer of the performance risks is carried out in terms of payment to the private sector according to their performance level (Soliño & Albornoz, 2021).

Relevant scholars discussed the necessity of clearly stipulated in the contract conditions that non-performance of the contract will be punished. Such punishment aims to force the contractor to bear controllable risks, to motivate and improve the performance of the project contractor, and ensure that the government has value for money (Abdel Aziz, 2007). And most studies discussed the design of payment structure from a different perspective. For example, availability payment (Mladenovic & Queiroz, 2014; Sharma & Cui, 2012), and security payment (Rangel et al., 2012; Vassallo & Gallego, 2005). Zhu and Cui (2014) constructed the availability payment design model based on bi-level stochastic dynamic programming. Abdel Aziz (2007) proposed a hybrid payment mechanism framework with a hybrid payment. Cui et al. (2017) proposed a two-layer stochastic model to maximize the availability payment for roads and optimize the deduction of the total payment amount and availability payment design. Some subsequent studies continue to introduce the implementation of mixed payment through case studies and contract analysis (Shang & Abdel Aziz, 2018).

From the current practice, most of the performance-based structure adopted in infrastructure PPP projects is mainly divided into fixed payment and performance payment (Abdel Aziz, 2007; Cui et al., 2017; Soliño & Albornoz, 2021; Zhu & Cui, 2014). Generally, the proportion of the fixed payment is too high and that of the performance payment is too low, which will lead to the incentive effect of payment from the public sector can not be used effectively. A natural problem here is how to allocate the fixed payment and performance payment. However, at present, there is also insufficient research on linking the objectives of the projects with PPP payment, and few research design payment structures scientifically through determining reasonable performance-liked rate.

Based on this, a problem should be solved: how to innovate the payment structure to fill in gaps on research without the proportion of the fixed payment and performance payment in the existing payment structure, which is of great significance to the design of the performance-based contract.

## 2. Research methodology

This section presents the method of designing the performance-based payment structure. The performance appraisal will be conducted during the operation and maintenance period of the projects but not during the construction period, where a part of the profit of the private sector will be linked to the performance appraisal results in the operation and maintenance period.

### 2.1. Problem description of the design for the performance-based payment structure

The design of the performance-based payment structure for infrastructure PPP projects is how the public sector pays to the private sector according to the performance for the operation and maintenance services of the private sector, in which the performance-linked rate is the key factor. The percentage of the payment of the performance-linked part in the total payment is regarded as the performance-linked rate. In other words, the payment from the public sector will be linked to the performance appraisal results of the private sector in the operation and maintenance process. The payment of the linked part is called the performance payment, and the proportion of the performance payment in total payment is performance-linked rate, which is the basis of the design of the performance-based payment structure, as shown in Figure 1. Specifically, if $P$ and $B$ denote the total payment and performance payment from the public sector, then the performance-linked rate is $b = \frac{B}{P} \times 100\%$. As shown in Figure 1, the total payment $P$ is the sum of the performance payment $P \times b$ and the fixed payment $P \times (1 - b)$. And the performance payment $P \times b$ is a function of the performance-based rate $b$. That is, the size of the performance payment $P \times b$ increases from $P \times b_1$ to $P \times b_2$ as the performance-based rate $b$ increases from $b_1$ to $b_2$, and the size of the fixed payment $P \times (1 - b)$ decreases from $P \times (1 - b_1)$ to $P \times (1 - b_2)$. A perfect performance structure needs to have a proper the performance-linked rate, which balances the interests between the different goals of the public and private sectors.

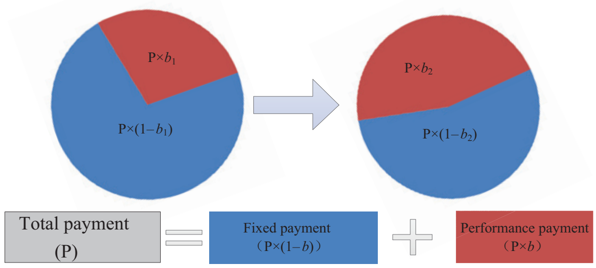



Figure 1. The structure of performance-based payment

### 2.2. The principle of payment structure

For the infrastructure PPP projects, the key for the public sector is to design the payment mechanism, which enables the private sector to continuously improve its work performance based on recovering the construction and operation and maintenance costs and obtaining the expected profits (An et al., 2018). The design of the payment mechanism for the infrastructure PPP projects shall follow four principles: attracting private sectors, the win-win between the public and private sectors, value for money, and proper sharing of risks. The purpose of introducing PPP mode into infrastructure projects is to attract the private sector to actively participate in the construction, operation and maintenance, and meeting their interests is the direct motivation for the private sector to actively invest in the project. A reasonable payment mechanism can not only attract the private sector to participate in the project but also ensure the smooth implementation of the project (Su et al., 2022).

From the practice of the project, the main driving force for the private sector to participate in the operation and maintenance of the project is to obtain relatively stable investment profits through establishing a long-term cooperative relationship with the public sector. Since the private sector is profit-driven, it hopes to obtain the maximum benefits at the minimum cost during the operation and maintenance period (Sang et al., 2019). And the government hopes to achieve the maximum social benefits, that is, the government wants the private sector to actively improve performance level of the project. When the performance appraisal results for the private sector fail to meet the performance standards set by the public sector, the payment from the public sector will be deducted. Therefore, in the cooperation process of projects, the private sector cannot blindly reduce the performance of projects to pursue huge profits. Meanwhile, when designing the payment mechanism for infrastructure PPP projects, the government should also avoid "fixed payment", various irrational guarantees or commitments, and excessive profit transfer. The incentive mechanism is embedded in the design of the payment mechanism to promote the private sector to continuously improve performance to achieve the win-win objectives of cooperation between the public and private sectors. Essentially, the PPP mode is to attract advanced management methods and governance concepts from the private sector through the cooperation between the public and private sectors, provide high-quality products or efficient services for the public, and maximize social benefits. And reasonable risk sharing can promote more effective cooperation between the two sides (Hosseinian & Carmichael, 2013; Suprapto et al., 2015).

For the public sector, it can change all the risks of the project originally undertaken by the government into a reasonable risk sharing between the public and private sectors, and then give full play to the advantages of both sides, reduce the risk management cost of both sides, reduce the overall risk loss of the project, and promote a virtuous circle of cooperation between both sides.

### 2.3. Model construction

Some basic assumptions need to be made before setting the performance-linked rate between the payment from the public sector and performance appraisal results during the operation and maintenance period for the infrastructure PPP projects, a symbol interpretation are as shown in Table 1.

Table 1. The symbol interpretation of the model

| Symbol | Interpretation of symbols |
|---|---|
| $W_1$ | The private sector's average maximum income in each performance appraisal period |
| $C_0$ | The basic operation and maintenance cost and average cost coefficient |
| $k_1$ | The average cost coefficient |
| $b$ | The performance-linked rate |
| $x_0$ | The performance appraisal score |
| $\alpha$ | The private sector's marginal cost |
| $\eta$ | The private sector's average ability during the operation and maintenance period |

For the total operation and maintenance period of infrastructure PPP projects, if $W_1$ denotes the private sector's average maximum income in each performance appraisal period, $C_0$ and $k_1$ denote the basic operation and maintenance cost and average cost coefficient, respectively, where the basic operation and maintenance cost is the cost when the private sector reaches the performance standard set by the government during operation and maintenance period, then the government payment corresponding to the basic cost of operation and maintenance is $W_0 = (1-b)\times W_1$, where $b$ is the performance-linked rate. Further, when the cost from the private sector is $C_0$, the performance appraisal score is $x_0$, and when the performance appraisal score is hiked from $x_0$ to $x_1$, the cost from private sector is also raised from $C_0$ to $C_1(C_1 \ge C_0)$. Therefore, the marginal cost of private sector is $\alpha = \frac{C_1 - C_0}{x_1 - x_0}$. Moreover, if $\eta$, $W_2$ and $W_3$ denote the average ability of the operation and maintenance, maximum deduction and actual deduction of performance appraisal, respectively, then $W_2 = b\times W_1$, $W_3 = W_2/(1+\eta\alpha)$.

Based on above analyses, the social benefits of the project and the private sector's total cost are:

$$U_{public} = W_2 - W_3 = b\times W_1 - \frac{b\times W_1}{1+\eta\alpha}$$

and

$$C_{private} = C_0(1+\alpha) + W_3 = C_0(1+\alpha) + \frac{b\times W_1}{1+\eta\alpha} = W_1 \times \left\{ k_1 \times (1+\alpha) + \frac{b}{1+\eta\alpha} \right\}.$$

Obviously, the performance-linked rate directly affects the objectives of the public sector and the investment risk of the private sector. Therefore, the government should select an appropriate performance-linked rate. On the one hand, it will motivate the enthusiasm of the private sector to improve the performance level, and finally achieve the goal of increasing social benefits. On the other hand, the project can be implemented smoothly through designing an appropriate performance-linked rate to reduce the risks in the project.

In the process of operation and maintenance, the public sector hopes that the private sector will try its best to improve the performance level to maximize the social benefits. However, the goal of the private sector is to maximize its interests, and it always expects that the less the cost is, the better, once the basic performance is completed. Therefore, the design of the performance-linked rate should satisfy both the public and private sectors about the goals at the same time. Obviously, a key issue to solve the optimal performance-linked rate is the determination of the marginal cost. Here, for the convenience of the solution, the problem of selecting the optimal performance-linked rate is firstly transformed into another equivalent optimization problem, which is the problem of finding the optimal marginal cost. And then the optimal performance-linked rate is obtained according to the relationship among marginal cost, performance-linked rate, and objective function.

To sum up, based on the different demands of the public and the private sectors, the maximum social benefit and the minimum total cost of the private sector are taken as the objectives, and the optimal objective function can be obtained as follows:

$$\begin{aligned} \min_{\alpha} \mathrm{F} &= \min_{\alpha}\left\{ C_{private} - U_{public} \right\} = \\ & W_1 \times \left\{ k_1 \times (1+\alpha) + \frac{b}{1+\eta\alpha} \right\} - W_2 + W_3 = \\ & W_1 \times \left\{ k_1 \times (1+\alpha) + \frac{b}{1+\eta\alpha} \right\} - b\times W_1 + \frac{b\times W_1}{1+\eta\alpha}, \end{aligned} \quad (1)$$

where $0 \le b \le 1$, $0 \le \eta \le 1$, $0 < k_1 \le 1$, $0 \le \alpha \le 1$.

## 3. Research result

From the optimal objective function, the optimal marginal cost can be obtained by calculating the first derivative of the marginal cost in Eq. (1), and taking it as zero, that is

$$\frac{\partial \mathrm{F}}{\partial \alpha} = W_1 k_1 - \frac{2bW_1\eta}{(1+\eta\alpha)^2} = 0,$$

thus, the value of the optimal marginal cost is $\alpha_{optimal} = \sqrt{(2b)/(\eta k_1)} - 1/\eta$.

Assume that the average maximum cost paid by the private sector is equal to its average maximum income, that is, $C_0(1+\alpha) = W_1$, and the maximum marginal cost of the private sector is $\alpha_{\max} = 1/k_1 - 1$, then the value range of the optimal marginal cost is: $0 \le \alpha_{optimal} \le 1/k_1 - 1$.

The relationships among optimal marginal cost, performance-linked rate, and objective function are analyzed below, as shown in Figure 2.

(I) When $\alpha_{optimal} \ge \alpha_{\max}$, the optimal marginal cost is $\alpha_{optimal} = \frac{1}{k_1} - 1$, that is, $\sqrt{\frac{2b}{\eta k_1}} - \frac{1}{\eta} = \frac{1}{k_1} - 1$, then the objective function $F$ takes the minimum value at $b = \frac{1}{2}\eta k_1 \left( \frac{1}{\eta} + \frac{1}{k_1} - 1 \right)^2$;

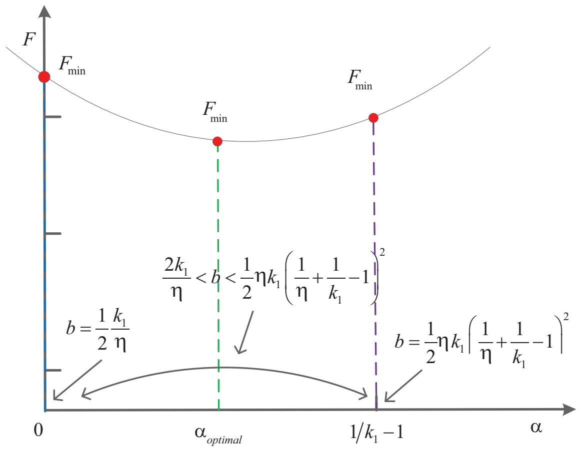



Figure 2. The relationship among marginal cost $\alpha_{optimal}$, performance-linked rate $b$ and objective function $F$

(II) When $\alpha_{optimal} \le 0$, the optimal marginal cost is $\alpha_{optimal} = 0$, that is, $\sqrt{\frac{2b}{\eta k_1}}-\frac{1}{\eta}=0$, then the objective function $F$ takes the minimum value at $b=\frac{k_1}{2\eta}$;

(III) When $0<\alpha_{optimal}<\frac{1}{k_1}-1$, the optimal marginal cost will be obtained in the interval $\left(0,\frac{1}{k_1}-1\right)$, that is, $0<\sqrt{\frac{2b}{\eta k_1}}-\frac{1}{\eta}<\frac{1}{k_1}-1$, then the objective function $F$ takes the minimum value in the interval $\frac{1}{2}\frac{k_1}{\eta}<b<\frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2$.

In summary, when $b=\frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2$, the private sector will give up trying to improve performance since the excessive marginal cost is produced to improve performance; when $b<\frac{k_1}{2\eta}$, the marginal cost in the process of operation and maintenance is zero. That is, the private sector has not made efforts to improve performance. And it cannot meet the goal for the government of maximizing social benefits. Therefore, the optimal range of the performance-linked rate is as follows:

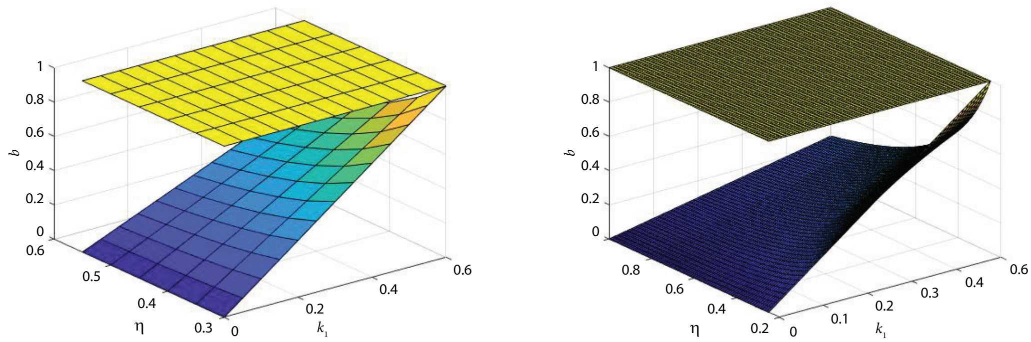
$$\frac{1}{2}\frac{k_1}{\eta}\le b\le\frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2. \quad (2)$$

Again both the average cost coefficient $k_1$ and average ability $\eta$ of the operation and maintenance meet the conditions: $k_1\in[0,1]$, $\eta\in[0,1]$, so $0<k_1/(2\eta)\le 1$, that is, $0<k_1\le 2\eta$. According to the value range of the performance-linked rate $b\in[0,1]$, two cases are obtained for the upper bound of $b$ the performance-linked rate:

(I) When $\frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2\ge 1$, the value range of the performance-linked rate $b$ is: $\frac{k_1}{2\eta}\le b\le 1$, and the conditions met by $k_1$ and $\eta$ are: ① $0<k_1\le 0.6$, $0.3\le\eta\le 0.55$ or $0<k_1\le 0.5$, $0.25\le\eta\le 1$. The value situation of the performance-linked rate $b$ in interval $[k_1/(2\eta),1]$ are shown in Figures 3a and 3b.

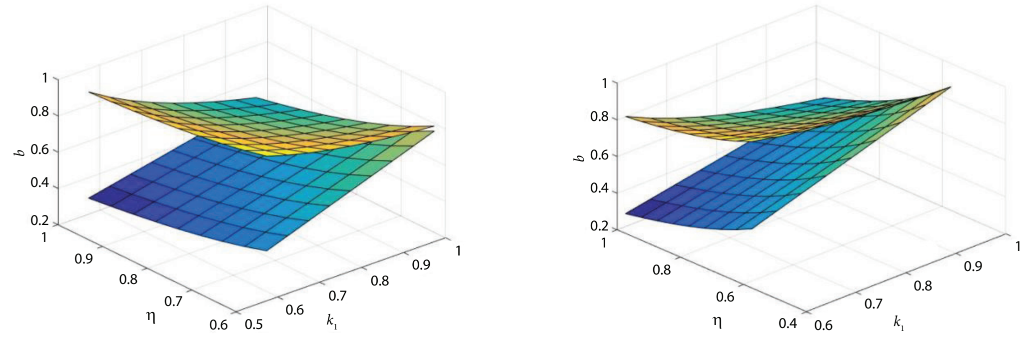
(II) When $\frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2\le 1$, the value range of the performance-based linked rate is: $\frac{1}{2}\frac{k_1}{\eta}\le b\le \frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2$. Since $\eta\in[0,1]$, the conditions met by $k_1$ and $\eta$ are: $0.573\le k_1\le 1$, $0.6\le\eta\le 1$ or $0.6\le k_1\le 1$, $0.573\le\eta\le 1$. As shown in Figures 4a and 4b, the value of the performance-based linked rate in space encircled by curved surfaces $b\ge\frac{1}{2}\frac{k_1}{\eta}$ and $b\le\frac{1}{2}\eta k_1\left(\frac{1}{\eta}+\frac{1}{k_1}-1\right)^2$.

From Figures 3 and 4, the performance-based linked rate $b$ is negatively correlated with the social average ability $\eta$ to the operation and maintenance, and is positively correlated with the social average cost coefficient $k_1$ of the operation and maintenance. It is shown that if the social average ability to the operation and maintenance is weak, then the social cost coefficient is also high, and the government can set a large performance-based linked rate to encourage the private to strive to improve the technologies and management level of the operation and maintenance, to reduce its operational risk. Conversely, when the social average ability of operation and maintenance is strong, the social average cost coefficient of operation and maintenance is relatively reduced. And the government should set a relatively low performance-based linked rate to reduce the income risk of the private sector to realize fair risk sharing.




a) b)

Figure 3. The changes of performance-linked rate in $[k_1/(2\eta),1]$




a) b)

Figure 4. The changes of performance-linked rate in $\left[k_1/(2\eta), \eta k_1 (1/\eta + 1/k_1 - 1)^2/2\right]$

Thus, the optimal interval of the performance-linked rate $b$ and the conditions satisfied by $k_1$ and η are as follows:

$$\begin{cases} \frac{1}{2}\frac{1}{\eta} \leq \quad \leq 1 & \begin{matrix} 0 \leq \ _1 \leq 0.6, 0.3 \leq \eta \leq 0.55 \\ 0 \leq \ _1 \leq 0.5, 0.25 \leq \eta \leq 1 \end{matrix} \\ \frac{1}{2}\frac{1}{\eta} \leq b \leq \frac{1}{2}\eta k_1 \left(\frac{1}{\eta} + \frac{1}{k_1} - 1\right)^2 & \begin{matrix} 0.573 \leq \ _1 \leq 1, 0.6 \leq \eta \leq 1 \\ 0.6 \leq k_1 \leq 1, 0.573 \leq \eta \leq 1 \end{matrix} \end{cases}. \quad (3)$$

From Eq. (3), the optimal values range of the performance-linked rate $b$ is related to the social average ability in operation and maintenance η and the social average cost coefficient $k_1$ of the private sector. That is, the values range of the performance-linked rate is determined once the social average operation and maintenance ability and the social average cost coefficient of the private sector are given.

## 4. Discussions and implication

The payment mechanism in infrastructure PPP projects is an important element of performance-based contracts, since it characterizes the payment from the public sector and the risks transferred to the contractor. Essentially, the payment mechanism with a fixed payment and a performance payment plays an important role in risk allocation problems in infrastructure PPP projects. A too large performance payment means that the private sector will take over more of the risks in the operation and maintenance process of infrastructure PPP projects.

Much research on the design of payment mechanism have appeared, such as availability payment mechanism with predetermined payments and adjustment payments, a hybrid payment mechanism with management (safety) payment, usage payment and capital payment (Abdel Aziz, 2007), availability and performance payment (Shi et al., 2020), the payment mechanism with a fixed payment to the contractor, a payment based on service quality and the number of users (Soliño & Albornoz, 2021). Comparing the existing literature, the advantage of this study is that an ignored problem "how to determine the amounts both of the fixed payment and performance payment" is solved by defining and calculating the performance-linked rate.

From the Eq. (3), the performance-linked rate is rated to the social average cost coefficient and the social average operation and maintenance ability. And using numerical simulation method, the relationships among them are stated. As shown in Figures 5a and 5b, when the social average cost coefficient $k_1$ is determined, the performance-linked rate $b$ decreases with increasing the social average operation and maintenance ability η, and the reduced speed is fast for the greater social average operation and maintenance ability η. Especially, for the greater social average cost coefficient $k_1$, the performance-linked rate $b$ is relatively larger than the smaller ones from the Figure 5c. Similarly, as shown in Figures 6a and 6b, when the social average operation and maintenance ability η is determined, the performance-linked rate $b$ increases with increasing the social average cost coefficient $k_1$, and the speed to reduce is lower for the greater the social average operation and maintenance ability η. Especially, for the greater social average operation and maintenance ability η, the performance-linked rate $b$ is relatively lower shown from the Figure 6c.

In this sense, when the social average operation and maintenance ability is relatively weak, the social average operation and maintenance cost is naturally high. From the public sector's perspective, to encourage the private sector to improve technology and management level during the operation and maintenance period, a relatively large performance-linked rate should be set to reduce operation income risks of the private sector. Conversely, if the operation and maintenance ability is strong, then the social average operation and maintenance cost is relatively low, the public sector should set a relatively low performance-linked rate to reduce the private sector's risks. Therefore, a reasonable risk sharing can be achieved by setting a perfect performance-linked rate for the public sector.

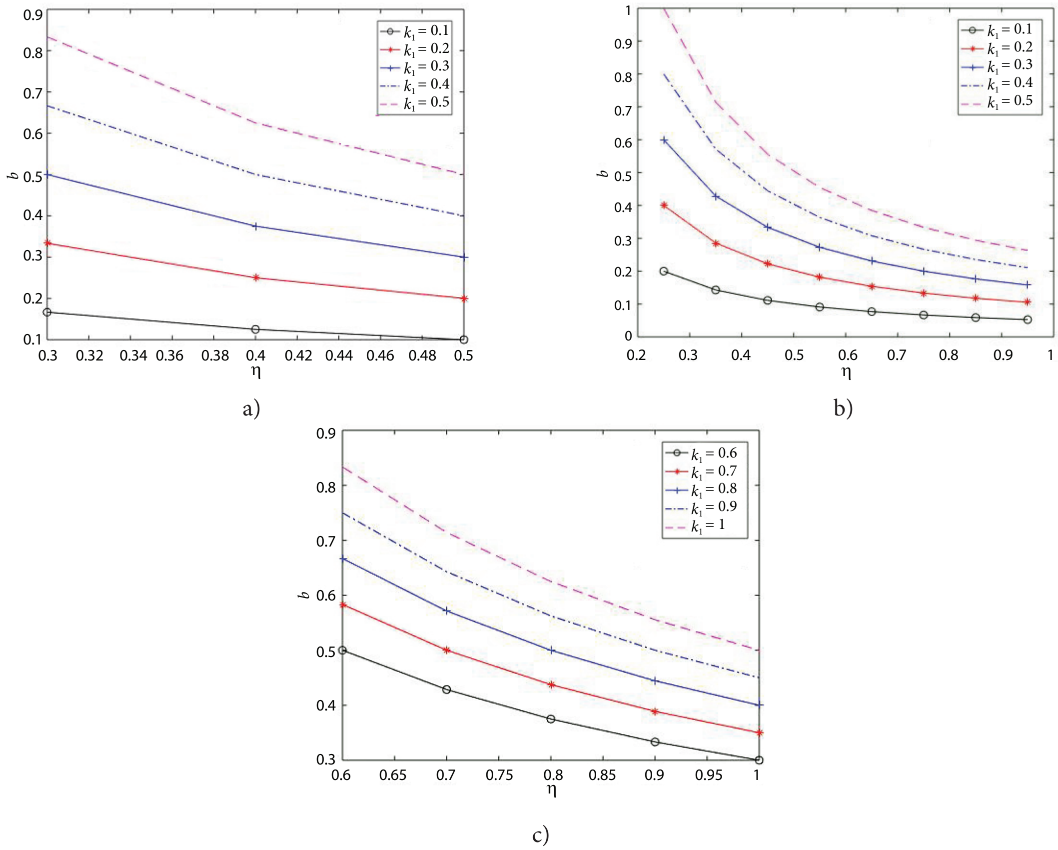



Figure 5. The change trend of the performance-linked rate $b$ with the change of the operation and maintenance ability η

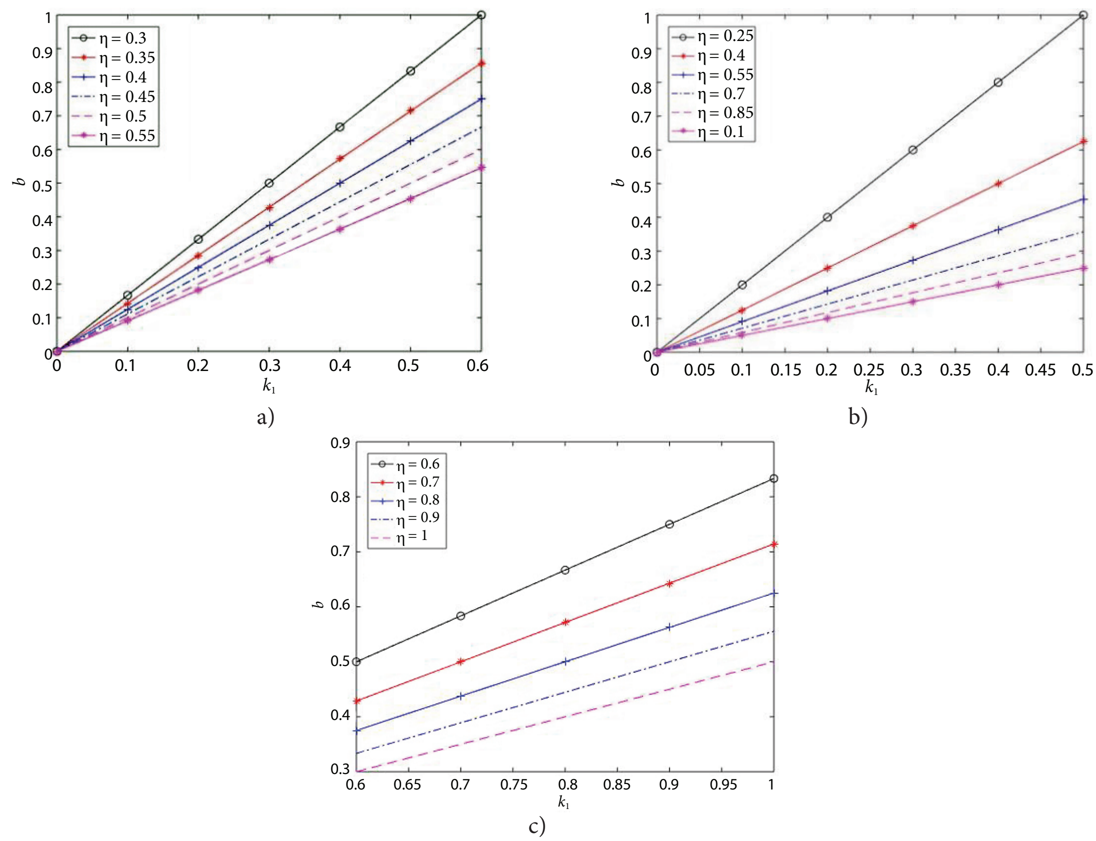



Figure 6. The change trend of the performance-linked rate $b$ with the change of the social average cost coefficient $k_1$

Additionally, according to Eq. (3), the private sector's social average ability cannot too poor when the values of the performance-linked rate are taken in the interval [0, 1]. Under these circumstances, from the public sector's perspective, the relevant data should be first collected to ensure the accuracy and timeliness of collected data, it can accurately grasp the private sector's social average cost and the social average ability during the operation and maintenance process as much as possible. In addition, to ensure that there will be no deviation in the evaluation results, the means of data processing also should be as reasonable as possible. It will avoid the misjudgement of the private sector's social average cost and the social average ability in the operation and maintenance process of infrastructure PPP projects.

Furthermore, some implications will be stated as follows. (1) From the stakeholders' perspectives, the negotiation and transaction costs will be reduced. A perfect performance-based payment structure will make the payment be carried out in a fair and transparent environment, which avoids multiple rounds of negotiations caused due to the unequal information. And it is beneficial to cooperating all parties smoothly. (2) From the public sector's perspective, the financial risk of infrastructure PPP projects will be decreased. For the imperfect performance-based mechanism, the payment from the public sector cannot reach to the private sector in time, which will lead to too high working capital pressure on the project company, so the financial risk is also too high. Therefore, when a perfect performance-based mechanism is established, the financial payment can be paid to the project company timely and efficient, it plays a great role in resolving the financial risks of the project company. (3) From the private sector's perspective, the perfect performance-based payment mechanism makes the payment from the public sector openness and transparency, which is good for the private sector to obtain the income accurately and timely. In addition, how to use the existing historical data and process them for the public sector will play a great auxiliary role in designing a reasonable payment mechanism, which further promotes the healthy and orderly development of the payment mechanism in related industry.

## Conclusions

Most of the performance-based payment structures of infrastructure PPP projects in the operation and maintenance process are composed of the fixed payment and the performance payment. The large fixed payment will not effectively incentive the private sector, and the large performance payment should increase the profit risk of the private sector (Su et al., 2022). Essentially, this involves the risk allocation between the public and private sectors. Therefore, it is of great significance in designing a reasonable proportion of the fixed payment and the performance payment in the performance-based payment structure, respectively.

This study tries to develop an ideal proportion of the fixed payment and the performance payment for the performance-based payment structure of infrastructure PPP projects. To achieve this aim, the definition of the performance-linked rate is first introduced, which is described the proportion of the performance payment in the total payment. The performance-linked rate is the basis of the design of the performance-based payment structure in the operation and maintenance process. Secondly, a suitable method is developed to determine the performance-linked rate from optimization and simulation perspectives. The method is firstly constructed by considering the social welfare of the public sector and the profit of the private sector, and then the value range of the performance-linked rate can be obtained using extreme theory. Finally, the results analyzed from the numerical simulation method show that the performance-linked rate is related to the social average operation and maintenance ability and the social average cost coefficient of the private sector. In other words, the performance-linked rate is related to the social average production level of an industry, so the government can determine the performance-linked rate according to the product development level of different industries. The values range can be determined once the social average operation and maintenance ability and the average social cost of the private sector are determined.

The design of the payment mechanism of infrastructure PPP projects should fully consider the contract structure and project characteristics of the project itself, and formulate a payment mechanism suitable for the actual needs of the projects. The contributions of this study mainly contain two aspects. (1) The design method of the performance-based payment structure is presented for the performance-based payment contract. The calculation method of the performance-linked rate is first developed, which is a proportion allocation for the fixed payment and the performance payment. And then the payment structure is designed by calculating the performance-linked rate, which provides a reasonable approach method of risk allocation between the public and private sectors. (2) The parameters affecting the performance-linked rate are identified. The performance-linked rate is rated to the social average cost and the social average operation and maintenance ability. And the values range can be determined once the social average operation and maintenance ability and the average social cost of the private sector are determined. So the government can determine the performance-linked rate according to the product development level of different industries.

There are some limitations associated with this study. When designing the payment mechanism, the existing financial capacity of the government and the construction plan and cash flow in the coming decades are considered to avoid causing an excessive financial burden to the government, and the financial capacity of the private sector should be considered to ensure sufficient funds in the process of project construction. If the payment is perfectly linked to the performance of the project, it will provide more control tools for decision-makers at the project governance level and further expands the degree of the bundling effect. Additionally, the validation of the model is verified using numerical simulation, and it is necessary to seek more theoretical methods, in which the validation of the model is verified using real data and avoiding simulation data.

## Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Funding

The authors acknowledge with gratitude the National Natural Science Foundation of China (No. 72271091; No. 71974056), Key Scientific Research Project of Universities in Henan Province (No. 23A630009), Key Science and Technology Projects in Henan Province (No. 232102321114), Doctoral Innovation Fund of North China University of Water Resources and Electric Power (No. NCWUBC202219). This study would not have been possible without their financial support.

## Author contributions

Limin Su and Yongchao Cao wrote the first draft of the article. Limin Su and Huimin Li conceived the study and were responsible for the design and development of the data analysis. Yongchao Cao were responsible for data collection and analysis.

## Disclosure statement

The authors declare that they have no conflicts of interest.

## References

Abdel Aziz, A. M. (2007). A survey of the payment mechanisms for transportation DBFO projects in British Columbia. *Construction Management and Economics*, *25*(4–6), 529–543. https://doi.org/10.1080/01446190601161465

Ameyaw, E. E., & Chan, A. P. C. (2016). A fuzzy approach for the allocation of risks in public – private partnership water-infrastructure projects in developing countries. *Journal of Infrastructure Systems*, *22*(3), 04016016. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000297

An, X., Li, H., Wang, L., Wang, Z., Ding, J., & Cao, Y. (2018). Compensation mechanism for urban water environment treatment PPP project in China. *Journal of Cleaner Production*, *201*, 246–253. https://doi.org/10.1016/j.jclepro.2018.08.003

Aziz, A. A., & Abdelhalim, K. (2017). Comparative analysis of P3 availability payments in the USA and Canada. In *Second International Conference on Public-Private Partnerships* (pp. 560–573), Austin, Texas. https://doi.org/10.1061/9780784480267.044

Beatham, S., Anumba, C., Thorpe, T., & Hedges, I. (2004). KPIs: a critical appraisal of their use in construction. *Benchmarking: An International Journal*, *11*(1), 93–117. https://doi.org/10.1108/14635770410520320

Carbonara, N., Costantino, N., & Pellegrino, R. (2014). Revenue guarantee in public-private partnerships: a fair risk allocation model. *Construction Management and Economics*, *32*(4), 403–415. https://doi.org/10.1080/01446193.2014.906638

Chan, A., Oseikyei, R., Yi, H. U., & Yun, L. E. (2018). A fuzzy model for assessing the risk exposure of procuring infrastructure mega-projects through public-private partnership: the case of Hong Kong-Zhuhai-Macao Bridge. *Frontiers of Engineering Management*, *5*(1), 64–77. https://doi.org/10.15302/J-FEM-2018067

Cheung, E., Chan, A., & Kajewski, S. (2010). The public sector's perspective on procuring public works projects – comparing the views of practitioners in Hong Kong and Australia. *Journal of Civil Engineering and Management*, *16*(1), 19–32. https://doi.org/10.3846/jcem.2010.02

Chung, D., & Hensher, D. (2015). Risk management in public-private partnerships. *Australian Accounting Review*, *25*(1), 13–27. https://doi.org/10.1111/auar.12062

Cui, C. Y., Liu, Y., Hope, A., & Wang, J. P. (2018). Review of studies on the public private partnerships (PPP) for infrastructure projects. *International Journal of Project Management*, *36*(5), 773–794. https://doi.org/10.1016/j.ijproman.2018.03.004

Cui, Q., Zhu, X., & D'Alessio, A. (2017). Public-private partnership: a design issue. In *2017 IEEE Symposium Series on Computational Intelligence* (*SSCI*) (pp. 1–6). IEEE. https://doi.org/10.1109/SSCI.2017.8285351

Ding, X., & Li, Q. (2022). Optimal risk allocation in alliance infrastructure projects: a social preference perspective. *Frontiers of Engineering Management*, *9*(2), 326-336. https://doi.org/10.1007/s42524-020-0145-x

Eliasson, J., & Fosgerau, M. (2013). Cost overruns and demand shortfalls-deception or selection? *Transportation Research Part B: Methodological*, *57*, 105–113. https://doi.org/10.1016/j.trb.2013.09.005

Engel, E., Fischer, R., & Galetovic, A. (2013). The basic public finance of public-private partnerships. *Journal of the European Economic Association*, *11*(1), 83–111. https://doi.org/10.1111/j.1542-4774.2012.01105.x

Feng, Z., Zhang, S., Gao, Y., & Zhang, S. (2016). Subsidizing and pricing private toll roads with noncontractible service quality: a relational contract approach. *Transportation Research Part B: Methodological*, *91*, 466–491. https://doi.org/10.1016/j.trb.2016.04.017

Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2005). How (in)accurate are demand forecasts in public works projects?: The case of transportation. *Journal of the American Planning Association*, *71*(2), 131–146. https://doi.org/10.1080/01944360508976688

George, H. B., & Matt, S. (2019). Risk model for energy performance contracting in correctional facilities. *Journal of Green Building*, *14*(2), 61–82. https://doi.org/10.3992/1943-4618.14.2.61

Higuchi, T. (2019). Natural resource and PPP infrastructure projects and project finance. In *Economics*, *law*, *and institutions in Asia pacific*. Springer. https://doi.org/10.1007/978-981-13-2215-0

HM Treasury. (2007). *Standardisation of PFI contracts*. London.

Hosseinian, S. M., & Carmichael, D. G. (2013). Optimal incentive contract with risk-neutral contractor. *Journal of Construction Engineering and Management*, *139*(8), 899–909. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000663

Iyer, K. C., & Sagheer, M. (2011). A real options based traffic risk mitigation model for build-operate-transfer highway projects in India. *Construction Management and Economics*, *29*(8), 771–779. https://doi.org/10.1080/01446193.2011.597412

Lawther, W. C., & Martin, L. (2014). Availability payments and key performance indicators: challenges for effective implementation of performance management systems in transportation public-private partnerships. *Public Works Management and Policy*, *19*(3), 219–234. https://doi.org/10.1177/1087724X14528476

Li, H., Su, L., Zuo, J., Zhao, X., Chang, R., & Wang, F. (2022). Incentive mechanism for performance-based payment of infrastructure PPP projects: coupling of reputation and ratchet effects. *International Journal of Strategic Property Management*, *26*(1), 35–55. https://doi.org/10.3846/ijspm.2022.15969

Liang, Y. M., Moroney, R., & Rankin, M. (2020). Say-on-pay judgements: the two-strikes rule and the pay-performance link. *Accounting and Finance*, *60*, 943–970. https://doi.org/10.1111/acfi.12391

Liu, J., Love, P. E. D., Davis, P. R., Smith, J., & Regan, M. (2015). Conceptual framework for the performance measurement of public-private partnerships. *Journal of Infrastructure Systems*, *21*(1), 04014023. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000210

Martinez, J., & Rodriguez, R. E. (2016). Performance-based indicators as a tool to manage energy efficiency in transport. Case study in Spain. *Procedia Computer Science*, *83*, 847–854. https://doi.org/10.1016/j.procs.2016.04.175

Mladenovic, G., & Queiroz, C. (2014). Assessing the financial feasibility of availability payment PPP projects. In *Second Transportation & Development Congress 2014* (pp. 602–611), Orlando, Florida. https://doi.org/10.1061/9780784413586.058

Mouraviev, N., & Kakabadse, N. K. (2014). Risk allocation in a public-private partnership: a case study of construction and operation of kindergartens in Kazakhstan. *Journal of Risk Research*, *17*(5), 621–640. https://doi.org/10.1080/13669877.2013.815650

Narbaev, T. (2022). A meta-analysis of the public-private partnership literature reviews: exploring the identity of the field. *International Journal of Strategic Property Management*, *26*(4), 318–331. https://doi.org/10.3846/ijspm.2022.17860

Ng, A., & Loosemore, M. (2007). Risk allocation in the private provision of public infrastructure. *International Journal of Project Management*, *25*(1), 66–76. https://doi.org/10.1016/j.ijproman.2006.06.005

Ng, T. S., & Wong, Y. M. W. (2007). Payment and audit mechanisms for non private–funded PPP–based infrastructure maintenance projects. *Construction Management and Economics*, *25*(9), 915–923. https://doi.org/10.1080/01446190701544396

Niu, B., & Zhang, J. (2013). Price, capacity and concession period decisions of Pareto-efficient BOT contracts with demand uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, *53*, 1–14. https://doi.org/10.1016/j.tre.2013.01.012

Pellegrino, R. (2021). Effects of public supports for mitigating revenue risk in public–private partnership projects: model to choose among support alternatives. *Journal of Construction Engineering and Management*, *147*(12), 04021167. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002098

Rangel, T., Vassallo, J. M., & Arenas, B. (2012). Effectiveness of safety-based incentives in public private partnerships: evidence from the case of Spain. *Transportation Research Part A: Policy and Practice*, *46*(8), 1166–1176. https://doi.org/10.1016/j.tra.2012.05.008

Roumboutsos, A., & Pantelias, A. (2015). Allocating revenue risk in transport infrastructure public private partnership projects: how it matters. *Transport Reviews*, *35*(2), 183–203. https://doi.org/10.1080/01441647.2014.988306

Salimian, S., Mousavi, S. M., & Antuchevičienė, J. (2022). Evaluation of infrastructure projects by a decision model based on RPR, MABAC, and WASPAS methods with interval-valued intuitionistic fuzzy sets. *International Journal of Strategic Property Management*, *26*(2), 106–118. https://doi.org/10.3846/ijspm.2022.16476

Sang, J. Y., Li, Z. C., Lam, W. H. K., & Wong, S. C. (2019). Design of build-operate-transfer contract for integrated rail and property development with uncertainty in future urban population. *Transportation Research Part B: Methodological*, *130*, 36–66. https://doi.org/10.1016/j.trb.2019.10.003

Shang, L., & Abdel Aziz, A. M. (2020). Stackelberg game theory-based optimization model for design of payment mechanism in performance-based PPPs. *Journal of Construction Engineering and Management*, *146*(4), 04020029. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001806

Shang, L., & Abdel Aziz, A. (2018). The USA PPP payment mechanisms: a comparison to the Canadian PPP systems. In *Construction Research Congress 2018* (pp. 129–138), New Orleans, Louisiana. https://doi.org/10.1061/9780784481295.014

Sharma, D., & Cui, Q. (2012). Design of concession and annual payments for availability payment public private partnership (PPP) projects. In *Construction Research Congress 2012: Construction Challenges in a Flat World* (pp. 2290–2299). ASCE. https://doi.org/10.1061/9780784412329.230

Shi, L., Li, W. W., & He, Y. J. (2020). An incentive analysis of availability payment mechanism in PPP projects. *IEEE Access*, *8*, 106046–106058. https://doi.org/10.1109/ACCESS.2020.2999932

Soliño, A. S., & Albornoz, C. D. V. A. (2021). Improving the payment mechanism in transport public–private partnerships. *Public Money and Management*, *41*(3), 246–254. https://doi.org/10.1080/09540962.2019.1684013

Song, J. M., Chen, L. M., Guan, X. Q., & Fan, W. Z. (2020). Research on risk sharing of PPP plus EPC sewage treatment project based on bargaining game mode. *Fresenius Environmental Bulletin*, *29*(2), 903–912. https://doi.org/10.1061/9780784481752.022

Su, L., Cao, Y., Li, H., & Zhang, C. (2022). Water environment treatment PPP projects optimal payment mechanism based on multi-stage dynamic programming model. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-04-2022-0291

Suprapto, M., Bakker, H. L. M., Mooi, H. G., & Moree, W. (2015). Sorting out the essence of owner–contractor collaboration in capital project delivery. *International Journal of Project Management*, *33*(3), 664–683. https://doi.org/10.1016/j.ijproman.2014.05.001

Tao, H. E., & Zhao, G. J. (2011). Risk allocation in public private partnerships based on stochastic cooperative game model. *Systems Engineering*, *29*(4), 88–92 (in Chinese).

Vassallo, J. M., & Gallego, J. (2005). Risk sharing in the new public works concession law in Spain. *Transportation Research Record: Journal of the Transportation Research Board*, *1932*(1), 1–8. https://doi.org/10.3141/1932-01

Wang, H., Liu, Y., Xiong, W., & Zhu, D. (2019). Government support programs and private investments in PPP markets. *International Public Management Journal*, *22*(3), 499–523. https://doi.org/10.1080/10967494.2018.1538025

Wang, Y., & Zhao, Z. J. (2018). Performance of public-private partnerships and the influence of contractual arrangements. *Public Performance and Management Review*, *41*(1), 177–200. https://doi.org/10.1080/15309576.2017.1400989

Wang, Y., Cui, P., & Liu, J. (2018). Analysis of the risk-sharing ratio in PPP projects based on government minimum revenue guarantees. *International Journal of Project Management*, *36*(6), 899–909. https://doi.org/10.1016/j.ijproman.2018.01.007

Xu, Z., Wang, X., Xiao, Y., & Yuan, J. F. (2020). Modeling and performance evaluation of PPP projects utilizing IFC extension and enhanced matter-element method. *Engineering Construction and Architectural Management*, *27*(8), 1763–1794. https://doi.org/10.1108/ECAM-08-2019-0429

Yescombe, E. R. (2007). *Public-private partnerships: principles of policy* & *finance*. Elsevier Ltd. https://doi.org/10.1016/B978-075068054-7.50025-3

Yu, B., Zhang, J., Wei, S., Cong, G., & Tao, C. (2007). The research on information system project performance evaluation based on fuzzy neural network. In *2007 International Conference on Wireless Communications*, *Networking and Mobile Computing* (pp. 6170–6174), Shanghai, China. https://doi.org/10.1109/WICOM.2007.1513

Yuan, J. F., Wang, C., Skibniewski, M. J., & Li, Q. M. (2012). Developing key performance indicators for public-private partnership projects: questionnaire survey and analysis. *Journal of Management in Engineering*, *28*(3), 252–264. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000113

Yuan, J., Ding, H., Huang, Z., Deng, B., Li, S., & Huang, W. (2021). Influence of market structures on concession pricing in public-private-partnership utilities with asymmetric information. *Utilities Policy*, *69*, 101162. https://doi.org/10.1016/j.jup.2020.101162

Zhang, Y., Yuan, J., Zhao, J., Cheng, L., & Li, Q. (2022). Hybrid dynamic pricing model for transport PPP projects during the residual concession period. *Journal of Construction Engineering and Management*, *148*(2), 04021200. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002218

Zhu, X., & Cui, Q. (2014). Availability payment design in public private partnership. In *POMS 25th Annual Conference on Atlanta* (pp. 9–12), GA, USA.