INSTITUTO
UNIVERSITÁRIO
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Strategies for Saving Public Authority and User Payment for Construction of China's PPP Project: Output Specifications, Incentives and Regulation

ZHANG Xiaoping

Doctor of Management

Supervisors:
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ISCTE University Institute of Lisbon
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PhD NI Debing, Professor,
University of Electronic Science and Technology of China

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I declare that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university and that to the best of my knowledge it does not contain any material previously published or written by another person except where due reference is made in the text.

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Abstract

In some PPP projects in China, public authority and user payment for construction (PUPC) has exceeded the budget, diminishing the efficiency of public funds. This thesis aims to explore strategies for the public authority to save PUPC in the transaction and construction stage.

Structured interviews are for the part assumptions (initial assumptions) of mathematical modelling of game theory, which collect real data from the field through interviews, conduct theme analysis, verify the reliability of the initial assumptions, and decide whether adjustments are necessary. The unstructured interviews are for the four research questions of this thesis, which conduct in-depth interviews, use NVivo 15 software and descriptive statistics for data analysis, obtain the theoretical model for saving PUPC. Mathematical modeling method of game theory is for the four research questions of this thesis, which establishes game tree and payoff functions, uses backward induction to solve for optimal solutions for each decision and optimal payoff functions, and finally analyzes their influencing factors and trends, forming Result 1 to Result 7.

For the similarities and differences in research results between unstructured interviews and mathematical modeling of game theory, this thesis uses expert focus group to further evaluate. This thesis derives optimal strategies for three sets of decisions (the level of detail of output specifications and tender offer; incentive intensity and technological innovation; regulation intensity and opportunism) closely related to PUPC, along with their influencing factors and trends. Furthermore, this thesis obtains factor strategy and path strategy for the public authority to save PUPC. Factor strategy is that from the perspective of the factors influencing PUPC, the public authority actively adjusts or optimally selects the exogenous variables (characteristic parameters) influencing PUPC. Path strategy is that from the perspective of the path to save PUPC, the public authority selects the equilibrium path in the strategic game of project implementation. These have significant value in saving PUPC, enhancing the efficiency of PPP project funds.

Keywords: PPP, Payment, Public Authority, Game Theory, Construction Cost
JEL: H41, C73

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Resumo

Em alguns projetos de PPP na China, o pagamento público pela construção (PUPC) excedeu o orçamento, diminuindo a eficiência dos fundos públicos. Este estudo visa explorar as estratégias para o setor público economizar o PUPC nas fases de transação e construção.

As entrevistas estruturadas destinam-se às premissas parciais (premissas iniciais) da modelagem matemática da teoria dos jogos, que coletam dados reais do campo por meio de entrevistas, realizam análises temáticas, verificam a confiabilidade das premissas iniciais e decidem se são necessários ajustes. As entrevistas não estruturadas destinam-se às quatro questões de pesquisa desta tese, que realizam entrevistas aprofundadas, utilizam o software NVivo 15 e estatísticas descritivas para análise de dados, obtendo o modelo teórico para economizar PUPC. O método de modelagem matemática da teoria dos jogos é para as quatro questões de pesquisa desta tese, que estabelece a árvore de jogo e as funções de pagamento, usa indução regressiva para resolver as soluções ótimas para cada decisão e funções de pagamento ótimas e, finalmente, analisa seus fatores de influência e padrões, formando os Resultado 1 a 7.

Para as semelhanças e diferenças nos resultados da investigação entre entrevistas não estruturadas e modelagem matemática da teoria dos jogos, esta tese utiliza um grupo de foco de especialistas para avaliar mais profundamente. Esta tese deriva estratégias ótimas para três conjuntos de decisões (o nível de detalhe das especificações de saída e oferta pública; intensidade de incentivo e inovação tecnológica; intensidade de regulamentação e oportunismo) intimamente relacionadas com a PUPC, juntamente com os seus fatores de influência e tendências. Além disso, esta tese obtém a estratégia de fatores e a estratégia de caminho para a autoridade pública salvar a PUPC. A estratégia de fatores consiste em que, da perspectiva dos fatores que influenciam a PUPC, a autoridade pública ajusta ativamente ou seleciona de forma otimizada as variáveis exógenas (parâmetros característicos) que influenciam a PUPC. A estratégia de caminho consiste em que, da perspectiva do caminho para salvar a PUPC, a autoridade pública seleciona o caminho de equilíbrio no jogo estratégico de implementação do projeto. Estes têm um valor significativo na salvação da PUPC, aumentando a eficiência dos fundos do projeto PPP.

Palavras-chave: PPP, Pagamento, Autoridade Pública, Teoria dos Jogos, Custo de Construção
JEL: H41, C73

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摘要

中国部分 PPP 项目出现公共公众建设付费(PUPC)超预算的现象，降低了公共资金的效率。本研究旨在探索公共部门在交易和建设阶段节约 PUPC 的策略。

结构式访谈是针对博弈论的数学建模的部分设定（原设定），通过访谈收集现场的真实数据，然后进行主题分析，并根据主题分析结果验证原设定的可靠性及决定是否需要调整。开放式访谈是针对本文的四个研究问题，开展深度访谈，然后采用 NVivo 15 软件和描述性统计进行数据分析，获得节约 PUPC 的理论模型。博弈论数学建模法是针对本文四个研究问题，建立博弈树和效用函数，采用逆向归纳法求各个决策最优解和最优效用函数，最后分析它们的影响因素及趋势，形成结果 1～结果 7。

针对开放式访谈法和博弈论数学建模法的研究结果的相同点和不同点，本文采用专家焦点组进行了评估。最终本文得出了与 PUPC 紧密相关的三组决策（产出说明的详细程度和投标报价；激励强度和技术创新；监管强度和机会主义）的最优策略及其影响因素和趋势，同时，本文也获得了公共部门节约 PUPC 的因素策略和路径策略。因素策略是从影响 PUPC 的因素角度出发，公共部门主动调整或择优选择影响 PUPC 的外生变量（特征参数）。路径策略是从实现节约 PUPC 的路径角度出发，公共部门在项目实施的策略博弈中选择均衡路径。这些对节约 PUPC、提升 PPP 项目资金效率有着重要的价值。

关键词：PPP，付费，公共部门，博弈论，建设成本

JEL: H41, C73

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Time flies, and five years have passed in the blink of an eye. I remember deliberating at length when I made up my mind to pursue a PhD in Management.

Looking back over the past five years, I have squeezed out time from my heavy workload to study, and experienced pain and hardship along the way. I often came home with exhaustion after finishing work, and then stay up late reading and writing the thesis. I frequently tossed and turned in the dead of night, and gradually, my hair has turned grey.

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In life’s journey, trying to accomplish truly meaningful things is not easy, therefore, we should seize today’s time to strive. Wishing everyone in my life a brighter tomorrow.

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回想四年以来，在繁重的工作中挤出时间来读书，历经了一路苦难。经常在完成工作后拖着疲惫身躯回到家，然后挑灯夜读、写论文。经常夜半辗转反侧，斑白了自己的头发。

读博士犹如孤舟泛海。莱安德罗·佩雷拉（Leandro Pereira）和卡洛斯·杰若尼莫（Carlos Jeronimo）两位教授，是我论文研究的灯塔和领航人，每当我不知道何处何从时，他们为我驱散前方海面的迷雾。尤其是在论文第四章的时候，我都快要绝望了，他们再次为我点燃希望之火。论文每前进一步，他们都给予了我很多有益的启示。在迷茫、徘徊、不知道前方是否有路可走的时候，他们引导我趟过这条充满荆棘的坎坷人生路。里斯本虽然远隔千山万水，但是，学术和心灵的沟通却很近，犹如在身边。感谢他们为我所做的一切。

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人生路漫漫，只争朝夕。祝愿我认识的人和认识我的人明天会更好。

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Acronyms

BOO	Build-Own-Operate
BOOT	Build-Own-Operate-Transfer
BOT	Build-Operate-Transfer
CCEA	China Cost Engineering Association
CNAO	National Audit Office of the People's Republic of China
CS	Construction Cost Calculated by Norm and Standard
DBFOT	Design-Build-Finance-Operate-Transfer
ESG	Environmental-Social-Governance
FNPV	Financial Net Present Value
FSR	Feasibility Study Report
IM	Interview Method
MM	Mathematical Modelling Method of Game Theory
MOF	Ministry of Finance of the People's Republic of China
MOHURD	Ministry of Housing and Urban-Rural Development
MOT	Ministry of Transport of the People's Republic of China
NDRC	National Development and Reform Commission of the People's Republic of China
PFI	Private Finance Initiative
PPP	Public-Private-Partnership
PSC	Public Sector Comparator
PUP	Public Authority and User Payment
PUPA	Public Authority and User Payment for All Other Matters
PUPC	Public Authority and User Payment for Construction
PUPO	Public Authority and User Payment for Operation
SPV	Special Purpose Vehicle

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Chapter 1: Introduction

1.1 Context

Scholars such as Grimsey and Lewis (2016) believe the PPP pattern originated with toll roads in the mid-17th century, and that the 'railway boom' in mid-19th century Europe represented its golden period. Since the advent of PPP, there has been efficiency and cost savings of PPP (S. Q. Wang & Wang, 2017). Over the past decade, the PPP pattern has developed rapidly in China (Political and Credit Research Institute of Central University of Finance and Economics, 2022), and at the same time, the problems such as low efficiency of PPP projects and overspending on project construction investment have been encountered (J. T. Zhou et al., 2019). Consequently, how to save public authority and user payment for construction (hereafter referred to as "PUPC") has become an issue of increasing concern.

The public authority and user payment (PUP) consists of three parts: public authority and user payment for construction (PUPC), public authority and user payment for operation (PUPO), and public authority and user payment for all other matters (PUPA) (Ministry of Finance of the People's Republic of China [MOF], 2015). The PUPC in this thesis refers to public authority and user payment for the construction expenditure of project participants, according to the PPP contract and the results of operational performance evaluations. The research in this thesis focuses on saving PUPC and does not involve PUPO and PUPA.

The primary participants in the PPP pattern are the public authority and the private partner (Asian Development Bank [ADB], 2008), however, the research is made specifically from the public authority's perspective, instead of the private partner. There is a big difference in the application of the PPP pattern in China and beyond (Huang et al., 2009), the research is based on the laws and regulations as well as the economic, social and cultural contexts of China.

The saving PUPC studied in this thesis is based on an indirect approach (output specifications, incentives, regulation) with principal-agent relationship (Zhang, 2012). The public authority will not and cannot directly control the construction cost of a PPP project (e.g., PDCA cycle, goal-path theory), otherwise it would not constitute a PPP pattern (S. Q. Wang & Wang, 2017).

This thesis studies how to save PUPC in the transaction and construction stages, rather than the finance and operation stages. Although PUPC is affected by different factors in the financing,

transaction, construction and operation stages (Grimsey & Lewis, 2016), measures taken by the public authority to save PUPC are mainly in the transaction and construction stages (World Bank Group [WBG], 2017). Therefore, this thesis does not consider the impact of project financing on PUPC, nor the impact of project operation on PUPC. It is assumed that the usage and performance evaluation results of the PPP project are in a normal state (the same as the planned values in the PPP contract), based on these, the strategies for saving PUPC are studied.

The level of detail of output specifications in this thesis refers to the level of detail of output specifications completed by the public authority before the contracting of a PPP project (MOF, 2014). It does not refer to the level of detail of implementation design completed by the private partner after the contracting of a PPP project (Grimsey & Lewis, 2016). The level of detail of output specifications should first meet the work needs of feasibility study and value-for-money evaluation, based on which the specific level of detail of output specifications can be selected (Global Infrastructure Hub [GIH], 2019).

The tender offer in this thesis refers to the total payment for construction quoted by the private partner in the PPP project transaction (China Cost Engineering Association [CCEA], 2018), or alternatively, the total payment for construction calculated based on economic indicators (required investment support, charging unit price, required operation subsidy, among others) quoted by the private partner (General Office of the State Council of the People's Republic of China, 2023). It is a transaction price between the public authority and the private partner, not between the private partner and suppliers (or contractors, or operators, among others).

Laffont and Martimort (2002) believe that in economic history, the emergence of the division of labor and exchange brought about incentive issues. Therefore, incentives are a very broad concept, whereas the incentives in this thesis specifically refer to measures taken by the public authority in the PPP project to encourage the private partner to save construction cost through technological innovation during the construction stage (S. M. Huang, 2020).

Technological innovation by the private partner in the PPP project includes design optimization and design deepening (Fidic, 2017). The design optimization in this thesis refers to in the construction stage, the private partner modifies and improves the design of engineering contents that have been specified in the output specifications, so as to enhance the value of the project (CCEA, 2022; Fidic, 2017). It is characterized by the private partner modifying the output specifications agreed in the contract, and requires prior approval from the public authority, resulting in a formal Variation Order.

Design deepening, studied in this thesis, refers to in the construction stage, the private partner supplements and refines the design of engineering contents that have not been specified in the

output specifications, so as to meet constructability and enhance the value of the project (CCEA, 2022; Fidic, 2017). It is characterized by the private partner not modifying the output specifications agreed in the contract, and is a contractual obligation of the private partner. Within the framework of the public authority's output specifications, design deepening is undertaken autonomously by the private partner without requiring item-by-item approval (unless explicitly stipulated in the contract). The design optimization and design deepening in this thesis refer to the actions taken by the private partner during the construction stage, excluding the establishment and transaction stages.

S. Q. Wang and Liu (2014) believe that the regulation of the PPP project can be primarily divided into two stages. The first stage is access regulation during the project establishment and concessionaire selection, while the second stage is performance regulation during the operation stage. Performance regulation encompasses various aspects, including quality, price, service level, and finances. The regulation in this thesis specifically refers to the public authority's supervision and management to curb opportunism from the private partner during PPP project construction stage.

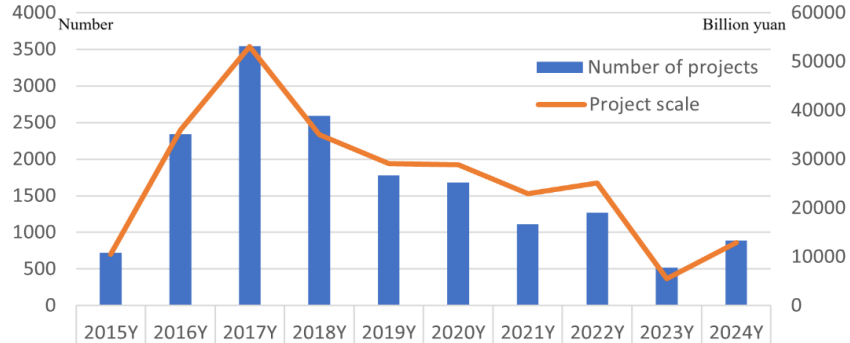
The opportunism studied in this thesis refers to the private partner's actions during the construction stage (Ni, 2019), which involves concealing design optimization or engaging in overestimation and miscalculation of additional PUPC outside the contract due to the events of public authority's liability (Han, 2023). The opportunism of previous construction contractors generally involves jerry-building and lowering of engineering quality standards. This is not the case with the PPP pattern. The private partner is responsible for the operation of the project, following its construction. The payment received by the private partner is contingent upon the public authority's performance evaluation. If the private partner engages in jerry-building and lowers quality standards during the construction stage, it will face adverse consequences in the subsequent operation stage. These consequences may include higher operation cost, failure to meet performance criteria, and potentially more severe issues. Therefore, the private partner is generally unlikely to engage in practices such as jerry-building or lowering engineering quality standards (Y. L. Yin et al., 2014).

1.2 Practical background

1.2.1 China's PPP pattern

China's PPP pattern has a large scale and impact. By the end of 2024, a total of 16,530 PPP

projects had been successfully transacted nationwide, accounting for a total investment of RMB 26.13 trillion (Ma, 2025). The annual completed transaction volume of China's PPP projects from 2015 to 2024 is shown in Figure 1.1. The Chinese government defines its core value as "an important initiative to integrate the two resources of government and market, facilitate change in the quality, efficiency and impetus of public service supply, and realize the modernization of the national governance system and capacity" (The State Council of the People's Republic of China, 2015).



	2015Y	2016Y	2017Y	2018Y	2019Y	2020Y	2021Y	2022Y	2023Y	2024Y
Project scale (Billion yuan)	10550	35991	53082	34984	29024	28835	22940	25081	5499	12921
Number of projects	721	2338	3546	2593	1781	1684	1109	1271	519	885

Figure 1.1 Annual completed transaction volume of China's PPP projects

Source: Ma (2025)

From 1980 to 2013, the PPP industry was in the exploration stage. In this stage, the PPP project was mainly characterized by investment promotion, concession management (National Development and Reform Commission of the People's Republic of China [NDRC] et al., 2015), and market-oriented operation. The cooperation methods commonly used included BOT and TOT (Grimsey & Lewis, 2016). At the beginning of this century, China experienced rapid urbanization, resulting in fast-paced urban expansion and an increased demand for municipal public utilities. However, the government faced financial constraints to meet this growing demand. In this context, attracting foreign investment emerged as a viable solution to address these challenges (J. T. Zhou et al., 2019). From 2002 to 2005, the State Council issued the policy documents such as the *Circular on the Proper Handling of Issues Related to Existing Projects Guaranteeing Fixed Returns on Foreign Investments* and the *Opinions on Encouraging, Supporting, and Guiding the Development of the Individual, Private, and Other Non-Public Ownership Economies*. These policies have created favorable conditions for attracting foreign capital and domestic private capital to invest in infrastructure and municipal public utilities. As a result, the PPP pattern has evolved from investment promotion to concession management.

From 2014 to 2022, the PPP industry experienced a rapid development stage. The release of the PPP pattern operating guidelines by the MOF (Ministry of Finance of the People's Republic

of China, 2014) marked the start of a rapid advancement in the PPP industry. This development was closely associated with the proactive fiscal policies implemented during the same period and the risks of debt from local financing platforms. In the context of the central government's efforts to control the debt scale of local governments and reduce their debt risks, the promotion of the PPP pattern was accelerated to address government debt problems (Ma, 2020; Tang et al., 2019). In a relatively short period of time, several national ministries and commissions, including the Ministry of Finance (MOF), introduced a series of policies on the PPP pattern. This action helped establish a unified, standardized, transparent, and efficient PPP market (J. T. Zhou et al., 2019). Furthermore, extensive implementation of these policies through demonstration and promotion project across the country has facilitated the formation and development of the PPP theoretical framework.

From 2023 to the present, the PPP industry is in new mechanism stage. After a period of development, the PPP pattern has revealed some problems. These include low development quality of the PPP project prior 2017 (Ma, 2020), the transfer or disguised transfer of construction and operational risks that should be borne by the private partner to the government sector in the form of a promise of a fixed return or guarantee of a minimum return (MOF, 2019), and the frequent occurrence of construction investments exceeding the budget estimate during project implementation (J. T. Zhou et al., 2019). In response to the problems that have arisen in the development of PPP, the state has introduced the *Guidance on new mechanism to regulate the implementation of PPPs* (GBH [2023] No. 115), which clearly encourages concessionaires to reduce construction cost and operation cost and improve investment efficiency through technological innovation and other measures (General Office of the State Council of the People's Republic of China, 2023).

1.2.2 Global PPP pattern

The emergence of the PPP pattern on a global scale can be traced back to the 1980s (Grimsey & Lewis, 2016). It is often regarded by scholars as a "revolution in infrastructure" (Grimsey & Lewis, 2016). There are also differences in the management systems of the PPP pattern in different countries around the world, with specific comparisons shown in Table 1.1 (S. Q. Wang & Liu, 2016). The latest developments in the PPP pattern globally are primarily observed in their applications at the project level in countries such as the UK, Australia, Canada, South America, and the US. The attractiveness driving the development of the PPP pattern can be attributed to three main factors: firstly, the evolving market for public services (New Public Management);

secondly, private finance patterns; and finally, the concept of partnership (Grimsey & Lewis, 2016; S. Q. Wang & Wang, 2017).

Table 1.1 Comparison of management systems of the PPP pattern in some countries or regions

Country/ Region / Systems of management	Australia	Hong Kong	South Africa	UK
PPP governing body	National Public Private Partnership Forum, Infrastructure Australia	Efficiency Units	PPP Unit	HM Treasury / National Audit Office and Public Utilities Regulatory Commission
Policy system	Central-government policies and guidance documents + local special requirements	Central-government policies and guidance documents	Guidance documents	No specific laws, mostly in the form of policies and guidelines
Government regulation	Regulation in the bidding and operation stages	Regulation in the bidding and operation stages	Regulation in the bidding and operation stages	Regulation in the bidding and operation stages
Principal documents	1. National PPP Policy, Dec 2008 2. National PPP Guidelines, Dec 2008 (Volume 4: Public Sector Comparator Guidance) The State of Victoria: 1. PSC Technical Note, 2001 2. PSC Supplementary Technical Note, 2003 3. Partnerships Victoria Statement, Feb 2009 4. Partnerships Victoria Requirements, Feb 2009 (PSC Development FAQs)	1. An Introductory Guide to Public Private Partnerships, Aug 2003 (Chapter 8 The Public Sector Comparator) 2. An Introductory Guide to Public Private Partnerships (2nd Edition), Mar 2008 (Chapter 4 Making a Business Case - Annex D Constructing a Public Sector Comparator 12 Steps)	1.Municipal Service Delivery and PPP Guidelines (Module 4: Feasibility Study - Stage 6: Value Assessment) 2. The No.16 Code of MOF 3.Public-Private Partnership Manual 4.Standardized PPP Provisions	1. The Green Book 2. The Green Book Guidance: A Toolkit Guide 3. Supplementary Green Book Guidance (Adjusting for Taxation in PFI vs PSC Comparisons) 4. Value for Money Assessment Guidance, Nov 2006 5. Quantitative Assessment User Guide, Mar 2007 6. PFI: Meeting the Investment Challenge 7. PFI：Strengthening Long-term Partnerships 8. Infrastructure Procurement: Delivering Long-term Value 9. A New Approach for Public Private Partnerships 10.Standardisation of PFI Contracts

Source: S. Q. Wang and Liu (2014, 2016)

From 2013 to 2022, the global average annual investment in PPP projects (across 140 countries) stood at US$97.75 billion (Djekic et al., 2024). The PPP pattern has played a central role in infrastructure development in Australia, PPP has become an integral part of the Federal and State Governments procurement strategies in Australia, and Australia's PPP market is considered one of the most mature in the world. PPP is a common infrastructure supply model in the UK, around 800 PFI contracts worth approximately £57 billion had been signed up to 2011, and over the past 10 years, the average cost savings from using the PPP pattern have ranged from 17% to 25%. PPPs in the USA are regarded as an evolving market with new opportunities, with PPP projects in the USA having moved through three generations. Emerging markets such as South Africa, Brazil, and India are also witnessing an increasing demand for the PPP pattern. The involvement of the private partner in infrastructure, as indicated in the infrastructure database of the World Bank and the Public-Private Infrastructure Advisory Facility, has shown steady growth in infrastructure investments made by the private partner of developing countries (Javed, 2013).

1.3 Theoretical background (Current state of theory and knowledge gaps)

As Grimsey and Lewis (2016) states in the concluding remarks of *Public Private Partnerships：The Worldwide Revolution in Infrastructure Provision and Project Finance*, "the most important goal of infrastructure project is to meet the social and economic needs of the public at low cost and high efficiency, which is also the foundation for the existence of PPP". Saving PUPC has always been an important part of PPP theoretical research and has run through all important decisions of the public authority in the transaction and construction stages.

1.3.1 Level of detail of output specifications

Theoretically, the content that the output specifications should cover is clear, and it should include the key indicators and specific contents of the standards for project assets, products or services (Javed, 2013). Many scholars in China argue that the PPP pattern has four core principles, one of which is "clear output specifications" (S. Q. Wang & Wang, 2017). The output specifications are undoubtedly the core document of a PPP project, serve as the foundational documents for the procurement and regulation of PPP/PFI project, form an essential component of the contractual documents throughout the project life cycle (Lam & Javed, 2015).

However, there are many different views on the level of detail of output specifications. Some

scholars believe that overly rough output specifications can lead to pitfalls. Rough output specifications can result in an unclear vision for the public authority, ambiguous in risk allocation among the parties, and conflicts between input and output norms, all of which cause difficulties during the implementation of the PPP project (Javed, 2013). Some scholars also believe that overly detailed output specifications constrain the private partner's space for innovation (S. Q. Wang & Wang, 2017). Some other scholars believe that the level of detail in output specifications should account for potential renegotiations and changes during the later stages. PPP or PFI project in the UK and Australia have encountered numerous issues that require changes to the output specifications (Lam & Javed, 2015). The long concession period of PPP/PFI project means that changes are inevitable, these problems can be solved through pre-set provisions in the output specifications or through renegotiation when changes occur (Ni, 2019). Throughout the transaction and construction stages of the PPP project, how to determine the optimal level of detail of output specifications is a decision that the public authority needs to face, and there is currently little theoretical research in this area.

1.3.2 Incentives for technological innovation

The methods of incentives for technological innovation in the PPP project are diverse, including: finance and taxation, concession period, revenue distribution, risk allocation, and rights of control (Han, 2023; S. M. Huang, 2020; Z. X. Liu, 2018). In addition, some scholars have further proposed that recognition is also a form of incentives (Han, 2023). While most methods of incentives are stipulated in policy documents, the implementation strategy for revenue distribution primarily comes from the public authority's own decision-making. Revenue distribution generally refers to the private partner sharing a proportion of the revenue generated by technological innovation (Fang et al., 2018; M. S. Li & Meng, 2018; S. J. Wu & Li, 2019). Some scholars believe that the incentives of revenue distribution have a positive effect on technological innovation. The proportion of revenue distribution to the private partner can promote technological innovation from the private partner, exhibiting a positive relationship (M. S. Li & Meng, 2018). There are two equilibrium solutions to the game between incentives and technological innovation: ① (public authority, private partner) = (no incentives, no innovation); ② (public authority, private partner) = (incentives by return, efforts to innovate), with the former being the prisoners' dilemma and the latter being the optimal strategy after eliminating dominated strategies (Fang et al., 2018). Some scholars also believe that excessive incentives in revenue distribution may undermine the public interest of the PPP project, and could even form the

transfer of benefits (S. M. Huang, 2020).

Consequently, an excessively low intensity of incentives (the proportion of revenue distribution to the private partner) fails to effectively stimulate technological innovation and promote construction cost savings; conversely, an excessively high intensity of incentives leads to excessive incentive cost expenditure from the public authority, thereby failing to protect the public interest adequately. Throughout the transaction and construction stages of the PPP project, how to determine the optimal intensity of incentives is a decision that the public authority faces, and there are currently gaps in theoretical knowledge.

1.3.3 Regulation against opportunism

Regulation and penalty mechanisms for the PPP pattern are essential. The role of regulation from the public authority in the construction stage includes curbing opportunism by the private partner and ensuring that PPP project outputs meet user requirements. The role of the regulation from the public authority includes curbing opportunism from the private partner and ensuring that the output of the PPP project meets the requirements of users (Z. X. Liu, 2018; S. Q. Wang & Wang, 2017). Other scholar further proposed that the incompleteness of contracts and the failure of the market mechanism also necessitate regulation (Z. X. Liu, 2018). In addition, the level of penalties is very important is very important (Cai & Zhou, 2016). The way to prevent rent-seeking from the private partner is to increase the intensity of regulation (Chen et al., 2014).

Based on the necessity of regulation, the regulation system for the PPP pattern has also gradually been refined. It includes both the whole-process regulation of the PPP project and the regulation of the compliance of the performance by all participants (Cui et al., 2020). It includes the right to know, supervision over contract performance, administrative supervision, performance evaluation, information disclosure, and public monitoring (MOF, 2014).

However, while the regulation of the PPP pattern plays a vital role, it also incurs regulation cost. The behavior cost of regulation is generally positive to the proportion of random inspection and the amount of the regulated target (NDRC, 2007). Now, the application of the PPP pattern in China is becoming increasingly mature, which requires the regulation in the construction stage to be implemented at a specific operational level. Low regulation intensity cannot curb opportunism and prevent the false increase of PUPC; however, high regulation intensity increases the regulation cost from the public authority and cannot effectively protect public interest. Throughout the transaction and construction stages of the PPP project, how to determine the optimal intensity of regulation is a decision that the public authority faces, and there are currently

gaps in theoretical knowledge.

1.4 Research problem

In recent years, the domestic PPP pattern has developed rapidly with a huge investment amount. once problems arise, they attract particular attention. Government departments are rectifying the issues existing in the PPP industry, including overspending on project construction investment and low efficiency in fund utilization (General Office of the State Council of the People's Republic of China, 2023). Many public authorities intend to save on PUPC, and have made some exploration. However, in practice, there are no specific methods or guidelines that can provide guidance, and they do not know how to determine the optimal decision at the important decision-making nodes (output specifications, incentives, regulation) involving PUPC. As a result, the reality often deviates significantly from the objectives, affecting the quality of PPP development. This is the problem faced by the public authorities and the PPP industry.

1.4.1 Decision on the level of detail of output specifications

Rough output specifications may have adverse effects. If the output specifications are too general or rough, the subject matter (characteristics, standards, requirements) of the PPP project transaction is unclear. The boundaries of contractual rights and obligations become ambiguous, making it difficult to assess whether the products or services provided by the private partner comply with the contractual requirements during the later operational stage (S. Q. Wang, 2018). Rough output specifications often lead to contract renegotiation (Ni, 2019; S. Q. Wang, 2018), increasing the risk of PUPC overspending.

However, excessive detail in the output specifications can have adverse effects. Firstly, the lengthy evaluation of output specifications by the public authority may result in deferred provision of public products or services. Moreover, the detailed content of the output specifications, which serves as the defining standard for the subject matter of the PPP project transaction, may limit the private partner's space for independent innovation (S. Q. Wang & Wang, 2017), which is not conducive to saving PUPC.

In the transaction stage of the PPP project, the estimation of construction content that is not explicitly defined in the output specifications, such as special roadbed construction in the case of expressway project, often relies on experiential estimation by both the public authority or the private partner (Ministry of Transport of the People's Republic of China [MOT], 2020). However, these empirical estimates are subject to the risk of deviation, which can lead to amount deviations

in the investment estimation or budget estimate of the project. The feasibility study, construction mode selection, tender sum limit, and other economic evaluations and measurements of a PPP project are all based on investment estimation or budget estimate. If the risk estimation deviation in the investment estimation or budget estimate is large, it may increase risk of PUPC getting out of control (Song et al., 2020). Moreover, this risk estimation deviation is also closely related to the level of detail of output specifications.

1.4.2 Decision on the intensity of incentives

Currently, in domestic PPP project, the public authority is generally responsible for writing the output specifications, while the private partner is responsible for the detailed construction drawing design. As the government department, the public authority in general emphasizes the safety and aesthetics of the design plan in the output specifications, while often overlooking the requirements for cost reduction (J. T. Zhou et al., 2019) . The public authority often only requires that project construction investment does not exceed budget estimate (Y. Y. Xie, 2019), and is not held accountable, but rarely plans how to use incentives to save construction cost and reduce PUPC. This is a prevalent drawback in the management of the PPP project by the public authority (M. S. Li & Meng, 2018). Another direction is also worthy of vigilance, excessive incentives will also cause adverse effects, first, harms public interests, and second, leads to the loss of state-owned assets (B. Gao, 2018).

The private partner is responsible for the detailed construction drawing design. Due to imperfect or even non-existent incentives, the private partner only focusses on quality, safety, schedule and profit, and has no motivation to engage in technological innovation. Some domestic PPP project even exhibit adverse incentives, for example, the public authority approved construction cost settlement for the private partner using the unit-prices (i.e., the quantities of construction works are settled according to the actual amount incurred), and the PUPC is derived from this settlement (J. T. Zhou et al., 2019). As a result, the construction risk that should be borne by the private partner is essentially transferred to the public authority, significantly undermining the value-for-money and core value of the PPP pattern.

1.4.3 Decision on the intensity of regulation

The private partner's opportunism has a significant impact on the PPP project and reduces the efficiency of utilizing public funds (Y. L. Wang et al., 2016). The regulation of the public authority during the construction stage mainly manifests in two aspects: first, the regulation of

contract performance (including the implementation of output specifications); second, the regulation of contract price adjustments during the construction stage (Chen et al., 2014).

The regulation of domestic PPP project has encountered some problems. The first is over-regulation. There is a trap in the public authority's regulation of the private partner (Lam & Javed, 2015), which involves simply adopting the regulatory approach used in the traditional construction contracting pattern. The regulation of the PPP pattern is ideally function- or result-oriented. In principle, the private partner has the right to decide on the design of the project, the selection of equipment, and the rational construction organization plan, without facing undue interference from the public authority. Regulating the design and construction of the private partner too tightly would indeed contradict the original intention of the PPP pattern.

The second is inadequate regulation (J. T. Zhou et al., 2019). There are various reasons for the public authority's inadequate regulation of the private partner's opportunism (S. M. Huang, 2020). First, the public authority lacks control power over SPV. The controlling shareholders of SPV are typically from the private partner. While the public authority has administrative power, it is not permitted to misuse this power or exceed the boundaries set by the PPP project contracts when implementing regulation. Therefore, the regulation for opportunism in SPV may encounter resistance. The public authority may find itself with insufficient sway over private-partner-led projects (Phuong, 2022). Second, in terms of regulation for project construction, the public authority is relatively weaker than the private partner in terms of capacity, energy, and experience. Government departments are busy with their daily affairs and do not have the energy to manage specific matters of the project. If they commission a third-party consulting agency to carry out the regulation, this will incur regulation cost.

1.5 Research questions

Based on the aforementioned theoretical background and practical problems, output specifications that are either too rough or excessively detailed are inappropriate; the public authority should seek the optimal level of detail of output specifications. Incentives for technological innovation that are either absent, perverse, or excessive are inappropriate; the public authority should seek the optimal incentive intensity. Regulation for opportunism that is either excessive or inadequate is inappropriate; the public authority should seek the optimal regulation intensity. To save PUPC, it is essential to research optimal strategies for important decisions of the public authority during the transaction and construction stages, analyze the factors and trends affecting PUPC, and systematically summarize the path to saving PUPC.

Based on this, the research questions for this thesis can be refined as follows:

1. In the project transaction stage, how does the public authority choose the optimal level of detail of output specifications to save PUPC?

2. In the project construction stage, how does the public authority choose the optimal intensity of incentives to save PUPC?

3. In the project construction stage, how does the public authority choose the optimal intensity of regulation to save PUPC?

4. What are the factors and trends influencing PUPC, and what are the paths to saving PUPC?

1.6 Research objectives

From the perspective of the public authority saving PUPC, this thesis researches optimal strategies for the level of detail of output specifications, intensity of incentives, and intensity of regulation, analyses factors and trends influencing PUPC, and summarizes the path to saving PUPC, thereby enhancing project efficiency and demonstrating the core value of the PPP pattern. The specific research objectives are as follows:

First, by researching the level of detail of output specifications in the transaction stage of the PPP project, this thesis seeks to find the optimal strategy for the level of detail of output specifications in the public authority, analyses the factors and trends influencing this optimal strategy, and provides theoretical guidance for decision-making regarding the level of detail of output specifications in the public authority. Along the decision-making pathway throughout the transaction and construction stages, the optimal tender offer in the private partner corresponds to the optimal level of detail of output specifications in the public authority. Consequently, researching the optimal tender offer is indispensable, enabling the optimal strategy in the public authority to be implemented within an equilibrium environment.

Secondly, by researching the intensity of incentives and the intensity of regulation in the construction stage of the PPP project, this thesis seeks to find the optimal strategies for the intensity of incentives and the intensity of regulation in the public authority, and analyses the factors and trends influencing these optimal strategies, and provides theoretical guidance for decision-making on the intensity of incentives and the intensity of regulation in the public authority. Along the decision-making pathway throughout the transaction and construction stages, the optimal technological innovation strategy and optimal opportunism strategy in the private partner correspond respectively to the optimal intensity of incentives and optimal intensity of regulation in the public authority. Consequently, researching the optimal technological

innovation strategy and optimal opportunism strategy is indispensable, enabling the optimal strategies in the public authority to be implemented within an equilibrium environment.

Finally, by researching the logical relationships between exogenous variables (independent variables), various decision variables (intermediate variables, including *the optimal level of detail of output specifications, optimal tender offer, optimal intensity of incentives, optimal technological innovation strategy, optimal intensity of regulation, and optimal opportunism strategy,* hereinafter referred to as the "six optimal strategies"), and PUPC (dependent variable), this thesis seeks the exogenous factors and trends influencing PUPC, summarizes the path to saving PUPC, and provides theoretical guidance for saving PUPC in the public authority.

1.7 Expected contribution

From a theoretical perspective, this thesis represents a new advancement in prior research by integrating the transaction and construction stages of the PPP pattern to study saving PUPC. Its research on decision chain and decision equilibrium aligns more closely with PPP management practices, and its corresponding results possess more operability.

From a practical application perspective, this thesis will construct both a qualitative theoretical model and a quantitative mathematical model for saving PUPC. It will find the optimal strategies for the level of detail of output specifications, the intensity of incentives for technological innovation, and the intensity of regulation against opportunism. Concurrently, it will analyze the factors and trends influencing PUPC, providing an operational pathway for the public authority to save PUPC. Over the past three years, China's PPP industry has undergone comprehensive rectification to address issues of construction investment overspending and local government debt risks in PPP projects, resulting in a marked cooling of the PPP pattern (General Office of the State Council of the People's Republic of China, 2023). Consequently, researching on saving PUPC in this background holds important practical significance. The research in this thesis will contribute to correcting the current "irregularity" in the level of detail of the output specifications of the PPP project in China, and will contribute to promoting the public authority to "do good deeds and be good at doing them" in the incentives and regulation of the PPP project.

1.8 Planned literature

This literature review aims to read and sort out previous research results about the research themes, accurately and systematically grasping knowledge about the research themes. On this

basis, it clarifies the application of existing knowledge in this thesis and its role as the theoretical support for this thesis, and identifies the innovation points of this thesis compared with existing knowledge and the progress made on the basis of previous research.

Firstly, the research object of this thesis is the PUPC of the PPP pattern. Consequently, the literature review describes the PPP concept, PPP core value, PPP characteristics, stages of PPP experience, PUPC in the public authority, construction cost and tender offer in the private partner, and PPP risks.

Secondly, this thesis will use Mathematical Modelling of Game Theory to study saving PUPC. This research method is not as widely applied in management research as the interview method; Therefore, the literature review needs to explain the concept of game theory, the classification of games, and dynamic game of complete information.

Thirdly, the research themes of this thesis are output specifications, incentives, technological innovation, regulation, and opportunism within the PPP project. Consequently, the literature review describes the concepts, classifications, methods, and measurements for the research themes.

Fourthly, building upon the above, the end of each third-level heading within the literature review summarizes the application of existing knowledge and its role as theoretical support for this study. The end of each second-level heading within the literature review analyses the differences and progress between this study and previous research.

1.9 Research method

1. Interview method

Interview method, as a research method, is widely used in management research (Y. F. Wang, 2009), and it is one of the main research methods in this thesis.

The interview method is a method in which the interviewer systematically and methodically collects data through individual interviews or group conversations according to the requirements and aims of the research (Y. F. Wang, 2009). It has five elements: (1) the interviewer; (2) the interviewee; (3) the social context; (4) the process of questioning or conversation; and (5) the information or data (Lu, 2022).

Interview methods are divided into structured interviews, semi-structured interviews and unstructured interviews (Fan et al., 2024). The first half of the interviews in this thesis is a structured interview, and the second half is an unstructured interview.

2. Mathematical modeling method of game theory

It is generally accepted that the game theory began with the publication of The Theory of Games and Economic Behavior by Von Neumann and Morgenstern in 1944. Nash's articles on Nash equilibrium of non-cooperative game published in 1950 and 1951, and Tucker's definition of "prisons' dilemma" in 1950 have laid the foundation of the modern non-cooperative game theory (Zhang, 2012).

Many scholars have used game theory to study the cost and payment of the PPP project (Y. Li, 2017; H. J. Liu, 2010; Y. Liu & Liu, 2020; Owusu-Manu et al., 2018; Rahel, 2020). The mathematical modeling method of game theory is another main research method in this thesis.

Mathematical modeling is a research method that uses game theory, structural equation modeling, system dynamics, and other methods to calculate, reason, and simulate to discover the various relationships and mechanisms of the object under study. It involves establishing mathematical models based on real-world problems, solving the models, and then using the results to solve the real-world problems (Baidu, 2024). With the rapid development of computer technology and artificial intelligence, the application of mathematical modeling in the field of social sciences is receiving more and more attention (H. Z. Li, 2022).

Mathematical model is an abstract and concise description of the essential properties of the research object mathematical symbols, equations, procedures, diagrams, among others. It may explain certain objective phenomena, or predict the future development law, or provide the optimal strategy or better strategy for controlling the development of a certain phenomenon in a certain sense (Zhong, 2005).

3. Focus groups of experts

A focus group is a group interview consisting of several people with similar characteristics or common interests (Barnett, 2018). A facilitator guides the group based on a predetermined set of topics. The facilitator creates an environment that encourages participants to share their perceptions and points of view. The key components of a focus group include developing the focus group guide and deciding the number and type of participants. This thesis uses the focus groups of experts to evaluate the research results from the interview method and modelling method of game theory.

4. Other methods

This thesis applies the theory of construction cost management, in which, the construction cost of the PPP project is calculated and adjusted according to the conventional methods of the construction cost industry; the level of detail of output specifications is expressed as "the proportion of the CS (Construction cost calculated by Norm and Standard) of works specified in the output specifications to the CS of the entire project".

1.10 Structure of the thesis

This thesis consists of seven chapters, with the relationships among them shown in Figure 1.2.

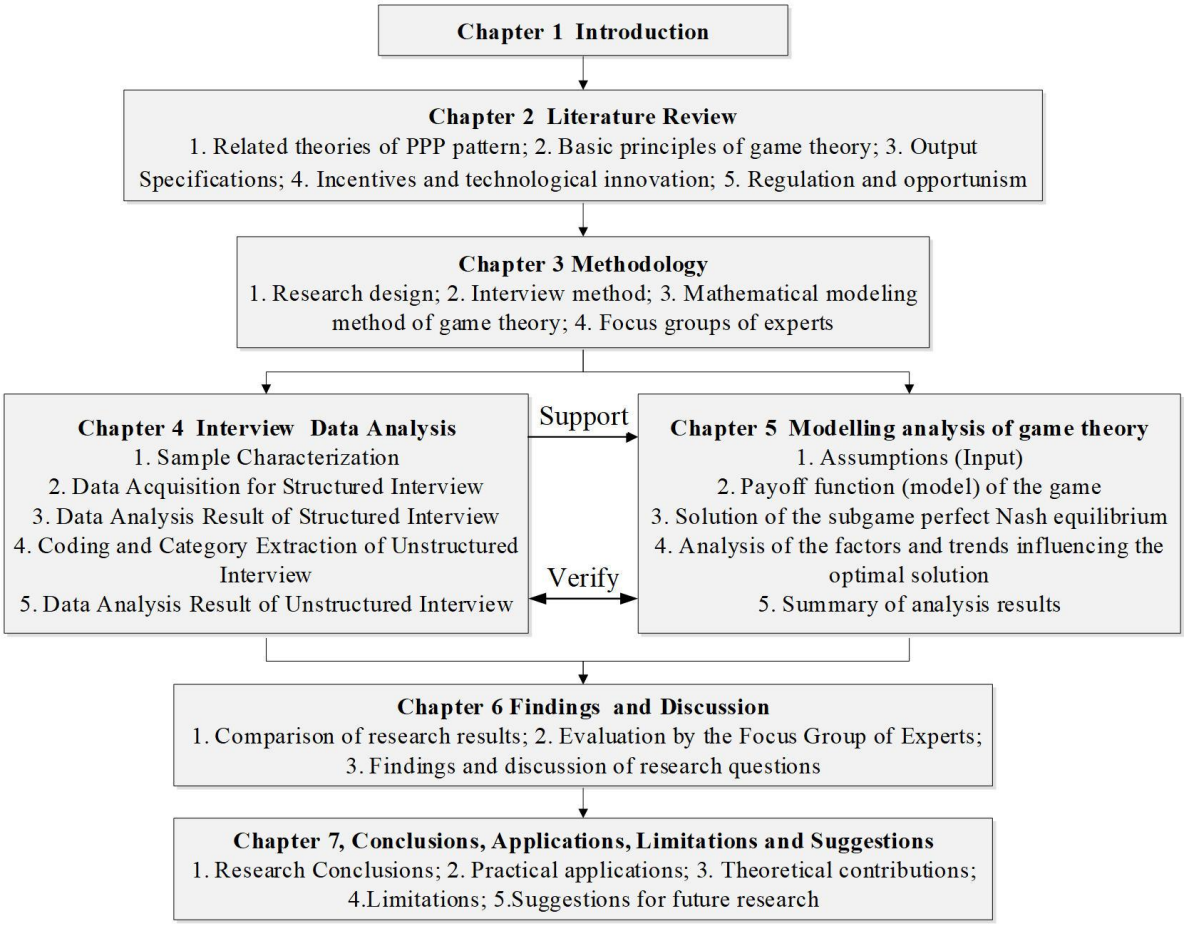


Figure 1.2 Research framework

Chapter 1, Introduction. Firstly, clarify the context of key concepts in this thesis and the practical background of the research object. Secondly, overview the theoretical knowledge related to the research object and identify existing knowledge gaps. Thirdly, sort out the problems in the PPP practice and refine the research questions of this thesis. Fourthly, analyze the research objectives of this thesis in relation to the research questions. Fifth, clarify the correlation between this thesis and real-world and expected contributions, and elaborate on the close connection between the literature review and this research. Sixth, overview the research methodology and structure of this thesis.

Chapter 2, Literature Review. Firstly, review, organize and summaries theoretical knowledge concerning the PPP pattern, game theory, output specifications, incentives and technological innovation, regulation and opportunism. Secondly, elucidate the application of existing knowledge in this thesis and its role in theoretical support, and analyze the innovation and progress of this research based on previous research.

Chapter 3, Methodology. Firstly, describe the overall research design of this thesis. Secondly, detail the research design and process for the interview method, Mathematical Modelling of Game Theory, and expert focus group.

Chapter 4, Data Analysis. Firstly, describe the sample characterization of the interview method. Secondly, elaborate on data collection of structured interviews and the results of data analysis of structured interviews. Finally, elaborate on coding and category extraction of unstructured interviews and the results of data analysis of unstructured interviews.

Chapter 5, Modelling Analysis of Game Theory. Firstly, clarify the scenarios (inputs) for the modelling analysis method of game theory. Secondly, list the payoff functions (models) for the game between the public authority and the private partner. Thirdly, derive the subgame perfect Nash equilibrium solution and analyze the factors and trends influencing the optimal solution of game theory. Fourthly, summarize the results of the modelling analysis.

Chapter 6, Findings and Discussion. Firstly, summarize the similarities and differences between the research results from unstructured interviews and modeling analysis of game theory. secondly, evaluate the results of both research methods using an expert focus group. finally, debate and commentary on the research findings for each of the four research questions in this thesis.

Chapter 7, Conclusions, Applications, Limitations and Suggestions. First, summarize the research conclusions of this thesis. Secondly, elaborate on the practical applications and theoretical contributions of the research conclusions. Finally, explore the limitations of this thesis and suggestions for future research.

Chapter 2: Literature Review

2.1 Related theories of the PPP pattern

2.1.1 PPP pattern concept, core values and characteristics

There is no universal definition of the PPP pattern worldwide (Grimsey & Lewis, 2016). Because different countries, governments, regional economies and social users have different behaviors and habits, different development levels and different public needs, the PPP pattern is also different in the world (Meng, 2019; J. T. Zhou et al., 2019). Table 2.1 lists the definitions of the PPP pattern by some authorities. Of course, the PPP pattern can be summarized into one model, and of course there are common characteristics and essential meanings.

Table 2.1 Definition of the PPP pattern

Institutions	Definitions
European Commission	PPP refers to a partnership between the public authority and the private partner in which the private partner provides public services that traditionally should be provided by the public authority.
National Council for PPP of Canada	PPP is a partnership between the public authority and the private partner, which is based on the respective experiences of both parties and achieves the best efficiency in meeting clearly defined public needs in advance through appropriate resource distribution, risk allocation and benefit sharing mechanisms.
The State Council of the People's Republic of China	PPP pattern is a major innovation in the supply mechanism of public services. It means that the government adopts a competitive way to select the best private sector with the ability to invest and operate. The two sides sign a contract in accordance with the principle of equal consultation to clarify the relationship between responsibilities, rights and interests. The private sector provides public services, and the public authority pays the corresponding fees to the private sector based on the results of the performance evaluation.
The World Bank	PPP is a long-term contract between the public authority and the private partner for the supply of a public products or services, in which the private partner assumes substantial risk and management responsibility.
United Nations Institute for Training and Research	PPP is a form of cooperation between different ownership systems to solve certain complex local problems. The PPP has two meanings, one is a partnership between the public authority and the private partner, and the other is the implementation of large-scale public project and the supply of public products or services.
U.S. National Committee on PPP	PPP is a way of providing public products that mediates between outsourcing and privatization, which makes full use of the private partner to design, build, invest, operate and maintain public infrastructure, and provide related services to meet public needs.

Source: J. T. Zhou et al. (2019)

To sum up the above definitions, the PPP pattern should include the following keywords: long-term partnership, risk allocation and benefit sharing, construction and operation, provision

of public products or services, clearly defined public needs in advance, performance evaluation.

To further clarify the concept of the PPP pattern, it is necessary to analyze the core values and basic characteristics of the PPP pattern, which can promote the accurate understanding of the concept.

Domestic scholars believe that the core value of PPP pattern includes four aspects (S. Q. Wang & Wang, 2017): (1) True risk allocation. Only reasonable risk allocation can realize the value for money of the PPP pattern. (2) Clear output specifications. Unclear output specifications make it difficult for governments to regulate and measure whether a private partner's products or services meet the requirements. (3) Emphasis on the performance of whole life-cycle's integration. The key to the PPP project is to utilize the integration of whole life-cycle (including: financing, construction, operation, maintenance) cost to improve efficiency. (4) Return is linked to performance. The PPP pattern is results-oriented.

The PPP pattern is one type of functional privatization (Weber et al., 2018). Grimsey and Lewis (2016) argue that the essence of the PPP is: (1) The public authority defines the services it needs in the long term through output specifications and performance standards. (2) The private partner is responsible for the construction and operation of infrastructure. (3) The public authority does not pay for the infrastructure until it is put into operation, and pays according to the results of performance evaluations when the assets are put into operation and public services are provided. (4) The private partner must have control of the facility during the operational period. They argue that the core value of the PPP is highly effective incentive-compatible contracts.

Compared with traditional public procurement, the cost-effectiveness of the PPP depends on a financing structure that combines upfront infrastructure construction with future asset return. All of this is due to the inherent incentives of the return mechanism, as well as the risk transfer brought by the PPP pattern. The characteristics of PPP (Grimsey & Lewis, 2016): (1) Benefit sharing and risk allocation. (2) Focus on services rather than procurement of public infrastructure. (3) Innovation. The public authority defines output specifications and provides incentives to the private partner to promote innovation and improve the efficiency of service provision. (4) Risk allocation.

The evaluation of efficiency and performance in the PPP projects is very important. Israel's healthcare PPP project for undocumented migrants uses cost-effectiveness as an efficiency evaluation indicator (Chemtob et al., 2019). The study of PPP projects of healthcare perspective in Saudi Arabia indicates that corporatization should be further stimulated by a standardized set of performance indicators, which include quality criteria and economic efficiency (Khan & Nasrulddin, 2022). PPP program's goal is acknowledging the importance of improving the

nation's infrastructure while also fully aware of the profitability of such infrastructure investment from the perspective of business and private partner (Islami & Hazhiyah, 2020).

Combining the aforementioned literature and the research content of this thesis, the "PPP concept, core values and characteristics" are summarized as follows:

(1) The concept of the PPP pattern. The PPP pattern is a long-term partnership of benefit sharing and risk allocation between the public and private partners, which requires a clear definition of public demand (output specifications) in advance, the private partner undertakes investment, design, construction, operation and maintenance of public infrastructure, and provides public products or services, and the public authority and users pay the private partner according to the results of performance evaluations. This definition aligns with the strategic triangle model of public value theory: public value consensus, legitimacy and support, and operational capability (Moore, 2016).

(2) Designation of the public authority and the private partner. In *Guidance on PPP Contractual Provisions, UNCITRAL Model Legislative Provisions on Public-Private Partnerships* and *UNCITRAL Legislative Guide on Public-Private Partnerships*, the two parties of the PPP model are named as "contracting authority" and "private partner", and used "public authority" in the terminology explanation of "contracting authority" (United Nations Commission on International Trade Law, 2020a, 2020b), in order to correspond with the first two Ps of "PPP", this thesis expresses the two parties of the PPP model as "public authority" and "private partner".

(3) The core values and characteristics of the PPP pattern within the scope of this thesis. First is PUPC. As mentioned above, "results-oriented, performance-based payment", the financing and operation of the project will also affect PUPC (Grimsey & Lewis, 2016). For the purpose of research focus, this thesis does not consider the impact of project financing on PUPC, nor does it consider the impact of project operation on PUPC. Instead, it assumes that the usage and performance evaluation results of the PPP project are in a normal state (the same as the planned values in the PPP contract). Second are output specifications, incentive compatibility, and innovation. Output specifications at the core of public value, incentive compatibility is one of the essential characteristics of the PPP, and innovation is one of the specific characteristics of the PPP.

2.1.2 Stages of the PPP pattern

The PPP pattern is divided into six stages: project establishment, PPP identification, project

preparation, project procurement, project implementation, and project handover (CCEA, 2018).

The PPP pattern is usually divided into development stage and implementation stage. The development stage includes service demand, scheme selection, business forecast, project development, bidding process, and project review. The implementation stage includes finance, design, construction, operation, and handover (Grimsey & Lewis, 2016).

Not all partnerships between the public authority and the private partner are suitable for the PPP pattern (Almaaz et al., 2020). Only those projects that have passed the feasibility demonstration can be implemented using the PPP pattern (NDRC, 2019).

Combining the aforementioned literature and the research content of this thesis, the "stages of the PPP pattern" are summarized as follows:

(1) In summary, the PPP pattern is divided into six stages: project establishment, PPP identification, project transaction, project construction, facility operation, and facility handover. See Figure B.1 in Annex B for details.

(2) This thesis studies the transaction and construction stages of the PPP project. At this point, the PPP project has already passed the project establishment and the PPP identification.

2.1.3 Payment mechanism of the PPP project

Project payment mechanism refers to the way in which the public authority and user pay for public services or public products, including user charges, viability gap funding and government payment (MOF, 2014).

The return mechanism of the PPP project determines the manner and stability of return to the private partner and is the key to the success of the PPP project (Bai et al., 2019). The payment mechanism of the PPP project directly affects the distribution of risks and benefits of the PPP project, and is the core clause of PPP project contracts. the payment mechanism should be selected according to local conditions based on the cooperation expectations of the parties, the users' affordability, industry characteristics and operation pattern (MOF, 2014).

In the payment mechanism of the PPP pattern, user charges are clearly more popular (General Office of the State Council of the People's Republic of China, 2023). China's policy documents state that the PPP pattern is mainly applicable to public services and infrastructure projects that the government has the responsibility to supply and is suitable for market operation (The State Council of the People's Republic of China, 2015). S. Q. Wang and Wang (2017) believes that the PPP pattern is suitable for project with large demand, large project investment, reliable technology, easy charging, and clear output specifications. For example, the Gautrain Rapid Rail

Link in South Africa (Teng et al., 2016; Xiao & Zhang, 2020).

Combining the aforementioned literature and the research content of this thesis, the "payment mechanism of the PPP project" is summarized as follows:

(1) The "payment mechanism" is described from the perspective of public authority and users, and if changed to the private partner, it is the return mechanism. Project return mechanism refers to the source of funds from which the private partner obtains a return on its investment in the project. Since this thesis studies the problem from the perspective of the public authority and users, the term "project payment mechanism" will be used more in the following discussion.

(2) The PUPC studied in this thesis is part of the payment by public authority and users. Of course, PUPC is established on meeting performance evaluations and producing public value (Moore, 2016).

2.1.4 Construction cost of the PPP project

Construction cost is the construction expenditure of the private partner, while PUPC is mainly composed of the payment for construction cost invested by the private partner. To save PUPC, it is necessary to study the concept of construction cost, its compositions, and calculation of construction cost.

2.1.4.1 Concept and compositions of construction cost

According to W. Y. Wang and Xia (1991), "construction cost" is the sum of the monetary expenditures for physical and living labor expended in the project construction, which can be divided into: cost of building and installation work, cost of equipment procurement, deferred fee, other investment expenditure, transferred out investment expenditure, written off investment expenditure.

According to *Financial Rules for Capital Construction* (MOF Decree No. 81) (MOF, 2016), "construction costs" means the expenditures of project construction funds incurred to complete the approved construction content, including cost of building and installation work, cost of equipment procurement, deferred fee, other investment expenditure.

According to *Transport Engineering Technology and Metrology*, the composition of the total investment of highway project (Professional Qualification Center of Ministry of Transport, 2020). The standard glossary of project costs is the national standard for project cost's glossary, which describes the meaning of the professional vocabulary of construction cost (Ministry of Housing and Urban-Rural Development [MOHURD], 2013). MOHURD, Ministry of Housing and Urban-Rural Development (2015) defines the meaning and composition of investment estimation,

budget estimate at design stage, budget and settlement account. The relationship between the total investment of construction project and construction cost is shown in Figure B.2 of Annex B.

2.1.4.2 Classification of construction cost

There are two dimensions of construction cost for the PPP project (Z. M. Wu, 2023): the subject to which the cost belongs and the time when the cost occurs. According to these two dimensions, the classification of construction cost is shown in Table 2.2.

Table 2.2 Classification of construction cost

Categories of construction cost	Whose construction cost	Time: first → last		
		Transaction stage	Point in time for signing	Construction stage
Construction cost calculated by Norm and Standard (CS)	Average construction cost to society (the public)	Construction Cost Calculated by Norm and Standard for the Entire Project (C)		
Internal construction cost of the enterprise (C')	Internal construction cost of the private partner	Forecasted internal construction cost of the enterprise		Actual internal construction cost of the enterprise
Transactional construction cost	Transaction and settlement account between the public authority and the private partner	Quoted construction cost	Agreed construction cost	Actual paid construction cost

Source: Z. M. Wu (2023)

The construction cost calculated by Norm and Standard (abbreviated as "*CS*") is the construction cost calculated based on socially average cost indicators, such as the consumption standard of factors of production (labor, materials, machinery, equipment) stipulated by Norm and Standard of the country or industry, the market average unit prices of factors of production, the industry average overhead cost rate, the industry average profit rate, and the benchmark lending rate. Construction cost calculated by norm and standard for the entire project (*C*) is the sum of the CS of the engineering elements of the entire project. It reflects the average social level of construction cost and is the common knowledge of both sides of the game. The composition of *C* can be summarized by this equation: *C*=Cost of factors of production×(1+Overhead cost rate)×(1+Profit rate)×(1+Tax rate)+Other fee of construction+ Contingency fee+ Interest during construction period (Z. M. Wu, 2023). See Table B.1 in Annex B for details.

In *Technology and Measurement of Transportation Engineering*, Professional Qualification Center of Ministry of Transport (2020, p. 357) defines the calculation method and procedure of C of highway engineering. Annexes 3 and 4 of *Costs composition of building and installation work* describe the calculation method and procedure of C of building construction project from

two different perspectives: that of the employer and that of the contractor (MOHURD, 2013).

The quoted construction cost is the construction cost of the project as set out in the bidder's tender offer document. It is the construction cost quoted in the tender offer document by the private partner, considering C, the internal construction cost of the enterprise, the tender offer strategy, and the potential construction cost savings at a later stage (Professional Qualification Center of Ministry of Transport, 2020).

The internal construction cost of the enterprise (C') refers to the construction cost of the project calculated by the private partner based on its own cost indicators, such as the enterprise's internal consumption standard of production factors (labor, materials, machinery, equipment), enterprise's internal procurement unit prices of production factors, enterprise's internal overhead cost rate, enterprise's internal profit rate, and the enterprise's own lending rate, see Table B.1 in Annex B for details. Its compositions are the same as *C*, but each composition is calculated based on the enterprise's own cost indicators rather than the socially average cost indicators. It is the private partner's private information (Professional Qualification Center of Ministry of Transport, 2020).

If the private partner does not have the enterprise's internal control data on the consumption, or does not have a supplier quotation system, it can also extrapolate the enterprise's internal construction cost based on *C* (Z. M. Wu, 2023). *C* reflects the average level of the society, the private partner as an individual of the society, its level of project management and engineering technology will be generally higher than the average level of the society (in general, only large enterprises or investors with strong strength can participate in the construction of the PPP project), and this advancement of the project management and engineering technology will be ultimately reflected in the reduction of the construction cost (*the private partner's internal construction cost is lower than C*), therefore, the enterprise's internal construction cost will be appropriately discounted on the basis of C. This discount rate is called "θ". Therefore, C'=θ×C (Professional Qualification Center of Ministry of Transport, 2020).

2.1.4.3 Construction cost of each stage

In the transaction stage of the PPP project, the private partner should forecast the quoted construction cost. The private partner calculates its quoted construction cost based on the forecast internal construction cost of the enterprise (Professional Qualification Center of Ministry of Transport, 2020).

At the signing of the PPP project, the private partner can calculate the agreed construction cost of the project based on the agreed PUPC and the conversion relationship between the

construction cost and PUPC (J. T. Zhou et al., 2019).

In the construction stage of the PPP project, the private partner focuses on internal construction cost of the enterprise and actual paid construction cost, and reduce cost and increase efficiency through design deepening and design optimization.

2.1.4.4 Summary

Combining the aforementioned literature and the research content of this thesis, the "construction cost of the PPP project" is summarized as follows:

(1) The "construction cost" in this thesis refers to the forecasted or actual total fixed assets investment expenditure incurred to complete a construction project, which includes cost of building and installation work, cost of equipment procurement, other fee of construction, contingency fee, and interest during the construction period (Z. M. Wu, 2023). The definition of this concept is entirely consistent with domestic cost management practices.

(2) C in this thesis can be calculated by the public authority through output specifications and industry standards; C' can be calculated by the private partner through output specifications, C, discount rate of productivity level, and the deviation coefficient of quantities (Professional Qualification Center of Ministry of Transport, 2020).

2.1.5 PUPC in various stages of the PPP project

PUPC consists of two parts: the payment for construction cost from the private partner and the expenditure for regulation from the public authority, with the latter accounting for a very small proportion. For simplicity, PUPC in this section only includes the payment for construction cost from the private partner and excludes the expenditure for regulation from the public authority.

At present, the payment models of the PPP project include: the payment model based on project investment and the payment model based on usage (J. T. Zhou et al., 2019). No matter what kind of payment model is based on cash flow analysis as the basic tool. The cash flow for construction cost expenditure and PUPC is shown in Figure B.3 of Annex B.

2.1.5.1 PUPC forecasted in the transaction stage

In the transaction stage of the project, the public authority needs to forecast PUPC, which aims to calculate the PUPC's tender sum limit (MOHURD, 2015).

In the transaction stage of the project, the private partner forecasts the PUPC's offer based on the quoted construction cost, as follows:

1. PUPC forecasted by investment-related payment model (J. T. Zhou et al., 2019)

The investment-related payment model refers to the method of calculating PUPC by the FNPV formula based on the forecasted total construction cost of the project, the forecasted reasonable profit rate, and the forecasted annual discount rate. Forecasted total construction cost of project is composed of building cost, other fee of construction, contingency fee, interest during construction period, and all these components are forecasted. Municipal roads and sponge cities generally use the investment-related payment model.

2. PUPC forecasted by usage-related payment model (China International Engineering Consulting Corporation, 2021)

The usage-related payment model refers to the method of calculating PUPC by the FNPV formula based on the forecasted usage, forecasted PPP service price, forecasted other revenue, forecasted operation and maintenance cost, and forecasted annual discount rate. Urban rail transit and expressway projects generally use the usage-related payment model., such as: Agreed Fare Method, Vehicle-Kilometer Subsidy Method (Q. Yang et al., 2021).

In summary, regardless of the payment model, when the private partner's forecasted construction cost decreases, the tender offer of the PUPC decreases accordingly.

The charging price is the main evaluation indicator for determining the successful bidder of the PPP project. The evaluation generally follows the principle of "low price priority" (General Office of the State Council of the People's Republic of China, 2023).

2.1.5.2 PUPC (contract price) at the time of contracting

1. Investment-related PUPC (contract price) (J. T. Zhou et al., 2019)

The investment-related PUPC (contract price) is the PUPC amount calculated based on the total agreed construction cost, agreed profit rate, and agreed annual discount rate.

2. Usage-related PUPC (contract price) (China International Engineering Consulting Corporation, 2021)

The usage-related PUPC (contract price) is the PUPC amount calculated based on the agreed usage, agreed PPP service price, agreed annual discount rate, among others.

Construction risk is generally borne by the private partner (Grimsey & Lewis, 2016). According to industry practice, PUPC (contract price) is generally signed as a lump sum contract, which means that PUPC will not be adjusted if there are no contract changes or risk events and the results of the operational evaluation are the same as the planned values (S. Q. Wang & Wang, 2017). For the parties, an exogenously given fixed-price contract solves the moral hazard problem (Laffont & Martimort, 2002).

2.1.5.3 PUPC (actual payment) in the operation stage

PUPC (actual payment) is the actual amount paid by public authority and users to the private partner after the private partner has provided products or services that meet performance standards.

1. Investment-related PUPC (actual payment) (J. T. Zhou et al., 2019)

PUPC (actual payment) = [PUPC (contract price) + adjustments to payment resulting from contract changes] × Performance evaluation coefficient

Adjustments to payment resulting from contract changes: Events for which the public authority should bear responsibility and risk may result in adjustments to the PUPC. In addition, if design optimization results in savings in construction cost, the public authority should share these savings, which will lead to a reduction in the PUPC. These two types of payment adjustments are referred to as "adjustments to payment resulting from contract changes".

Performance evaluation coefficient: The results of the public authority's evaluation of the operation of the PPP project according to the agreed evaluation method. Public authority and user payment is based on performance evaluation, while performance evaluation is based on output specifications (GIH, 2019; MOF, 2020).

2. Usage-related PUPC (actual payment) (China International Engineering Consulting Corporation, 2021)

PUPC (actual payment) = [PUPC (contract price) + adjustments resulting from usage and unit price +adjustments to payment resulting from contract changes] × Performance evaluation coefficient

Adjustments resulting from usage and unit price: Adjustments to the PUPC resulting from the actual usage or unit price of the PPP project being lower (or higher) than the minimum (or maximum) value specified in the contract. Such adjustments are subject to the prerequisite that the public authority should bear the excess risk (or excess revenue) as agreed in the PPP contract.

Other concepts have the same meanings as above.

Contract changes are inevitable (Z. X. Liu, 2018). Changes in construction cost due to contract changes are handled in accordance with risk allocation principles (Ministry of Transport of the People's Republic of China [MOT], 2015). Contract changes in PUPC are incurred in the following situations:

(1) PUPC (Contract changes) occurs when risks assumed by the public authority occur. During the construction of a project, there are risks that should be borne by the public authority, and the bearing of risks means increasing payment. For example, changes in laws and regulations,

which are risks to be assumed by the public authority, will generate changes in PUPC.

(2) PUPC (Contract changes) also occurs when events occur for which the public authority is responsible (or entitled). The private partner saves internal construction cost of the enterprise through design optimization, and at the same time, according to the incentive strategy of the public authority, it can also cause PUPC changes.

2.1.5.4 Summary

Combining the aforementioned literature and the research content of this thesis, the "PUPC in various stages of the PPP project" is summarized as follows:

(1) The calculation process of PUPC in this thesis is divided into the forecast value in the transaction stage, the contract price at the time of contracting, and the final actual payment value.

(2) In the transaction stage, the evaluation of tender offer generally follows the principle of "low price priority" under equivalent conditions. In accordance with public value management theory, public products or services need to select suitable suppliers through open competition (Moore, 2016).

(3) In the construction stage, construction risk is generally borne by the private partner, so the PUPC (contract price) generally adopts a lump sum contract. This is determined by the risk allocation principle of the PPP pattern (where the private partner bears the general investment, construction, and operation risks, while the public authority bears the policy and legal risks) (MOF, 2019).

2.1.6 Risk of the PPP project

Grimsey and Lewis (2016) describes the risk characteristics of the PPP project. The characteristics of "risk" are that future results are uncertain, but can be analyzed through probability and expected values.

According to the definition of *Risk* in *Guidelines for the Successful Implementation of Public-Private Partnership (PPP) Projects*: "Risk can be defined as any factor, event or effect that threatens the successful completion of the project within the specified time, cost and quality" (Meng, 2019).

2.1.6.1 Classification of the PPP project risk

J. T. Zhou et al. (2019) argue that the risks of PPP project are classified into systematic and non-systematic risks. Systematic risks are classified into force majeure risks, policy risks, economic risks, and legal risks, and non-systematic risks are classified into construction risks, design risks,

investment risks, management risks, operation and maintenance risks, handover risks, and cooperation risks.

Weber et al. (2016) argue that the risks of PPP project are classified into general risks and specific risks. General risks are classified into market risks, interest rate risks, exchange rate risks, ESG (Environmental, Social and Governance) risks, political and legal risks, and force majeure risks. Specific risks are classified as design risks, construction risks, completion risks, technical and performance risks, finance risks, syndicate risks, operation risks, contract and counterparty risks, and realization risks (Grimsey & Lewis, 2016; Weber et al., 2018).

Haqq and Gultom (2022), Hemanta (2012) and Su (2019) also classified the risk of the PPP project. PPP construction risks have been categorized by Standard and Poor in accordance with the kind of assets, indicating that the funding bodies acknowledge the presence of a relationship between construction risks and kinds of PPP assets (Yahya & Saleh, 2020).

2.1.6.2 Procedures for risk management of the PPP project

Weber et al. (2018) argue that risk management refers to managing various types of identified risks as a series of steps, which include: identification, analysis and evaluation, allocation, and monitoring. The best way to mitigate risks is risk management. S. Q. Wang and Wang (2017) constructs the risk structure system model of the PPP project by using SIM theory.

Risk estimation and evaluation of the PPP project is generally expressed in terms of "risk cost", because various risks ultimately lead to increased project cost (J. T. Zhou et al., 2019). Grimsey and Lewis (2016) argue that a characteristic of PPP is "bundling". "Bundling" and "classified transaction" are two completely different contract types and cooperation pattern, "bundling" means increased risk of the private partner.

2.1.6.3 Response strategies for the PPP project risk

CCEA (2018) sets out the principles of risk allocation in the PPP project in *Cost consultation guide for the whole life cycle of PPP projects*. J. T. Zhou et al. (2019) summarize recent domestic documents on risk allocation and describes the principles of risk allocation in the PPP project. Du (2020) demonstrates that the risk of geological conditions in a PPP project should be allocated according to the principle of equity. According to *PPP Project Contract Guide (Trial)*, the basic principles of risk allocation for the PPP project are as follows (MOF, Meng, 2019; 2014; Zhao, 2016):

(1) The party bearing the risk has more control over that risk and is more efficient in managing it compared to other participants. (2) The party bearing the risk can reasonably transfer

that risk (e.g., through the purchase of an insurance policy). (3) The party bearing the risk has a greater economic interest or motive for controlling that risk than the other participants. (4) If the risk eventually occurs, the party bearing the risk should not transfer the corresponding fees and losses to the other participants.

According to the risk allocation framework of the PPP pattern (CCEA, 2018; S. Q. Wang & Wang, 2017; J. T. Zhou et al., 2019), risk resulting from changes in laws and regulations, administrative approvals, changes to output specifications proposed by the public authority, and Supporting facilities outside the scope of the PPP project shall be borne by the public authority; macro market price risk, unforeseeable social risk, force majeure risk, and changes to output specifications proposed by the private partner shall be shared by the public authority and the private partner, and other general risk (including: general investment, construction, and operation risks) shall be borne by the private partner.

There are clear benefits to risk transfer through the PPP pattern (Nisar, 2007). The public authority uses its deterrent position to transfer risk of the PPP project to the private partner. By bargaining, the actual proportion of risk transferred is "probability that the public authority will utilize the deterrent position × the expected proportion of risk transferred by the public authority" (L. Li et al., 2013; Y. Li, 2015).

2.1.6.4 Summary

Combining the aforementioned literature and the research content of this thesis, the "risk of the PPP project" is summarized as follows:

(1) Considering the focus of the research theme and the complexity of the payoff function in this thesis, for risk estimation and evaluation, the "deviation risk of the quantities" is included in the research model as a separate parameter; other risks are not included as separate parameters, but are implied in the corresponding cost parameters (without explicitly expressing the risks). For example, the "behavioral cost of design optimization" implies the risk cost of design optimization.

(2) The main strategies of the public authority for responding to the deviation risk of the quantities are risk-averse and risk transfer. If the risk-averse strategy is adopted, the output specifications need to be more detailed; if the risk transfer strategy is adopted, the output specifications need to be rougher. The deviation risk of quantities is one of the research contents of this thesis.

2.1.7 Literature commentary on the PPP pattern

The theoretical knowledge of the PPP pattern related to this thesis is summarized in each sub-section above, the PUPC of the PPP pattern is the subject of this research.

The PUPC in this thesis is analyzed by running through the transaction stage and the construction stage, which reflects the third core principle of the PPP project "emphasizing the integration of all stages and forming performance" (S. Q. Wang & Wang, 2017, p. 229). Splitting the PUPC into the contract price and contract changes price, where the contract price corresponds to the transaction stage and the contract changes price corresponds to the construction stage, which is closer to the practical application of the PPP pattern. There are some scholars who have studied how to realize the optimal solution of benefit distribution of the PPP project in the transaction stage, and there are also some scholars who have studied the performance-based PUPC adjustment in the construction stage or the renegotiation of PUPC based on the unanticipated situations that occur, but there are very few of them who have studied the saving PUPC by running through the transaction stage and the construction stage of the PPP project.

The PUPC in this thesis is based on a lump sum contract. According to the characteristic of the PPP pattern that construction risks should be borne by the private partner, the public authority should manage PUPC by lump-sum contract. The choice of lump-sum contract or unit-price contract is the most basic issue of cost management or payment management. When many scholars study the distribution of benefits from the PPP project and the improvement of public service efficiency, they emphasize more on the positive relationship between the payment obtained by the private partner and the inputs (L. Li et al., 2013), and more on the positive relationship between the payment obtained and the risk borne (L. Li et al., 2013; Y. Li, 2017; Meng, 2019; Song et al., 2020). This thesis emphasizes that the payment obtained is positively correlated with the planned inputs before signing the contract. However, after signing, the payment obtained is not necessarily positively correlated with the actual inputs. this differs from previous research.

2.2 Basic principles of game theory

2.2.1 Concept of game theory

Generally, it is believed that game theory began in 1944 with the publication of *The Theory of Games and Economic Behavior* by Von Neumann and Morgenstern (1944).

According to Zhang (2012), game theory is a theory that studies the different players'

strategies which can interact with each other and the strategies equilibrium. According to S. Y. Xie (2021), game theory is a theory that studies the players' decision-making behaviors which characterized by strategy interaction and interest dependence.

The basic concepts of game include player, action, strategy, information, payoff, outcome, equilibrium. The player, action and outcome are collectively referred to as game rules. Player, action, strategy, payoff and information are the elements that make up the game (S. Y. Xie, 2021; Zhang, 2012).

Game representations include strategic form representation and extensive form representation, the former generally uses game tables and the latter generally uses game tree. The game tree is composed of decision node, terminal node, branches, information set and payoff vectors (Zhang, 2012).

Combining the content of this thesis, the "concept of game theory" can be summarized as follows:

According to the above concept, this thesis studies the game between the public authority and the private partner in the transaction and construction stages of the PPP project. The actions of the public authority include the level of detail of output specifications, the intensity of incentives, and the intensity of regulation; the actions of the private partner include tender offer, technological innovation, and opportunism. These actions all have their own strategic space. After the game, the corresponding payoff function is finally formed. The PPP pattern possesses the original scenario for the game, which creates the conditions for adopting game theory to study the payment mechanism of the PPP pattern.

2.2.2 Classifications of the game

Game can be divided into static game and dynamic game according to whether the behavior of the players has a time sequence (S. Y. Xie, 2021; Zhang, 2012). In the game, the players at the same time to choose action, or not at the same time to choose action, but the latter actor does not know the former actor chose what action, this game is called a static game. In the game, the actions of the players have a time sequence, and the latter actor can observe the action chosen by the former actor, this game is called a dynamic game. Common understanding: the actions of the players in the "Prisoners' Dilemma" are at the same time, which belongs to the static game, while the actions of the players in the "Go Game" are sequential, which belongs to the dynamic game.

According to whether the payoff function of all players is the common knowledge, the game can be divided into complete information game and incomplete information game (S. Y. Xie,

2021; Zhang, 2012). In a game, each player knows exactly the payoff function of all players in all situations, this game is called a complete information game. In a game, one or more players do not know accurately (including: do not know, know but not accurately) the payoff function of other players, this game is called an incomplete information game.

At present, the games can be divided into: static game of complete information, dynamic game of complete information, static game of incomplete information, dynamic game of incomplete information, see Table B.2 in Annex B for details.

The principal-agent relationship established between the public authority and the private partner is an important element of cooperation in the PPP project (Song et al., 2020).

Many scholars believe that the public authority and the private partner in the PPP pattern are rational person, and study the game between them as a dynamic game of complete information. as shown in Table 2.3.

Table 2.3 Summary of different scholars' research results on the types of games in the PPP project

No.	References	Thesis or book	Categories of the PPP game
1	H. J. Liu (2010)	*Revenue distribution of PPP model based on game theory*	Based on the dynamic game of complete information, the issue of interest distribution in the PPP project can be studied.
2	L. Li et al. (2013)	*Game model for PPP project's risk allocation under the asymmetry*	The bargaining process between the public authority and the private partner can be understood as a dynamic game of complete information.
3	Zhao (2016)	*PPP cooperation mode of government and state-owned enterprises in transportation infrastructure projects construction*	Based on the dynamic game of complete information, the game pricing model of operational PPP project and the game pricing model of quasi-operational and non-operational PPP project were studied separately.
4	Meng (2019)	*Research on game strategy of risk allocation for public-private partnership projects*	Based on a dynamic game of complete information, the sequential bargaining negotiation in the transaction stage and the renegotiation in the construction stage of the PPP project are studied.
5	Ni (2019)	*Research on the renegotiation of PPP project based on game analysis*	The PPP project renegotiation stage is simulated into two stages: initial renegotiation and in-depth renegotiation. Then, the behavior and results of the two stages are analyzed using a dynamic game of complete information.
6	Phuong (2022)	*Networking Actors in Private Public Management Tourism*	All parties need to share information and work together, ensuring collaboration is carried out in a transparent and responsible manner. This can improve the overall efficiency and effectiveness

No.	References	Thesis or book	Categories of the PPP game
		Development Partnership	of the project, enhance coordination and collaboration among numerous participants, and reduce disagreements.

Combining the aforementioned literature and the research content of this thesis, the "classifications of the game" is summarized as follows:

Following the previous research methodology, this thesis also studies the game between the public authority and the private partner using "dynamic game of complete information". The "dynamic game of complete information" is a common and representative game type in the PPP pattern.

2.2.3 Dynamic game of complete information

2.2.3.1 Understanding of sub-games

The subgame is a part of the original game. When the subgame is cut from the original game, the information set of the original game cannot be cut. That is: (1) The subgame starts with a singleton information set. (2) Both the information sets and the payoff vectors of the subgame directly inherit the original game. The information set of a decision node of the subgame is equal to the information set of the decision node of the original game, and the payoff function of a terminal node of the subgame is equal to the payoff function of the original game. The relationship between these two equations does not change because the subgame is cut from the original game (Zhang, 2012).

2.2.3.2 Subgame perfect Nash equilibrium

Sequential rationality means that regardless of what happened prior to a decision node of the game, the players should optimize their decisions at the point in time of that decision node. Subgame perfect Nash equilibrium requires the players to be sequentially rational. The strategy of a subgame perfect Nash equilibrium is the optimal action choices for any player in any possible situation (i.e., at every decision node), even if that situation may not actually occur. A player may have multiple action paths in the strategy of the subgame perfect Nash equilibrium, but there is only one equilibrium path corresponding to the strategy of the subgame perfect Nash equilibrium (or, equivalently, there is only one), and it is the Nash equilibrium of the original game. Other than this equilibrium path, the other paths in the strategy of subgame perfect Nash equilibrium are just the Nash equilibrium of some subgame, not the Nash equilibrium of the original game (Zhang, 2012).

2.2.3.3 Backward induction

Backward induction is the most convenient method for solving "the subgame perfect Nash equilibrium" of the dynamic game of perfect information (Zhang, 2012)，which excludes the implausible strategies among the players' strategies, and reasoning forward from the last stage of the dynamic game.

The specific steps for solving the subgame perfect Nash equilibrium by backward induction are as follows (Zhang, 2012):

(1) The player of the last decision node (not the terminal node) of the original game judges his optimal choice, which is the Nash equilibrium of the subgame starting from that decision node.

(2) According to the optimal choice of the last decision node and the relevant information of the game tree, judge the optimal choice of the penultimate decision node (the immediate predecessor node of the last decision node), which is the Nash equilibrium of the subgame starting from the penultimate decision node.

(3) In this way, the judgment is constantly made from the back to the front, and the Nash equilibrium of the corresponding subgame is obtained at each step, until finally, the Nash equilibrium of the whole game (the original game) is obtained, then, this Nash equilibrium is the subgame perfect Nash equilibrium of the original game.

2.2.3.4 Summary

Combining the aforementioned literature and the research content of this thesis, the solving of "dynamic game of complete information" is summarized as follows:

The strategy space of all actions from the public authority and the private partner in this thesis are continuous variables. Consequently, each action can be taken as a parameterized decision branch for research, and then the subgame perfect Nash equilibrium solution is obtained using backward induction. The method for solving in this thesis is similar to that for solving the *Stackelberg Model*.

2.2.4 Literature commentary on game theory

The game of the PPP project studied in this thesis is a multistage dynamic game of complete information. There are also many literatures that use the dynamic game of complete information to study the public authority's payment of the PPP project, however, few of them combine the transaction stage and the construction stage to build the game tree, study how to save the PUPC.

The characteristics of "complete information" in the PPP project are mainly reflected in

(Professional Qualification Center of Ministry of Transport, 2020):

(1) The private partner can observe the level of detail of output specifications from the public authority in advance. The public authority also knows the behavior rule of the private partner's tender offer in advance.

(2) The private partner can observe the incentive strategy of the public authority in advance. The public authority knows in advance the behavior rule of technological innovation of the private partner, and the results of technological innovation can be measured jointly through Norm and Standard (which is common knowledge) in the industry.

(3) The private partner can observe the intensity of regulation from the public authority in advance. Although the public authority does not know in advance whether the private partner will engage in opportunistic behavior and the amount of opportunistic behavior, the public authority knows in advance the behavior rule of opportunistic behavior of the private partner.

(4) The public authority obtains the characteristic information through pre-tender market testing, pre-tender Q&A and solicitation of opinions, and visits to the private partner.

The private sector obtains the characteristic information of the public authority by reading the bidding documents, conducting site surveys, participating in Q&A sessions, and economic negotiations, so that the information of both sides is close to complete information. In our study of realistic problems, it is difficult to achieve the theoretical state of "complete information", but it is possible to come close to this state.

The characteristic of "dynamic game" in this thesis is that the two stages of the PPP project (transaction stage and construction stage) have a time order (CCEA, 2018).

2.3 Output specifications

2.3.1 Concept and framework of output specifications

Output Specifications refer to the economic and technical standards that the project assets should meet after completion of the project, as well as the scope and standards of delivery of public products and services, and the level of performance to be achieved (MOF, 2014). In the case of highway project, for example, output specifications is dispersed in the various chapters of the feasibility study report (FSR) on the traffic flow analysis and forecasting, construction necessity, construction conditions, technical standards, and construction plans (MOT, 2010).

The output specifications are a component of the overall contract between the owner and the private partner. The output specifications are the part of a contract that defines the performance

requirements of the project: the functional requirements, the minimum technical requirements for the design and construction, and the scope and level of performance for services. It is the technical foundation of the procurement, delivery and –in a PPP– the operational phases of the contract, and is used to determine compliance at all phases of the project lifecycle (GIH, 2019).

Output specifications are very important documents in the procurement of the PPP/PFI project. It defines the public services and public products to be output from the PPP project and the performance objectives to be achieved, however, it is not required to describe how these objectives will be achieved. It also describes the constraints or limitations on the public services or public products, e.g., on holidays, the use of expressways is free for users. Output specifications are formed progressively in the establishment stage and PPP identification stage, and are formalized before the project procurement documents are issued (Javed, 2013).

HM Treasury (2006) points out that PPP/PFI contracts require the private partner to design, build and operate infrastructure to deliver assets and services that meet the output specifications agreed with the public authority, and then handover the facilities to the public authority at the end of the contract. Output specifications contain expectations, objectives, aims, scope, and performance requirements, and address standards, constraints, risks allocation, and solutions that encourage alternatives and innovation. Output specifications should leave space for technological innovation and cost-effectiveness improvement for the private partner, and encourage the private partner to seek the best way to achieve output objectives.

The output specifications are the core of the procurement and monitoring documents of the PPP or PFI project. The output specifications specify the requirements for project and public services, not how to deliver them. Performance standards or output parameters are used in evaluation of tender documents and monitoring of operations. PPP/PFIs in the UK and Australia have encountered common pitfalls and change management issues. Common pitfalls include conflicts between input elements and the output specifications, and compromises between performance standards and affordability. The public authority tends to make small changes that result in the change management of the output specifications. Preset terms in output specifications can be adjusted through negotiation when circumstances change. The long cooperation period of PPP/PFI Project means that changes in preset terms are inevitable and, therefore, output specifications should be managed as a tool (Lam & Javed, 2015).

A well written set of output specification can induce innovation, bring about increased efficiency and effect appropriate risk transfer from the public to the private partner in the PPP project. Even though all three projects are different in nature, sizes and located in different countries, they share the common approach about development of output specifications, payment

and change mechanism. Output specifications were flexible to accommodate future changes. Change protocols were parts of the project agreements in all three case study projects (Javed et al., 2011). The output specifications are one of the core documents of the PPP contract, and contract governance can directly influence and enhance the performance of the partnership (Latif et al., 2023).

In *Guideline on Whole Life-cycle Consulting for PPP*, CCEA (2018) made a systematic summary on domestic output specifications, and divided the output specifications into two modules: (1) Project asset standards (Economic standards, technical standards). (2) Delivery standards for public products and services (Quality, price, and quantity of products and services, concession period, sustainability of the project, public authority's benefit).

Javed (2013) made a systematic summary on foreign output specifications in his article "*A Model of Output Specifications for Public-Private Partnership Projects*". He believed that, The output specifications is divided into 10 modules (See Figure B.4 in Annex B). He took output specifications as the core tool of the PPP project to the whole process management.

Combining the aforementioned literature and the research content of this thesis, the "concept and framework of output specifications" are summarized as follows:

(1) The "output specifications" in this thesis refer to the economic and technical standards that the project assets should meet after completion of the project, as well as the scope and standards of delivery of public products and services, and the level of performance to be achieved. From the perspective of public value theory, the output specifications are the consensus on public value and also the basis for public value management.

(2) Output specifications are part of the contract and the core content of PPP project procurement and monitoring documents. Good output specifications need to be appropriately detailed, provide incentives for innovation, and improve the efficiency of the PPP project.

2.3.2 Level of detail of output specifications

The basic level of detail of output specifications refers to a certain level of detail that output specifications should achieve, which should meet the work requirements of feasibility study, value-for-money evaluation, and financial affordability evaluation, and clearly express public demands. In the concluding remarks of *PPP Revolution*, Grimsey and Lewis (2016) summarize six factors for the success of the PPP. Factors, two of which are: (1) Service results can be clearly demonstrated and measured, (2) some space and incentives exist to introduce design innovations and operational innovations to improve efficiency.

In the preliminary stage of the PPP project, the level of detail of output specifications should meet the work requirements of feasibility study, value-for-money evaluation, and financial affordability evaluation. The demand analysis, construction content and scale, site selection, product scheme, construction condition, land and environmental resource, operation scheme and investment estimation in *General Outline for Writing Feasibility Study Report of Government Investment Projects* are closely related to the output specifications (NDRC, 2023). The calculation of the construction and operation cost, PPP value**,** and PSC value related to the value for VFM is based on the output specifications (MOF, 2015). The calculation of project construction cost, annual operation cost, and concession period related to the financial affordability evaluation is also based on the output specifications (MOF, 2015).

The optional level of detail of output specifications refers to the level of output specifications chosen by the public authority according to actual needs on the premise of reaching the basic level of detail. Optional level of detail≥ basic level of detail. The level of detail in output specifications should be set reasonably. They should not be too detailed or too rough (S. Q. Wang, 2017).

Some contents of output specifications, including technical standards, design plans, and project sustainability, are not required to be specified in detail by the public authority for every project, and optional arrangements can be made according to public demands and the actual needs of the project (S. Q. Wang & Wang, 2017). For example, in the output specifications of a expressway project, the description of roadbed engineering and slope support engineering can be detailed or rough, which can be determined by the public authority according to the situation of the specific project.

GIF (2019) believes that output specifications can be further refined through procurement negotiations, including: (1) Amendments from tender clarifications and competitive dialogue. (2) Evaluate compliance of proposed solutions against the specification. The procurer can negotiate with the private partner on variable details in the project contract, including technical and service requirements in the procurement requirements (MOF, 2014).

Design documents for construction project can usually be used as part of the output specifications, with different levels of detail required for different design stages. According to the *Regulation for Drawing up Design Documents of Highway Engineering*, two-stage design is generally adopted for highway project, i.e.: preliminary design and construction drawing design. For small-scale construction project with simple technology and clear programs, one-stage design, i.e. construction drawing design, can be adopted. For construction project with complex technology and lack of basic information, three-stage design, i.e. preliminary design, technical

design and construction drawing design, is adopted (MOT, 2007). According to the level of design detail, the design of building construction project can be divided into: scheme design, preliminary design, and construction drawing design (MOHURD, 2016).

Combining the aforementioned literature and the research content of this thesis, the 'level of detail of output specifications' is summarized as follows: the value range of the level of detail of output specifications is [basic level of detail, maximum optional level of detail]. The level of detail of output specifications should try to enhance the public value of the PPP project.

2.3.3 Literature commentary on output specifications

The theoretical knowledge of output specifications related to this thesis is summarized in each sub-section above. The output specifications are the core document of the PPP pattern, which is the starting point of the research for enhancing the public value of the project and saving PUPC.

This thesis will study the impact of output specifications on tender offer in the transaction stage and technological innovation in the construction stage, and then analyze the optimal level of detail of output specifications. Most of the literature mainly deals with the core role of output specifications, e.g., it can be used as objectives for output, basis for regulation, basis for performance evaluation, and tool for whole-process management, which differs from the study in this thesis.

2.4 Incentives and technological innovation of the PPP project

2.4.1 Concept of incentives

Incentives are the process of stimulating the enthusiasm of organizations or individuals through external stimuli or intrinsic motivation, guiding their behavior to achieve objectives. The innovation incentives mean to promote the innovation activities by means of property right, market and macro policy. At the macro level, the effect of innovation incentives depend on the following factors (X. L. Liu, 2014):

(1) People's willingness to innovate is related to the benefits to the innovator. (2) People's willingness to innovate is related to market transaction and market system. (3) The incentive effect of innovation depends on what means the government adopts to make the private rate of return of the innovation subject consistent with the social rate of return. Government incentives can make up for the defects of market incentives. (4) The incentive effect of innovation also depends on whether the mechanism of incentives for employees to innovate is effective.

In the case of uncertain demand and user intervention, the incentive mechanism of the PPP project can achieve the following effects: (1) Based on the "one man's loss is another's gain" with sharing benefit, a competitive mechanism can be established among private partners of the same capacity. (2) Strong private partners can obtain an "immunity barrier" to prevent weak private partners from sharing the benefit. (3) Strong private partners create benchmark effect, while weak private partners imitate and learn from them (He, 2022).

Although the PPP pattern is a complex institutional arrangement, its basic theory is very simple, and its core idea is centered around the word "incentives" which is reinforced in every element of the PPP contracts (Grimsey & Lewis, 2016).

Combining the aforementioned literature and the research content of this thesis, the core idea of "incentives" can be summarized as follows:

The core concept of the PPP pattern is "incentives". Research on saving PUPC needs to introduce incentive mechanisms, which are frequently studied themes in game theory or rational choice institutionalism.

2.4.2 Methods and cost of incentives

The main incentive methods of the PPP project include (Han, 2023): (1) Financing support. For example, the public authority issues a financing comfort letter, (2) Benefit distribution. For example, the private partner is rewarded as a percentage of the net income of technological innovation. (3) Recognition. For example, recognizing innovation and publicizing it in the industry and society.

S. M. Huang (2020) systematically summarized the incentive methods of the PPP project, and believed that the PPP project had the following incentive methods:

(1) Incentives by finance and taxation, such as reducing and exempting part of the taxes (including enterprise income tax, value-added tax and environmental protection tax), standardizing tax collection and management methods, providing financial subsidies and using PPP fund for support. (2) Incentives by concession period, such as adjusting the concession period according to SPV's financial indicators, internal control management level, public satisfaction, innovation and growth. (3) Incentives by revenue distribution, such as giving a certain incentive revenue to motivate the agent according to the work performance. (4) Incentives by risk allocation. such as giving the public authority to bear the risks that are appropriate for the public authority to bear is also an incentive for the private partner. (5) Incentives by rights of control, such as the reasonable arrangement of residual claim rights and residual control rights

according to the theory of incomplete contracts.

The public authority can establish incentive mechanism for highway PPP project from two aspects: risk allocation and benefit distribution (Z. X. Liu, 2018).

In the PPP project, the core interest of the public authority is social well-being, while the core interest of the private partner the is return on investment. As the stakeholders of the project, the two partners have different standards to judge the success of the PPP project, and the corresponding incentive cost should also be different (Anna & Joanna, 2019). The calculation method for the incentive cost for technological innovation in the public authority is shown in Table 2.4.

Table 2.4 Summary of research results from different scholars on the incentive cost of innovation (in the public authority)

No.	References	Thesis or book	Incentive cost	Description
1	Fang et al. (2018)	Game model and empirical analysis of revenue distribution between contract subjects in the PPP project	Revenue distribution, Incentives=Cδ	1. (public authority, private partner) = (incentives, innovation) is the optimal strategy after eliminating dominated strategies 2. The public authority gives additional incentives (Cδ) to the private partner to incentivize private partner innovation. C: The project cost. δ: The incentive coefficient. $\delta^*=(\alpha+\beta)/2$ α: Retained rate of return for the public authority β: The effort level of the private partner.
2	M. S. Li and Meng (2018)	Incentive mechanism model of the PPP project based on principal agent theory	Revenue distribution	To incentivize technological innovation, the public authority provides the private partner with the additional incentives (αT_1). α: The incentive coefficient, T_1: The increase of project revenue after technological innovation.
3	S. J. Wu and Li (2019)	Impact of PPP return mechanism on innovation under uncertain market demand	Revenue distribution	1. When the market demand is very low or very high, "complete insurance contract" is the best choice for the public authority. In this case, the public authority cannot incentivize innovation from the private partner by increasing the revenue distribution. 2. When the market demand is not very high and not very low, increase the revenue distribution of the private partner "E (η, a)-e (η, a)" to incentivize private partner innovation.

Combining the aforementioned literature and the research content of this thesis, the "methods and cost of incentives" can be summarized as follows:

The incentive cost in the public authority refers to the reward given by the public authority to the private partner for technological innovation, generally calculated as a proportion of the benefits generated by technological innovation. This is also the usual practice in incentive theory (Campbell, 2013; Zhang, 2012).

2.4.3 Concept and Classifications of technological innovation

Schumpeter (1968, p. 73), in *The Theory of Economic Development*, proposed the concept of "innovation", which, according to him, refers to introducing a "new combination of production elements that has never existed before" into the production system. This "new combination" includes: (1) Introduction of new products, (2) Introduction of new technologies, (3) Opening a new market, (4) Control of new supply sources of raw materials. (5) Realization of a new organization of industry.

X. L. Liu (2014) pointed out that technological innovation was the innovation for the purpose of creating new technology, or the application of innovation based on new technology and the new resources created by the new technology. The former includes new technological innovation, while the latter includes the application of new material, new equipment and new process.

In *Economics of Technological Innovation,* X. L. Liu (2014) pointed out that technological innovation refers to the activities of technology, design, manufacturing and business related to the first commercial application of new products and new production courses, including product innovation, course innovation and diffusion. Product innovation is characterized by the formation of a new product, and course innovation is characterized using a new process, or a new design, or a new material, or a new equipment. Diffusion refers to the spread of innovation through market or non-market channels. Non-technical innovation plays an important role in economic development, including management innovation, service innovation, business pattern innovation, supply chain innovation.

The extrinsic motivation for technological innovation in the private partner is derived from the incentives provided by the public authority, while the intrinsic motivation is the need for the private partner to maintain the competitiveness of its tender offers (as a means to maintain the core competitiveness of the enterprise) (Grimsey & Lewis, 2016). In the presence of sufficient market competition, the private partner tends to offer lower tender prices when it perceives a greater potential for technological innovation in a PPP project. Conversely, if the perceived potential for technological innovation is lower, the tender offers are more likely to be higher (CCEA, 2022). The successful experience of medical and health PPP projects is to encourage

improvements in quality and safety while creating new demands (Ikumanozaki et al., 2021). The Private Schools established through Education Service PPPs hold greater advantages than public schools, as private schools possess stronger motivation to reduce the cost and promote the innovation, and provide high-quality, low-cost educational solutions (Osorio et al., 2022). An important area of development of the PPP is the implementation and formation of innovative infrastructure facilities (Desfonteines et al., 2020).

Technological innovation in the construction stage of the PPP pattern refers to the private partner's efforts to enhance project quality and cost-effectiveness through actions in project design, engineering construction, and cost management. The level of the private partner's effort to technological innovation is positively associated with the intensity of incentives provided (M. S. Li & Meng, 2018).

Combining the aforementioned literature and the research content of this thesis, the "concept and classifications of technological innovation" is summarized as follows:

Technological innovation in this thesis refers to modification, improvement, supplementation and refinement of the original design scheme, construction process, material and equipment in the construction stage of the PPP project to save PUPC and enhance the value of the project. According to change management theory (Ries, 2011), technological innovation may occur at various stages of the PPP project; however, this thesis focuses only on technological innovation in the construction stage.

2.4.4 Input and output of technological innovation

Technological innovation is a complex "process" from input to output. Studies on this "process" showed two completely different views from 1960s to 1980s (X. L. Liu, 2014). The first view was that technological innovation was driven by technology, and the famous case was the invention of laser. The second view was that technological innovation was pulled by the market, and the famous case was the invention of the transistor.

Mowery and Rosenberg (1983, p. 195) in *Inside the Black Box* suggested that science and technology (the basis for fundamental, continuously updated knowledge) and market demand (the structure of potential consumer demand) played an important role in the innovation process in an interactive way. Later, this conclusion was endorsed by most economists (X. L. Liu, 2014).

In *An Overview of Innovation*, Kline and Rosenberg (1986) proposed the *Composition of Chain-linked Model*, which identified five paths of innovation.

After clarifying the innovation process, the input and output of innovation need to be

measured.

The technological innovation of the PPP project is mainly in the design stage, which can be divided into general scheme comparison and special innovative development. The cost of general scheme comparison can be calculated according to the *Engineering Survey and Design Charges* (NDRC, 2002), while the cost of special innovation development can be calculated according to the specific development scheme.

Zhang (2012, p. 256) in *Game Theory and Information Economics* cited the model by Holmström and Milgrom (1987), these scholars made the following discussion.

Conditions:

a: The agent's effort variable.

α: The agent's fixed revenue.

β(a+θ): The agent's variable revenue.

θ: Exogenous variable, $\theta \sim N(0,\sigma^2)$.

b: The agent's cost coefficient.

Conclusion:

Excluding the risk factor, the agent cost is $\frac{1}{2}ba^2$, and the agent net income is α+β (a+θ)-$\frac{1}{2}ba^2$

Table 2.5 lists the research results of some scholars on the input and output of technological innovation in the PPP project.

Table 2.5 Summary of research results of different scholars on input and output of technological innovation in the PPP project

No.	References	Thesis or book	Inputs	Outputs (Revenue)
1	H. J. Liu (2010)	Revenue distribution of the PPP model based on game theory	C_{1o} is the normal construction and operation cost of the public authority. C_{2o} is the normal construction and operation cost of the private partner.	$U=0.5\ (e_1d_1+e_2d_2)^2+(e_1d_1+e_2d_2)+u_0$ U: Revenue generated from technological innovation. e_1, e_2: The value of resources input by the public authority and the private partner, respectively. d_1, d_2: The coefficients of the public authority and the private partner contribution to the construction and operation, respectively. u_0: The constant for revenue.
2	Y. L. Wang et al. (2016)	A game of research on the incentive mechanism of PPP projects based on	$C_1=\lambda W_1$ C_1: The Cost of technological innovation in the private partner. W_1: The sum of	$R_1=KW_1$ R_1: The revenue from technological innovation in the private partner. W_1: The sum of incentives. K: The revenue coefficient.

No.	References	Thesis or book	Inputs	Outputs (Revenue)
		investors opportunism	incentives. λ: The cost coefficient.	
3	M. S. Li and Meng (2018)	Incentive mechanism model of the PPP project based on principal agent theory	$C(a)=0.5ba^2$ C(a): The cost of technological innovation in the private partner. a: The effort level of technological innovation in the private partner. b: The cost coefficient of technological innovation in the private partner.	$T_1=k_1a+\varepsilon_1$ T_1: The increase in revenue after technological innovation. k_1: The capability of technological innovation in the private partner. a: The effort level of technological innovation in the private partner. ε_1: The exogenous variable for the impact of technological innovation on revenue, $\varepsilon_1 \sim N_1(0, \sigma_1^2)$.
4	J. Q. Wang (2018)	A mechanism for the governance incentive and supervision of the PPP project from the principal-agent perspective	$C_s=0.5ax^2$ x: The effort level of the agent. a: The cost coefficient of the agent's hard work.	$\Phi=kx+\theta$ Φ: The revenue from the agent's efforts. k: The revenue coefficient x: The effort level of the agent. θ: The exogenous variable, $\theta \sim N(0, \sigma^2)$.
5	China International Engineering Consulting Corporation (2021)	Implementation Plan for the Concession Project of the Rapid Railway from XiongAn New Area to Beijing Daxing International Airport	Calculating the innovation cost by the railroad industry's norm and the drop rate of the tender offer.	When cost savings rate is within 10%, the corresponding net income is shared between the private partner and the public authority; when cost savings rate is above 10%, the net income from the excess belongs to the private partner.

Combining the aforementioned literature and the research content of this thesis, the "input and output of technological innovation" can be summarized as follows:

(1) The purpose of technological innovation in this thesis is to save construction cost and PUPC, which also serves the public authority's need to enhance public value.

(2) The behavior cost (**inputs**) of technological innovation can be measured as follows: Behavior cost of technological innovation = $\frac{1}{2}\Phi dx^2$, where d is the internal construction cost of the enterprise before technological innovation, Φ is the behavior cost coefficient of technological innovation, and x is the construction cost saving rate due to technological innovation. The revenue (**outputs**) of technological innovation can be expressed as a positive proportional function of the construction cost savings rate. These are commonly used measurement methods in game theory (Zhang, 2012).

2.4.5 Literature commentary on incentives and technological innovation

The theoretical knowledge of incentives and technological innovation related to this thesis is summarized in each sub-section above. Incentives are common measures for public value management in the public authority (Moore, 2016), whilst technological innovation is common measures for change management in the private partner (Ries, 2011).

Technological innovation in this thesis mainly refers to the design optimization and design deepening of the PPP project, and the target of incentives in this thesis is, of course, to encourage the private partner to save PUPC through design optimization and design deepening. Most of the literature measures incentives and technological innovation through the variable of the effort level, but the effort level variable is difficult to observe and quantify. This thesis employs the saving rate of construction cost to measure technological innovation in the private partner, which is closer to the actual practice of the PPP project. This approach differs from previous research.

2.5 Regulation and opportunism of the PPP project

2.5.1 Regulation and Accountability in the PPP project

2.5.1.1 Necessity of regulation in the PPP project

Regulation means regulation and management. At present, there are many problems in the implementation of the PPP pattern, which arouse people's thinking on the regulation of the PPP project. According to the annual audit of PPP projects by National Audit Office of the People's Republic of China (2023), by the end of June 2022, there were 151 projects with the slow progress and construction investment exceedance, which resulted in a loss of state-owned assets of 1.722 billion yuan. There were 10 districts that changed construction content without authorization, and illegally constructed conference halls and landscaping projects, involving construction investment of 7.566 billion yuan.

The necessity of government regulation of the PPP project: (1) the administrative function of government departments; (2) The incompleteness of the contract; (3) The characteristics of the PPP project itself (public service or product, large scale, long cycle, payment by the government or the people); (4) The failure of the market mechanism for the public product or service; (5) The differentiation of interests between the public authority and the private partner (Z. X. Liu, 2018). To address skepticism about motives for the private partner engaging in public health partnerships and to ensure public trust, the public authority needs to emphasize shared

goals and implement ethical oversight (Friedman et al., 2025).

The role of "admission regulation" of the PPP pattern is to weed out PPP schemes and concessionaires that fail to deliver value-for-money in order to improve efficiency, while the role of "performance regulation" is to solve market failures and avoid situations where the products or services provided do not meet performance requirements in order to protect the public interest (S. Q. Wang & Wang, 2017).

The regulation of the public authority has two purposes. First, to curb opportunism from the private partner. Second, to ensure that the output of the PPP project meets the requirements of users (S. Q. Wang & Wang, 2017).

Although incentives can curb opportunism to a large extent, it is difficult to rely solely on incentives due to the existence of inconsistent interests (Han, 2023). The case study of Qingdao Metro Line 1 project concluded that there was a need to establish a comprehensive regulation system, which included both the whole process regulation of the PPP project and the performance regulation of each participant (Cui et al., 2020).

2.5.1.2 Accountability mechanism

S. M. Huang (2020) argues that the accountability mechanism of the PPP pattern can motivate the cooperating parties to better assume the corresponding responsibilities, and can cultivate the spirit of contract and business civilization. The incentives are accompanied by the accountability mechanism, which is important for the modernization of national governance and inclusive development.

The accountability to the public authority in the PPP pattern includes: accountability for breach of trust, and accountability for misbehavior. The reasons for accountability for breach of trust include: breach of the spirit of contract, violation of the terms of the contract, and frequent changes in governmental order. The reasons for accountability for misbehavior include: the public authority's misbehavior and failure to fulfill the public authority's legal responsibilities. After accountability, party discipline punishment, administrative punishment, economic punishment, and criminal punishment will be imposed on the relevant responsible persons.

The accountability to the private partner in the PPP pattern includes: accountability for breach of trust, accountability for breach of contract, and accountability for violation of the law. The reasons for the accountability for breach of trust include: the private partner's breach of trust (or failure to keep promises), and breach of trust in economic dealings with cooperative units. The reasons for accountability for breach of contract include: the private partner's failure to complete the financing, construction, operation, and other obligations agreed upon in the PPP

contracts. The reasons for accountability for violation of the law include the private partner's violation of the law in financing, construction, and operation. After accountability, the private partner should bear the consequences: responsibility for breach of contract, involvement by the public authority in the project, punishment for breach of trust, disqualification, and criminal punishment.

2.5.1.3 Summary

Combining the aforementioned literature and the research content of this thesis, the "regulation and accountability of the PPP project" is summarized as follows:

The regulation of the PPP project is necessary, which is a common regulative behavior within new institutionalism (Douglass, 1991). Through regulation, the opportunism of the private partner is effectively curbed, which is a frequent theme in principal-agent research.

2.5.2 Institution, content and methods of regulation

2.5.2.1 Regulation Institution

There are several ways to set up regulation institution in developed countries (S. Q. Wang & Wang, 2017): (1) Setting up a separate institution, e.g., the United States. (2) Setting up relatively opposing regulatory institution in the integrated administration, e.g., the UK. (3) Setting up an industry institution, which is also responsible for the approval, service, and regulatory functions of PPPs, e.g., Singapore. (4) Not setting up an institution, but only setting up a coordinating mechanism, e.g., France. In addition, the regulation institution needs to have the following characteristics: independence, legitimacy, impartiality, broadness, and professionalism.

During the whole lifecycle of a PPP project, the audit department should conduct audit supervision at all stages of identification, preparation, procurement, implementation, and transfer of the PPP project, and at the same time, it should play the roles of authentication, supervision, evaluation, recommendation, and guidance (K. Liu, 2021).

2.5.2.2 Regulation content

PPP Project Contract Guide (Trial) provides an authoritative description on the regulation content of the PPP project (MOF, 2014):(1) Right to know during the implementation of the project. (2) On-site inspection and testing. (3) Right to supervise the private partner's performance of contracts. The public authority shall supervise the private partner's performance in the whole process according to the contractual agreements of the PPP project. (4) Administrative regulation. The public authority, as the administrator, has the function of

administrative management over the private partner. The private partner shall abide by national, industry and local laws, regulations, and systems in all stages of the PPP project. Administrative regulation adopts the principles that are separation of powers for checks and balances, corresponding rights and responsibilities, and accountability (L. L. Yin, 2010). (5) Equity participation in the project company. (6) Performance evaluation. Regular performance evaluation by the public authority is needed to realize the core value of the PPP pattern. (7) Information disclosure and public monitoring (S. Q. Wang & Wang, 2017).

Some scholars also believed that the regulation of the PPP project included (Han, 2023): price regulation, quality and service regulation, information disclosure regulation. From the perspective of the whole process of the PPP project, PPP regulation contents include (S. Q. Wang & Wang, 2017):(1) Access regulation. Selecting the most appropriate private partner. (2) Price regulation. Reviewing pricing and price adjustment. (3) Regulation of quality and safety of products or services. Ensuring environmental protection, hygiene, safety, health, and uninterrupted service. (4) Exit regulation. Supervising the compliance of the exit at the end of the contract or the exit in the middle of the contract. (5) Regulation of users' demands. Implementing problems generally expressed by users.

The government regulation of expressway PPP project includes: (1) Market access regulation; (2) Price regulation; (3) Quality regulation; (4) Market exit regulation (Z. X. Liu, 2018).

2.5.2.3 Regulation methods

The regulation methods of the PPP project include (S. Q. Wang & Wang, 2017): (1) "pre-qualification and credit pre-examination", "bidding and competitive negotiation" in the transaction stage. (2) "performance evaluation", "contract performance regulation" and "administrative regulation" in the construction and operation stages. (3) "government's equity participation" to carry out regulation and check the financial status of the project company. 4)Ensure users and third-party regulation by means of "user complaints", "media monitoring", "hearings", "administrative reconsideration" and "judicial ruling".

Effective regulation of the PPP project for community-based elderly services is divided into three levels: government, market, and social forces (Y. Liu & Liu, 2020).

It is sometimes difficult for the public authority to directly observe a particular indicator of the private partner. In this case, it is possible to observe other related indicators (Song et al., 2020).

The regulatory principles for the PPP project include: regulation according to law, multi-level regulation, and combination of positive and negative incentives (F. Gao, 2017).

Government regulation of expressway PPP project: (1) Regulation according to the contract; (2) Regulation by incentives; (3) Social supervision; (4) Accountability (Z. X. Liu, 2018). Malaysia's PPP project uses concession agreement as a governance instrument to prevent opportunism (Latif et al., 2023).

Through the regulation of output performance, the following regulatory measures are implemented (Du et al., 2020): (1) The results of output performance regulation are linked to payment. (2) For better inspection results, regulation is reduced and incentives are given. For poor inspection results, regulation is increased and notification and penalties are given if necessary. (3) The cost of the first regulation is borne by the public authority. If the inspection results are not passed, the private partner should bear the cost of the second regulation.

Methods to reduce opportunism in the private partner (Chen et al., 2014): (1) Increasing the cost of opportunism. Adopting the bidding method to purchase services, expanding the scope and number of bidders, prompting rent-seeking competition, and increasing the cost of rent-seeking. (2) Reducing the opportunities and benefits of opportunism. Cutting government intervention into the market and letting the market play its role. Letting the rights restrain each other and limiting officials' monopoly rights. Improving the system of official selection and appointment, and improving the moral quality of officials. (3) Reducing regulation cost. Improving the degree of information disclosure and improving the information disclosure system. Through the disclosure of information in the whole process, lowering the cost of information collection and the cost of proving the evidence, and playing the roles of government regulation and users' regulation. (4) Increasing punishment. According to the seriousness of the circumstances, the following punitive measures can be taken against the opportunistic behavior of the private partner: recording the opportunistic behavior of the private partner on the qualification certificate or on the public platform, publishing the disciplinary action, restricting its entry into the PPP market within a certain number of years, and revoking the qualification certificate. Officials involved in opportunism are penalized as follows: party discipline punishment, administrative punishment, economic punishment, and criminal punishment, so that they will suffer huge losses in spirit, reputation, material, and future, forming a deterrent effect.

The vulnerability of opportunism in the PPP pattern is inherent and cannot be easily eliminated, but opportunism can be reduced through regulation. Specific regulation suggestions include (Rahel, 2020): (1) Proper combination of regulation and punishment. (2) Improving the transparency of the PPP project. (3) Greater use of professional contract guidelines to reduce "the discretion by the public authority". (4) Performance-based audit, specific whistle-blower scheme, job rotation, and widespread use of the "four-eyes principle".

2.5.2.4 Summary

Combining the aforementioned literature and the research content of this thesis, the "regulation institution, content and methods" are summarized as follows:

The regulation in this thesis refers to the public authority entrusting independent third-party institutions to supervise the opportunism from the private partner, through methods such as on-site inspection and testing, approval of the private partner's application documents, and checking compliance.

2.5.3 Regulation cost and penalties

For the PPP project, there is no uniform standard for calculating the cost of regulation. The industry authorities introduced *The Billing Standard for Regulatory and Related Services of Construction Projects,* a specific reference is given for the charging standard of regulation of construction project (NDRC, 2007). The behavior cost of regulation is generally positive to the proportion of random inspection and the amount of the regulated target.

The public authority, in deciding whether to set penalties, will consider factors such as: the private partner's benefits from opportunism, the impact of the public authority's benefits from opportunism, and the public authority's cost of regulation. The penalty amount is also very important. First, the penalty amount should be able to make up for the losses that the private partner's opportunism brings to the public authority and users. Second, the penalty amount should be able to effectively constrain the opportunism of the private partner. Different penalty amount should be considered for different manifestations of opportunism. In addition to setting contractual penalties, the public authority can also punish opportunism with the help of laws, regulations, social opinion and credit mechanism (Cai & Zhou, 2016).

The public authority can adopt certain incentives to guard against possible opportunism in the private partner. Increasing rewards or penalties will not always lead to a shift in the private partner's behavior towards "high effort", and only reasonable rewards and penalties can achieve the aim (Y. L. Wang et al., 2016).

Punishment mechanisms can only effectively curb opportunistic behavior if penalties are greater than the potential additional gains from opportunism. Punishment mechanisms must be cautious and not infinitely increase the penalties (S. M. Huang, 2020).

In order to restrain the opportunism of the private partner, the public authority can set penalty amount (N) in addition to the fixed payment (M. S. Li & Meng, 2018), $N=p\beta T_2$, T_2 is the unjust enrichment obtained by the SPV as a result of the opportunism, p is the probability of the public

authority to discover the opportunism of the private partner, and β is the penalty coefficient.

When the public authority detects private partner's opportunism, penalties are imposed by confiscating the illegal gains (t) and imposing fines (mt) (Chen et al., 2014).

According to Ni (2019), when there is serious opportunism in the private partner, in addition to punitive measures, both parties should conduct contract renegotiation. The purpose of renegotiation is to change the risk allocation, benefit distribution, or project scope of the original PPP contract.

Combining the aforementioned literature and the research content of this thesis, the 'regulation cost and penalties' can be summarized as follows:

The regulation cost in this thesis is calculated as a positive proportional function with the amount of the regulated target and the proportion of spot checks. Once opportunism is detected, the unjust enrichment of the private partner will be confiscated and the penalties of m times the unjust enrichment will be imposed. These practices are common regulative measures in the current PPP pattern, aimed at promoting rational choices of the private partner.

2.5.4 Concept of opportunism

Transaction cost is the cost of obtaining accurate market information, as well as the cost of negotiating and routinely entering contracts. Socio-economic activities have cost to operate, and transaction cost cannot be eliminated by "internalizing transactions". Williamson (1985) believed if there is no institutional constraint, people are opportunistic. He defined "opportunism" as: one party of a transaction misleads or deceives the other party by disclosing relevant facts inadequately or untruthfully in order to obtain benefits.

Han (2023) summarized the reasons for opportunism of the PPP project, including five aspects: (1) Inconsistent interests. (2) Indirect management by the public authority. (3) Complexity of the PPP project. (4) Imperfect in the legal system. (5) Imperfect in the regulation mechanism. Han Jiao Jie believed that, according to the occurrence stage of opportunism in the PPP project, it was divided into: transaction stage opportunism, construction stage opportunism and operation stage opportunism (Han, 2023; Zhang, 2012).

Owusu-Manu et al. (2018) studied the moral hazard of the PPP project and conducted t-test based on samples. According to Owusu-Manu et al. (2018), the most important reasons of moral hazard in the PPP project were: unobservable level of effort, low risk transferred, lack of accurate information about project conditions, wrong selection of project executors, and contract renegotiation. The adverse effects due to moral hazard were: reduced competition, high

transaction cost, reduced project profitability, siphoning of funds, and reduced contract enforceability.

Opportunism in the PPP pattern has a significant impact on the success or failure of project, mainly (Rahel, 2020): (1) Opportunism affects the overall efficiency of the PPP project. Compared with the traditional public service supply, opportunism increases the transaction cost of the PPP. (2) Competition may be distorted. The private partner can suppress market competition through opportunism, so that the private partner becomes the price setter rather than the price taker. (3) Opportunism leads to "weak interest" in the PPP project. Public interests become less important than the commercial interests of the private partner's oligopoly. The public authority would be subject to the constraints of public law and political rationales, which generally does not exist in the private partner, and in these cases, the accountability of the public authority would not apply to the private partner, as a result, the private partner may damage the public interests.

During the construction period, the private partner's opportunism that affects PUPC mainly includes (Han, 2023): (1) Overestimating and miscalculating of additional PUPC outside the contract due to the events of public authority's liability. (2) Jerry-building in the construction stage. (3) Lowering the construction standard and quality grade of the project. (4) Concealing the savings from design optimization. Considering the unique characteristics of the PPP project, the private partner is responsible for the operation of the project after construction, and can only get payment through the performance evaluation in the public authority, once the private partner jerry-building and lowering the quality standard in the construction stage, the private partner will face serious problems in the later operation stage, so the private partner generally will not be jerry-building or lowering the quality standard of the project. Therefore, this thesis focuses on opportunistic behaviors such as: overestimation and miscalculation of additional PUPC outside the contract, and concealment of savings from design optimization.

Combining the aforementioned literature and the research content of this thesis, the "concept of opportunism" is summarized as follows:

The opportunism studied in this thesis is defined as: one party misleads or deceives the other party by disclosing relevant facts or circumstances inadequately or untruthfully in order to obtain benefits. This also is the moral hazard in principal-agent theory (Zhang, 2012). Specifically, it includes the private partner's concealment of savings from design optimization and overestimation and miscalculation of additional PUPC outside the contract.

2.5.5 Inputs (hidden cost and penalties) and outputs (revenue) of opportunism

Campbell (2013) believes that the behavior of hiding refers to a principal hiring an agent to complete a task, but the principal is unable to supervise the agent or the cost of supervision is extremely high. Then, the agent conceals some facts and circumstances, thereby affecting the welfare of the principal or others.

Hiding usually involves (Han, 2023): providing false information to conceal the truth; bribing the regulatory personnel to prevent the opportunism from coming to light; and Using legal means to make it more difficult for opportunism to be found out. By hiding, the private partner reduces the proportion of opportunism that is found. It is important to note that "bribing the regulatory personnel" refers to the private partner conspiring with regulatory personnel through bribery to achieve illegal goals.

Many scholars have studied the inputs and outputs of opportunism of the PPP project in the transaction stage and the construction stage, which are summarized in Table 2.6.

Table 2.6 Summary of the research results of different scholars on the input and output of opportunism

No.	References	Thesis or book	Inputs	Outputs (Revenue)
1	Chen et al. (2014)	PPP: rent-seeking game and regulatory countermeasures	c: The cost of the private partner's opportunism.	M=t-c-p(m+1) t M: The net income of the private partner's opportunism. t: Unjust enrichment due to the private partner's opportunism. p: Probability of public authority's regulation. m: When the public authority discovers opportunism of the private partner, penalties are imposed by confiscating illegal gains (t) and imposing fines (mt).
2	Y. L. Wang et al. (2016)	A game of research on the incentive mechanism of PPP projects based on investors opportunism	$C_2=\lambda W_2$ C_2: The cost of the private partner's opportunism. W_2: The amount of penalty. λ: The cost coefficient.	$R_2=kW_2$ R_2: The revenue of the private partner's opportunism. W_2: The amount of penalty. k: The revenue coefficient.
3	M. S. Li and Meng (2018)	Incentive mechanism model of the PPP project based on principal agent theory	$C(e)=0.5de^2$ C(e): The cost of the private partner's opportunism. d: The cost coefficient. e: The effort level of the private partner's opportunism.	$T_2=k_2*e+\varepsilon_2$ T_2: The unjust enrichment obtained by the SPV because of opportunism. k_2: The ability of the private partner's opportunism. e: The level of effort of the private partner's opportunism. ε_2: Exogenous variable affecting unjust enrichment from opportunism, $\varepsilon_2 \sim N_2(0, \sigma_2^2)$.

No.	References	Thesis or book	Inputs	Outputs (Revenue)
4	J. Q. Wang (2018)	A mechanism for the governance incentive and supervision of the PPP project from the principal-agent perspective	$Z_s=zt\xi$ Z_s: The loss incurred by the private partner from being penalized when opportunism is discovered. z: The penalty coefficient. t: The effort level of opportunism. ξ: The probability that opportunism is discovered.	$B_s=bt$ B_s: The revenue of the private partner's opportunism. t: The effort level of the opportunism. b: The revenue coefficient of the opportunism.

Combining the aforementioned literature and the research content of this thesis, the "inputs and outputs of opportunism" are summarized as follows:

(1) The inputs of opportunism by the private partner include the cost of hiding and possible penalties. The cost of hiding is calculated as a positive proportional function with the amount of hidden opportunism, and penalties are calculated as a multiple of the amount of opportunism discovered.

(2) The outputs (revenue) of opportunism in the private partner are undiscovered unjust enrichment, constituting moral hazard gains (S. Y. Xie, 2021).

2.5.6 Literature commentary on regulation and opportunism

The theoretical knowledge of regulation and opportunism related to this thesis is summarized in each sub-section above. Regulation is a common management measure within new institutionalism (Douglass, 1991), whilst opportunism is a common problem within the moral hazard of principal-agent relationships (Zhang, 2012).

The target of regulation in this thesis is private partner's opportunism. Private partner's opportunism mainly refers to the overestimation and miscalculation of additional PUPC outside the contract, and concealment of savings from design optimization. Most of the literature measures opportunism through the variable of the effort level, but the effort level variable is difficult to observe and quantify. This thesis measures private partner's opportunism based on the amount of unjust enrichment, and achieves result -oriented regulation. This approach is closer to the actual practice of the PPP project and differs from previous research.

2.6 Summary

The theories of the PPP and game theory, as well as a literature review of output specifications, incentives and technological innovation, regulation and opportunism, form the basis of this thesis. As can be seen from the above literature review, most of the current research on construction cost and PUPC, output specifications and tender offer, incentives and technological innovation, and regulation and opportunism are based on single-stage, scattered research. The results of systematic research that links these topics of the PPP project with multi-stage game are still unknown. This thesis is based on this thinking and studies the strategy for saving PUPC.

Chapter 3: Methodology

Based on the literature review, this chapter describes the research methodology and its corresponding research process design.

3.1 Research design

Among the four research questions in Chapter 1 of this thesis, the first three are three sets of decisions made between the public authority and the private partner during the transaction and construction stages of the PPP project. The latter one is to explore the factors and paths for saving PUPC. That is to say, they essentially constitute processes and outcomes along a through decision-making path. In response to the research questions in this thesis, three research methods will be adopted: interviews (including unstructured and structured interviews), mathematical modeling of game theory, and focus groups of experts. The specific research design is shown in Figure 3.1.

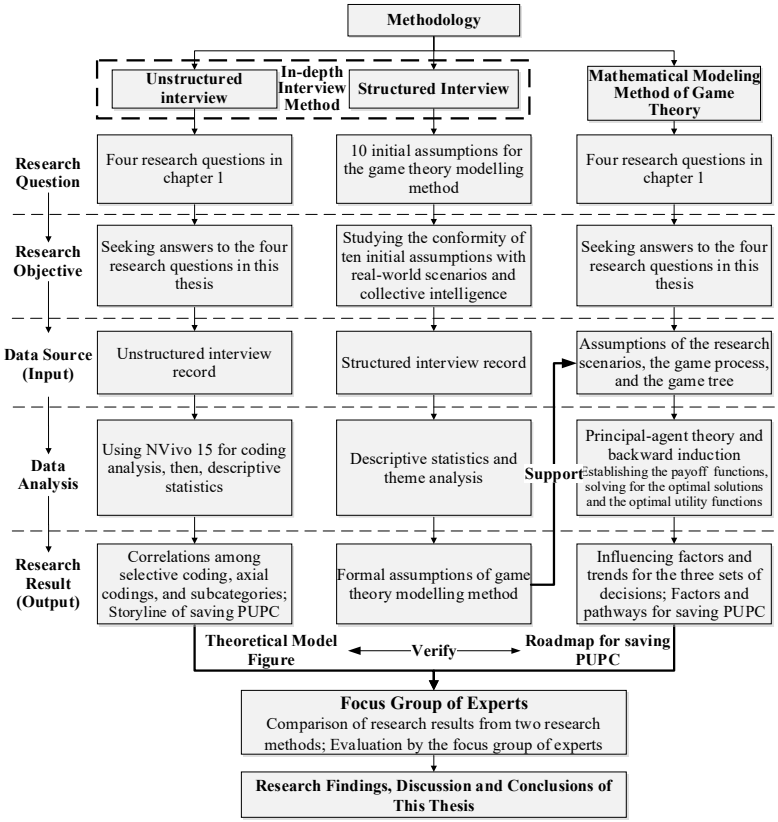


Figure 3.1 Research design

For the unstructured interviews, its research questions are the four research questions proposed in Chapter 1 of this thesis. Its research objective is to seek answers to these four research questions. its data source comes from the researchers' unstructured interview materials with middle and senior economic management persons in PPP projects. Its data analysis employs a combination of two methods: firstly, the coding analysis with software NVivo 15 is used to extract concepts (including axial codings and subcategories), factors, and paths influencing PUPC; secondly, descriptive statistics are used to obtain correlations among subcategories (namely: exogenous conditions), axial codings (namely: decision variables), and PUPC. Its research results are to obtain the factors and trends influencing each decision variable, as well as the factors and paths for saving PUPC, ultimately forming a theoretical model for saving PUPC and the research results for the four research questions in this thesis.

For the structured interviews, its research question is: do the ten initial assumptions (inputs) of the mathematical modelling of game theory align with real-world scenarios and collective intelligence? If not, how should they be modified? Its research objective is to ensure that the formal assumptions of mathematical modeling reflect real-world scenarios and collective intelligence. Its data source comes from the researcher's structured interview materials with middle and senior economic management persons in PPP projects. Its data analysis employs a combination of two methods: firstly, descriptive statistics are used to collect interviewees' support rates for the initial assumptions, mainstream views, and "dissenting opinions" that contradict the mainstream views; secondly, theme analysis is used to identify the authenticity, rationality, and degree of impact of these "dissenting opinions" on the initial assumptions, as well as to analyze the interpretation degree of auxiliary questions (answers) on main questions (answers) and the logical consistency between them. Its research results include determining whether the initial assumptions need to be modified and how to modify them, ultimately forming the formal assumptions to serve as the research scenario for mathematical modelling of game theory.

For the mathematical modeling of game theory, the research questions are the four research questions proposed in Chapter 1of this thesis. Its research objective is to seek answers to these four research questions. The assumptions (inputs) for mathematical modelling of game theory derive from theoretical summaries of relevant literature and research results from structured interviews, and form a generalized scenario for the PPP pattern (15 formal assumptions). The analysis method of mathematical modelling is the backward induction: firstly, payoff functions are established by using principal-agent theory; secondly, optimal solutions of each decision variable and the optimal utility functions of the public authority are solved by using backward

induction. The research results (outputs) are to obtain the factors and trends influencing each decision variable, as well as the factors and paths for saving PUPC, and ultimately form a roadmap for saving PUPC and the research results for the four research questions in this thesis.

For the expert focus group method, the research question is: how to focus on the similarities and differences between the research results of the interview method and the mathematical modelling method of game theory? Its research objective is to enhance the reliability and validity of the study, focus on the research results of the two aforementioned research methods, and ultimately form the research findings of this thesis. The research process involves the researchers firstly compare the similarities and differences, then submit them to the expert focus group meeting for discussion, gather the views of PPP industry experts, and ultimately form the expert focus group's evaluation opinions.

3.2 Interview method

3.2.1 Research questions and objectives

The interview methods in this thesis comprise unstructured interviews and structured interviews. The research questions and research objectives for the unstructured interviews are detailed in No. 16–19 of Table 3.1; those for the structured interviews are detailed in No. 6–15 of Table 3.1.

Table 3.1 Interview questions

NO.	Interview theme/ Question	Type of question	Research objectives
Part 1	**Structured interview**		
1	How old are you?	Descriptive question	The appropriateness of the theme of the interview to the interviewee
2	What is your occupation?		
3	How many years of professional experience do you have?		
4	What is your basis for judging the questions in the interview?		
5	How familiar are you with the questions in the interview?		
6	The public authority and the private partner are both rational persons. Do you agree with this view?	The main questions are single-choice questions. The auxiliary questions are "judgement questions + short answer questions".	Ensuring that part of the assumptions (inputs) of the mathematical modelling of game theory reflect real-world scenarios and collective intelligence.
7	Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), is there any room for savings in PUPC?		
8	In the transaction stage, all valid bidders that have passed pre-qualification are homogeneous bidders (homogeneous bidders: except for the tender offer, other technical and commercial scoring items have little effect on the probability of a bidder winning the bid). Do you agree with this view?		

NO.	Interview theme/ Question	Type of question	Research objectives
9	Transaction of the PPP project follows the market rules of "full competition and fair competition". Do you agree with this view?		
10	The successful bidder of the PPP project transaction is determined according to the principle of "reasonably low price". Do you agree with this view?		
11	When the private partner makes a tender offer, for both the specified and unspecified works in the output specifications, is the reservation profit rate greater than or equal to 0?		
12	Should the results of design optimization (changing output specifications) be shared between the public authority and the private partner?		
13	Should the results of design deepening (without changing the output specifications) be exclusive to the private partner?		
14	If the private partner does not hide, can the public authority detect all opportunism in the objects being inspected?		
15	Do you think the cost of regulation of the PPP project can meet "the cost of regulation ≤ the amount of fines and confiscations for maximum opportunism"?		
Part 2	**Unstructured interview**		
16	In the project transaction stage, to save PUPC, how does the public authority choose the optimal level of detail of output specifications?	Unstructured question	Seeking answers to the four research questions in Chapter 1.
17	In the project construction stage, to save PUPC, how does the public authority choose the optimal incentive intensity?		
18	In the project construction stage, to save PUPC, how does the public authority choose the optimal intensity of regulation?		
19	What are the influencing factors of PUPC? What are the paths to save PUPC?		

3.2.2 Steps in the interview method

1. Preparations

First, set up an interview team, which consists of one interviewer, one recorder, two data analysts (coders), and one data analysis moderator. Next, draw up an interview outline. Finally, conduct pre-interviews and pilot tests to revise the interview outline (J. J. Huang, 2020).

2. Interview implementation

First, a safe, quiet and relaxed interview environment is ensured. Before the interview begins, the interviewer explains the background of the research, the aim and significance of the interview to the interviewee, and asks for the interviewee's opinion on recording the interview.

The interview begins after the interviewee signs the "Informed Consent Form". No repeat

interviews are conducted. The interviewer and recorder jointly complete the interview with the interviewee, with the recorder responsible for recording the video or audio. Each interview is scheduled to last 90 minutes. After each interview, the coders conduct a preliminary analysis of the content of the interview. The selection of the next interviewee is based on a preliminary analysis of the previous interview data, and the next interviewee is selected as far as possible to be different from the previous interviewee in terms of characteristics and to obtain more information (Tian, 2020).

3. Data collection and transcription

The interview will be recorded, after the interview is completed, the interviewer and recorder will jointly organize and transcribe the interview data, including the interviewee's speech, as well as certain non-verbal sounds and movements. The interview data will be input into a computer and saved as a word document.

4. Data analysis

For unstructured interviews, coding analysis of grounded theory and descriptive statistical analysis are used. For structured interviews, descriptive statistics and theme analysis are used.

5. Research results

After analyzing the data and refining the concepts (Fan et al., 2024), new knowledge is formed. Then, this new knowledge is displayed in diagrams, and a memo is written.

3.2.3 Sampling for the interviews

According to policy documents (General Office of the State Council of the People's Republic of China, 2023), new PPP projects after 1 February 2023 will implement the "new mechanism" and be published on the new national PPP information platform (hereinafter referred to as the "new platform").The old national PPP information platform will be closed after 1 March 2023. PPP projects on the old platform will be taken over by various county-level government departments, and the information on these projects will no longer be published. The new mechanism is the future direction of PPP development. In addition, there are many operational methods for the PPP pattern, and only BOT, BOO, BOOT, and DBFOT include "build" in the full meaning (CCEA, 2018). The research objective of this thesis (saving PUPC) means that the research object should include "Build". Therefore, this thesis takes BOT, BOO, BOOT, and DBFOT projects on the new platform as the population, and then uses stratified sampling to determine the sample.

As of 12 January 2025, there were a total of 179 PPP projects that met the requirements on

the new platform. This thesis plans to select 22 samples for in-depth interviews, and the actual number of samples will be adjusted according to the theoretical saturation during the interview process. If theoretical saturation is reached ahead of schedule, the number of samples will be reduced; if theoretical saturation is reached behind schedule, the number of samples will be increased (Tian, 2020).

Before random sampling, the "population" was divided into three stratifications (H. Z. Li, 2022). The first stratification was based on the main participants in the PPP pattern. There were 11 representatives from the public authority and 11 from the private partner. The second and third stratifications were explained by the public authority as an example.

The second stratification was based on industry. Transportation (highways, waterways, ports), environmental protection, urban construction, and water conservancy (industries with a small share were not listed) accounted for 57.5%, 25.1%, 8.4%, and 5.0% of the projects, respectively. According to the principle of proportional allocation, these industries were allocated 6, 3, 1, and 1 sample, respectively.

The third stratification was based on region. The main regions in the transportation industry were Gansu, Shanxi, Anhui, Guizhou, Sichuan, and Chongqing (those with a small proportion were not listed), accounting for 17.5%, 16.5%, 15.5%, 8.7%, 6.8%, and 4.9% of the projects, respectively. Each of these regions was allocated one sample. The main regions in the environmental protection industry were Jiangsu, Fujian and Guangdong (those with a small proportion were not listed), accounting for 11.1%, 8.9% and 8.9% of the projects, respectively. Each of these regions was allocated one sample. The main region in the urban construction industry was Shandong, accounting for 26.7% of the projects, and it was allocated one sample. The main region in water conservancy industry was Hebei, accounting for 44.4% of the projects, and it was allocated one sample. In this way, the 11 samples from the public authority have been allocated, and the 11 samples from the private partner can also be allocated using the same method.

Finally, using a random number table, samples were drawn from PPP projects in the corresponding industries and regions, and representatives of the public authority and the private partner were determined from the corresponding sample projects. Some special cases were handled separately. Representatives of the public authorities of three projects were unwilling to participate in the interviews, so the interview team invited the engineering consulting agencies (commissioned by the public authorities) of these projects to participate on their behalf. For one project, it was not possible to determine suitable representatives, so the interview team commissioned the industry association (China Engineering Consulting Association) to

recommend other PPP project in the same industry and region to complete the sample. All interviewees are managers at or above the level of Investment Management (or Cost Management) Director for the PPP project.

3.2.4 Design of the interview outline

The interviews for this thesis are divided into two parts, with the specific interview questions shown in Table 3.1. The interview outline is provided in Annex A.

Structured interviews are conducted according to uniform interview outline, and all interviewees undergo exactly the same interview process (Fan et al., 2024). The structured interview has 15 standard questions to which the interviewee responds in a prescribed format. The options for the main questions in structured interviews are designed using a five-point scale, while supplementary questions are posed to respondents from a different perspective related to the main questions. This serves to verify whether respondents have accurately understood the meaning of the main questions and to capture more information about the interview theme.

Unstructured interviews, also known as in-depth interviews, have only a rough basic requirement for questions. During the interview, the interviewer can flexibly adjust the content and process of the interview based on the actual situation at the time. The purpose of the interview outline is to remind the interviewer to avoid missing important interview content. The interview process should maintain the principles of being open, flexible, and resilient, without being bound by formality (Fan et al., 2024).

All the interviewees agreed to the invitation. The interviewer explained to them the research objectives and content, as well as the requirements for the interviews. All the interviewees had the time and interest to participate in the interview and signed the *Informed Consent Form*.

3.2.5 Pre-interview

In order to ensure that interviewees accurately understand the interview questions and answer or explain them in the intended manner, and to minimize misunderstanding or misinterpretation of the text and terms in the interview outline, as well as to increase the reliability and validity of the interviews (Dylan, 2022; Schade, 2015), this thesis organized pre-interviews prior to the formal interviews. Pre-interview is the process of selecting a small sample from the target population to test the interview questions.

In order to achieve the objective of the pre- interviews, this thesis considered the following factors when selecting volunteers for the pre- interviews: First, they should be similar to the target

group. Volunteers should be participants in PPP projects that are on the "new platforms and new mechanisms". Second, volunteers should be representative. Although the interviewees in this thesis are all PPP professionals, different interest groups, ages, and experiences may lead to different ways of understanding questions, so volunteers should try to reflect different perspectives. Third, volunteers should be fully aware of the repetitive nature of pre-interviews, be patient, meticulous in their work, and be interested in this study. Finally, with the support of the China Engineering Consulting Association, after a period of understanding, two qualified volunteers were determined, one from the public authority with experience mainly in engineering design and PPP public management, and the other from the private partner with experience mainly in engineering construction, project business, and SPV management. The researchers patiently and carefully explained the purpose and significance of the pre-interviews to them, hoping that they would provide help and support for this study.

The pre-interviews lasted four days and yielded many reasonable suggestions, which played an important role in further improving the interview outline. In summary, the main points are as follows:

1. Feedback: It is unclear what is "engineering content specified in the output specifications". It is recommended to provide a clear explanation in the definition of "level of detail of output specifications".

Revision: The researchers added an explanation to section 1.4.4 of the interview outline.

2. Feedback: Section 1.4.5 of the interview outline, "The deviation coefficient of quantities $(\delta) = \frac{\text{Quantities for future design drawings}}{\text{Normally estimated quantities}}$" is questionable. There are many types of quantities in construction project, and they all have different units of measurement. Expressing the deviation coefficient as a ratio of quantities is not practical. It is suggested to use "the ratio of the CS (construction cost calculated by Norm and Standard) of the corresponding quantities" to express the deviation coefficient.

Revision: The suggestion is accepted.

3. Feedback: Does "external conditions" in the definition of "maximum opportunism" include regulation? It is recommended to clarify this in the definition.

Revision: Clarify that "external conditions" here does not include regulation.

4. Feedback: Does "exogenous conditions" in the definition of "maximum proportion of hiding" include regulation? It is recommended to clarify this in the definition.

Revision: Clarify that "exogenous conditions" here includes regulation.

5. Feedback: The meaning of "homogeneous bidders" in section 2.8 of the interview outline

is unclear. It is recommended that its meaning be explained separately.

Revision: The meaning of the concept is explained in parentheses after the name.

6. Feedback: Based on the context, it is suggested to add "optimal" before the theme words (e.g., level of detail of output specifications) of questions 1 to 6 of the unstructured interview (sections 3.1 to 3.3).

Revision: The suggestion is accepted.

7. Feedback: Question 8 in Section 3.4 of the interview outline: "What are the factors influencing PUPC from the perspectives of the project itself, the public authority and the private partner?" This question covers too broad ground, and interviewees cannot quickly provide the information the interviewer wants. It is recommended that Question 8 should be split into several smaller, more specific questions.

Revision: Revise the wording of Question 8.

8. Feedback: It is recommended that the meaning of "public authority" and "private partner" in the Chinese context be explained in section 1.1 of the interview outline, so as to avoid any confusion among interviewees.

Revision: Provide an explanation in the background information.

9. Feedback: As the interview outline is relatively long, it is recommended that key points be highlighted in bold or underlined. For example, key concepts in the background information and keywords for unstructured interviews.

Revision: Mark key points in the interview outline.

10. Feedback: The expression "rational economic person" in section 2.6 of the interview outline is inconsistent with game theory. It is recommended that it be changed to "rational person".

Revision: Change "rational economic person" to "rational person".

11. Feedback: Section 2.13 of the interview outline needs to clarify whether "the private partner submits construction drawings to the public authority for filing" constitutes the public authority participation in decision-making, as this is the basis for answering this question.

Revision: Add a note to this question.

In summary, based on the questions and suggestions proposed in the pre-interviews, this thesis revised and improved the interview outline to avoid misunderstandings and ensure the quality of the interviews.

3.2.6 Pilot test

Unlike pre-interviews, pilot tests are designed to identify practical problems in the interview process, enhance reliability and validity of the interviews, and test the entire interview process, so as to fix these problems before the formal interviews. The pilot test includes sending and accepting invitations, scheduling interviews and communication software, communicating before interviews, conducting interviews and recording, transcribing and organizing audio files, analyzing themes, importing data into software for coding, and consistency check.

In accordance with the method of selecting volunteers for the pre- interviews, this thesis selected four interviewees. These interviewees and the five members of the interview team all participated in the pilot test. The pilot test lasted for one week. Through the pilot test, the researchers discovered many problems in the implementation of the interviews. The interview team further refined the implementation requirements and improved the interview content. In summary, the main points are as follows:

1. During the pilot test, it was found that the planned interview time (1 hour) was too tight, so the interview time was adjusted to approximately 90 minutes.

2. During the pilot test, it was found that some interviewees spoke too quickly, which affected the accuracy of the transcription of the audio files. Therefore, in the communication before the Interview, interviewees should be reminded to control their speaking speed and use standard Mandarin as much as possible.

3. During the pilot test, one interviewee was not fully prepared when the interview began, which ultimately led to the interview being conducted twice. Therefore, a "communicating before interviews" session should be added before the formal interview, which can be conducted by telephone, WeChat, or video. Through communicating before interviews, it is possible to know whether the interviewee is familiar with the content of the interview outline, and at the same time, answer any questions the interviewee may have after reading the interview outline. The formal interview should be based on the interviewee's correct understanding of the background information and in-depth thinking.

4. During the pilot test, the short-answer questions in the structured interview took too long because the interviewees spoke at length and the interviewer did not know their final conclusions, requiring the interviewer to ask more questions to obtain the desired information. Therefore, the answer requirements should be added: the short-answer question is an extended description of the single-choice question, and the interviewee is required to first make a "yes" or "no" judgment, and then provides an explanation in one or two sentences.

5. During the pilot test, interviewees suggested further sorting out the background information of the unstructured interview to make it more systematic and easier for interviewees to understand quickly. To this end, the researchers adjusted the description of this part.

6. During the coding process of the four-interview data, two coders pointed out t the content of the interview data was rather extensive and disorganized. It is recommended that when organizing the interview data, the data organizer set up a dedicated text box at the beginning of each interview theme. Through these text boxes, the contents of different interview themes can be separated, and at the same time, the "core viewpoints" of the interviewees should be listed in the text boxes. In this way, the content of the interview data becomes clear and straightforward, and it is also convenient for later descriptive statistics.

7. Although the three data analysts were trained in advance, some new professional terms appeared in the conversations of the four interviewees during the pilot test. Therefore, the researchers provided explanation and training to the data analysts on the meaning of the new terms.

The pilot test enriched the preliminary preparation for the interviews, refined the specific requirements for the implementation process, optimized the allocation for interview time, and trained data analysts, laying a solid foundation for the subsequent formal interviews.

NVivo software uses the "Kappa coefficient" to test the reliability of the coding results. The Kappa coefficient is mainly used to measure the degree of consistency in coding the same text data by different coders. Its value range is between -1 and 1, where 0 indicates that the two sets of codings are randomly distributed data, 1 indicates that the two sets of codings are completely identical, and negative values indicate that the consistency between the two sets of codings is lower than the random level. Generally speaking, a Kappa coefficient above 0.8 is considered to have high consistency; Between 0.6 and 0.8, it is considered to have moderate consistency; If it is below 0.6, it is considered to have poor consistency (Fan et al., 2024).

In order to verify the results of the pilot test, the interview data of four interviewees were handed over to two coders for independent coding. The coded files were then given to the moderator, who imported them into NVivo 15 software for consistency checking. In the pilot test, coder 1 produced 56 open codings (initial concepts) (a1 to a56), and coder 2 produced 48 open codings (a1 to a48). After importing into NVivo 15, the Kappa value was calculated in "Queries-Coding comparison" of the "Explore" menu. The final Kappa coefficient of the 56 open codings of coder 1 was between 0.74 and 0.83, and the Kappa coefficient of the 48 open codings of coder 2 was between 0.76 and 0.86, both of which met the consistency check requirements.

3.2.7 Data analysis

For unstructured interviews, two data analysis methods will be combined: the first is coding analysis based on grounded theory; the second is correlation analysis based on descriptive statistics. For structured interviews, two data analysis methods will also be combined: the first is mainstream view statistics based on descriptive statistics; the second is theme analysis to judge the validity of "dissenting opinion" and the necessity of modifying the initial assumptions.

3.3 Mathematical modeling method of game theory

3.3.1 Research questions and objectives

The research questions in the mathematical modelling method of game theory are the four research questions proposed in Chapter 1 of this thesis, the research objectives of which are to seek answers to these four research questions.

3.3.2 Elements of the game

1. Game players, actions, and strategies.

The players in this thesis' game are the public authority and the private partner of the PPP pattern. The actions of the game comprise the level of detail of output specifications, incentive intensity, and regulation intensity from the public authority, as well as the tender offer, technological innovation, and opportunism from the private partner. The strategies of the game are plans of actions for the particular situations (Zhang, 2012).

2. Game information.

The dynamic game of complete information represents a relatively common and representative scenario for the PPP pattern, and this thesis conducts the research based on this scenario. The characteristic information of the public authority includes the regulation behavior cost coefficient and the penalty coefficient. The characteristic information of the private partner includes the behavior cost coefficient of technological innovation, the behavior cost coefficient of hiding, the discount rate of productivity level, the maximum effort degree of technological innovation, the maximum degree of opportunism and hiding, and the reservation profit rate. The characteristic information of the PPP project itself includes C (construction cost calculated by Norm and Standard) and the deviation coefficient of quantities.

3. Game payoff and outcome.

The payoff of the private partner is expressed as internal profit of the enterprise (revenue - internal construction cost of the enterprise). If the usage and operating performance of the PPP are in a normal state (i.e., the actual value = the expected value at the time of the transaction), the revenue of the public authority and the users is a stable fixed value, which does not change with the strategies of the two parties in the game of this thesis. Therefore, the public authority's payoff (E) need not calculate revenue but only expenditure, where E = -PUPC. The outcome in this thesis includes the equilibrium payoff function of the public authority (optimal payoff function), the equilibrium solution of each decision (optimal solution), and the results of further analysis of the optimal solution.

3.3.3 Steps of mathematical modeling

Mathematical modelling method of game theory follows the following steps (Baidu, 2024; Qi et al., 2006):

1. Preparation before modeling. Define the meaning of the parameters and terms used in mathematical modeling, describe the process of the dynamic game, and build the game tree.

2. Assumptions of the research scenario. To clarify the research scenario, some appropriate assumptions need to be made (Zhong, 2005). This thesis clarifies sixteen initial assumptions before mathematical modeling, which are the inputs for mathematical modeling of game theory.

3. Payoff model. Based on the assumptions, the appropriate mathematical tools are used to describe the mathematical relationship between variables, and establish the corresponding payoff functions (Zhong, 2005). Mathematical modeling follows the principles of simplification, deducibility, and reflectivity (Baidu, 2024).

4. Optimal solution of the model. Based on the three-stage game process, the optimal solution of each decision is obtained by backward induction. Then, the equilibrium payoff of the public authority under the equilibrium path is further obtained.

5. Analysis of the optimal solution. The optimal solutions and optimal utility function are analyzed to clarify their influencing factors and correlations, which form the results of the analysis.

6. Summarize the research results. Based on the analysis results above, summarize the factors affecting PUPC and the ways to save PUPC, and form the research results.

3.3.4 Process and parameters of the game

After the project establishment and PPP identification stages, the PPP project enters into the

transaction and construction stages (CCEA, 2018). This thesis studies the economic game between the public authority and the private partner in the transaction and construction stages.

The game is divided into three stages: Stage I, the level of detail of output specifications and tender offer; Stage II, incentives and technological innovation; Stage III, regulation and opportunism.

3.3.4.1 Process and parameters of Stage I

The terms and parameters used in Stage I of the game are listed in Table 3.2.

Table 3.2 Terms and parameters of the game in stage I

Terms and Parameters	Meaning
Public authority and user payment (PUP)	It refers to the public authority and user payment in the PPP project according to the performance evaluation results and the contract, abbreviated as "PUP" (MOF, 2014). PUP consists of three parts: public authority and user payment for construction (PUPC), public authority and user payment for operation (PUPO), and public authority and user payment for all other matters (PUPA).
Public authority and user payment for construction (PUPC)	It refers to the public authority and the user payment for construction of the private partner and project regulation services, according to the performance evaluation results and the contract, abbreviated as "PUPC" (J. T. Zhou et al., 2019). PUPC is the main target of this thesis.
Construction cost calculated by Norm and Standard (CS)	It refers to the construction cost calculated by norm and standard of the nation or industry, abbreviated as "CS". It reflects the social average of the consumption and price of production factors for project construction (Z. M. Wu, 2023). CS is the common knowledge of the public authority and the private partner, and can be used as a basis for the public authority to set the tender sum limit and as a reference for the private partner to determine the tender offer.
Construction Cost Calculated by Norm and Standard for the Entire Project (C)	It refers to the construction cost calculated by Norm and Standard for the entire project.
Level of detail of the output specifications (h)	The works specified in the output specifications refers to the works in the output specifications whose quantities can be accurately calculated. $h=\frac{\text{CS for works specified in the output specifications}}{\text{CS for the entire project (C)}}$ $0<h_0\leq h\leq h_1<1$
Basic level of detail of the output specifications (h_0)	It refers to the minimum level of detail required for output specifications to meet the needs of project feasibility study, implementation plan, value-for-money evaluation, and financial affordability evaluation (J. T. Zhou et al., 2019). It should clarify the functional requirements of the PPP project and the objectives of performance evaluation.
Maximum level of detail of the output specifications (h_1)	It is the maximum level of detail of the output specifications that can be achieved under the influence of exogenous conditions.
Tender offer for the	It refers to the private partner's tender offer for the PUPC of works

Terms and Parameters	Meaning
works specified (α)	specified in the output specifications.
Tender offer for the works not specified (β)	It refers to the private partner's tender offer for the PUPC of works not specified in the output specifications.
Number of valid bidders (n)	It refers to the number of valid bidders.
Probability of winning the bid (ζ)	It refers to the probability of winning the bid in the private partner. $0 \leq \zeta \leq 1$
Internal construction cost of the enterprise at the time of signing the contract (C_1')	C' refers to the internal construction cost of the enterprise in the private partner. It is information privately owned by the private partner and is not common knowledge (Z. M. Wu, 2023). C_1' is the expected C' at the time of signing the PPP contract.
Contract revenue (R_1)	R refers to the revenue that the private partner should obtain for the input of construction cost according to the PPP contract and the results of the performance evaluation. R_1 is the expected R at the time of signing the PPP contract.
Contract payoff (E_1)	E refers to the payoff of the public authority and users, which only calculates the payment for construction cost and expenditure for project regulation services, and does not calculate revenue. E = -PUPC. E_1 is the expected E at the time of signing the PPP contract. In calculating E_1, the public authority's regulation cost is excluded for the time being. E_1=- PUPC (contract price) E_1 is a negative number.
Contract profit (F_1')	F' refers to the internal profit of the enterprise in the private partner. F_1' is the expected F' at the time of signing the PPP contract.
Discount rate of productivity level (θ)	The construction cost calculated by Norm and Standard for the Entire Project (C) reflects the social average productivity level, the private partner as an individual of the society, its level of project management and engineering technology will be generally higher than the average level of the society (in general, only large enterprises or investors with strong strength can participate in the construction of the PPP project), and this advancement of the project management and engineering technology will be ultimately reflected in the reduction of the construction cost (the private partner's internal construction cost is lower than C), therefore, the enterprise's internal construction cost will be appropriately discounted on the basis of C. This discount rate is called "θ". $0<\theta\leq 1$ $\theta=\frac{\text{Forecasted internal construction cost of the enterprise}}{\text{C}}$
Deviation coefficient of quantities (δ)	In the transaction stage of the PPP project, for the works that are not specified in the output specifications, the private partner measures their regular estimated quantities and their corresponding CS according to the available information. Considering that there will be a deviation between such regular estimated quantities and the future design drawings, the private partner sets a deviation coefficient (δ) to reflect such deviation, with the specific meanings as follows: $\delta=\frac{\text{CS corresponding to quantities for the first set of design drawings}}{\text{CS corresponding to regular estimated quantities}}$ In the transaction stage of the project, the private partner does not have the complete set of design drawings for the works not specified in the output specifications and, therefore, can only estimate the coefficient of deviation (δ); whereas, in the construction stage of the project, the private partner has the first set of design drawings for the works not specified in the output specifications and, accordingly, is able to accurately calculate the coefficient of deviation of quantities (δ).

Terms and Parameters	Meaning
	This thesis incorporates the "risk of quantities deviation" as a separate parameter within the mathematical model; other risks are not introduced as separate parameters, but are implied within the corresponding cost parameters (without explicitly expressing the risk).
Losses for not winning the bid (C_t)	It refers to the private partner's losses due to not winning the bid.
Losses for unsuccessful bidding (C_b)	It refers to the public authority's losses due to unsuccessful bidding.
Reservation profit rate for the works specified (γ_1)	It refers to the profit rate that the private partner calculates for the works specified in the output specifications when submitting the tender offer of the PPP project. $\gamma_1 \geq 0$
Reservation profit rate for the works not specified (γ_2)	It refers to the profit rate that the private partner calculates for the works unspecified in the output specifications when submitting the tender offer of the PPP project. $\gamma_2 \geq 0$

The game process of Stage I is that in the transaction stage, the public authority chooses the level of detail of output specifications (h), and the private partner chooses the tender offer strategy.

I-1, Level of detail of output specifications (h) in the public authority. The public authority specifies the level of detail of the output specifications by publicly releasing bidding documents (GIH, 2019; S. Q. Wang, 2017). The public authority needs to make decisions on h. The larger (or smaller) h is, the more detailed (or rough) the functional requirements and quality technical indicators are, and the smaller (or larger) the space for technological innovation in design deepening is. Therefore, the public authority needs to tradeoff between "specifying detailed functional requirements and technical quality indicators" and "leaving sufficient space for technological innovation" (S. Q. Wang & Wang, 2017), and make the PUPC ($\alpha+\beta$ is the main component of PUPC) as small as possible, and then finally decide the value of h. Of course, the value of h should not be less than h_0.

I-2, the private partner's tender offer (α, β). According to the level of detail of the output specifications (h) issued, the private partner makes a decision on tender offer (α, β), considering the bidding conditions, project characteristics, and its own conditions (J. T. Zhou et al., 2019). The private partner knows h, predicts the cost savings of technological innovation and opportunistic benefit at a later stage, and then tradeoffs between "an appropriately high tender offer that realizes the enterprise's reservation profit" and "an appropriately low tender offer that increases the probability of winning the bid", and ultimately decides on the tender offer (α, β).

I-3, the winning price determined through bidding. After the private partner submits its bid, "nature" decides whether it wins the bid (Grimsey & Lewis, 2016). If successful, the private partner goes to the next stage of the game; if it does not, the game is over.

3.3.4.2 Process and parameters of Stage II

The terms and parameters used in Stage II of the game are listed in Table 3.3.

Table 3.3 Terms and parameters of the game in stage II

Terms and Parameters	Meaning
Intensity of Incentives (k)	The PUPC savings are ΔPUPC, and the private partner's share of ΔPUPC is k (He, 2022). $0\leq k\leq 1$
Savings rate of construction cost for design optimization (x)	It refers to the savings rate of construction cost due to design optimization. Design optimization refers to the private partner modifies and improves the design of engineering contents that have been specified in the output specifications during the construction stage, to enhance the value of the project (CCEA, 2022). Design optimization is characterized by the private partner modifying output specifications. $x=\frac{\text{CS before design optimization}-\text{CS after design optimization}}{\text{CS before design optimization}}$ $=\frac{hC-\text{CS after design optimization}}{hC}$
Savings rate of construction cost for design deepening (y)	It refers to the savings rate of construction cost for design deepening. Design deepening refers to the private partner supplements and refines the design of engineering contents that have not been specified in the output specifications during the construction stage, to meet constructability and enhance the value of the project (CCEA, 2022). Design deepening is characterized by the private partner not modifying output specifications. $y=\frac{\text{CS before design deepening}-\text{CS after design deepening}}{\text{CS before design deepening}}$ $=\frac{\delta(1-h)C-\text{CS after design deepening}}{\delta(1-h)C}$
Maximum cost savings rate of design optimization (x_0)	It is the maximum cost savings rate of design optimization that can be achieved under the influence of exogenous conditions. $0\leq x\leq x_0<1$
Maximum cost savings rate of design deepening (y_0)	It is the maximum cost savings rate of design deepening that can be achieved under the influence of exogenous conditions. $0\leq y\leq y_0<1$
Behavioral cost coefficient of design optimization (Φ_1)	If the behavioral cost of design optimization from the private partner is $\frac{1}{2}\Phi_1 d_1 x^2$, then d_1 is the enterprise's internal construction cost of specified work in the output specifications before design optimization. Φ_1 is the behavioral cost coefficient of design optimization. x is the saving rate of construction cost for design optimization.
Behavioral cost coefficient of design deepening (Φ_2)	If the behavioral cost of design deepening from the private partner is $\frac{1}{2}\Phi_2 d_2 y^2$, then d_2 is the enterprise's internal construction cost of not specified work in the output specifications before design deepening. Φ_2 is the behavioral cost coefficient of design deepening. y is the saving rate of construction cost for design deepening.
Quotation coefficient (J)	Quotation coefficient (J)$=\frac{\text{tender offer}}{\text{CS}}$
Internal construction cost of the enterprise after the technological innovation (C_2')	C' refers to the internal construction cost of the enterprise in the private partner (Professional Qualification Center of Ministry of Transport, 2020). It is information privately owned by the private partner and is not common knowledge. C_2' is the C' after private partner's technological innovation.
Revenue after the	R refers to the *revenue* that the private partner should obtain for the input

Terms and Parameters	Meaning
technological innovation (R_2)	of construction cost according to the PPP contract and the results of the performance evaluation. R_2 is the R after private partner's technological innovation.
Payoff after the technological innovation (E_2)	E refers to the payoff of the public authority and users, which only calculates the payment for construction cost and expenditure for project regulation services, and does not calculate revenue. E = -PUPC. E_2 is the E after private partner's technological innovation . In calculating E_2, the public authority's regulation cost is excluded for the time being. E_2=- PUPC (contract price) - PUPC (contract changes due to technological innovation) E_2 is a negative number.
Profit after the technological innovation (F_2')	F' refers to the internal profit of the enterprise in the private partner. F_2' is the F' after private partner's technological innovation.

The game process of Stage II is that in the construction stage, the public authority chooses incentive strategy, and the private partner chooses technological innovation strategy.

II-1, the intensity of incentives (k) from the public authority. The public authority issues incentives for technological innovation (k, 1), where "k" refers to the percentage of PUPC savings due to design optimization shared by the private partner (S. M. Huang, 2020), and "1" refers to 100% of PUPC savings due to design deepening shared by the private partner. The public authority knows h and α, and predicts the private partner's design optimization (x), and then decide on k. If k is too small, the intensity of incentives is too low, and the private partner cannot get extra profit from design optimization, and has no enthusiasm to design optimization. If k is too large, the intensity of incentives is too high, although the private partner has enthusiasm to design optimization, but the public authority will pay some unnecessary PUPC. Therefore, the value of k should be traded-off between "incentives for technological innovation" and "reducing PUPC" by the public authority, and the PUPC should be as small as possible.

II-2, Technological innovation (x, y) from the private partner. The private partner analyzes the incentives (k) and the space for technological innovation of the project, and makes a decision on technological innovation (x, y). Here, x and y refer to the "construction cost saving rate", which is used to indicate the private partner's technological innovation efforts (Zhang, 2012). The private partner knows h, (α, β), and k, predicts the regulation intensity (p) at a later stage, and then decide on technological innovation (x, y). Through technological innovation, the private partner increases the behavioral cost of technological innovation, but also decreases the construction engineering cost of the project. The private partner trade-off between "increasing the behavioral cost due to technological innovation" and "decreasing the construction cost due to technological innovation", and making the enterprise's internal profit (F') as large as possible.

3.3.4.3 Process and parameters of Stage III

The terms and parameters used in Stage III of the game are listed in Table 3.4.

Table 3.4 Terms and parameters of the game in stage III

Terms and Parameters	Meaning
Opportunism amount (t)	It refers to unjust enrichment of the private partner due to opportunism, and indicates the degree of opportunism in the private partner (Han, 2023).
Maximum amount of opportunism (t_0)	It is the maximum value of the unjust enrichment that can be achieved under the influence of exogenous conditions (in addition to factors of regulation). $0\leq t\leq t_0$
Behavior cost of hiding (C_h)	It refers to the behavior cost of hiding by the private partner (Han, 2023). $C_h=\Phi_3 et$
Behavior cost coefficient of hiding (Φ_3)	It is the coefficient of behavior cost of hiding in the private partner. $0\leq\Phi_3\leq 1$, $0\leq e\Phi_3\leq 1$
Proportion of hidden opportunism (e)	By hiding, the private partner reduces proportion of opportunism that is discovered, and this reduction is *e*. e = proportion of opportunism discovered before hiding - proportion of opportunism discovered after hiding
Maximum proportion of hidden opportunism (e_0)	It is the maximum value of the proportion of hidden opportunism that can be achieved under the influence of exogenous conditions and regulation.$0\leq e\leq e_0$
Intensity of regulation y (p)	It is the proportion of checking and finding opportunism by the public authority, assuming that the private partner does not hide (MOF, 2014). $0\leq p\leq 1$. When the private partner does not hide: $p=\frac{\text{Amount of opportunism discovered}}{\text{Total amount of opportunism}}$
Punishment coefficient (m)	If the public authority finds opportunism of the private partner, the public authority will confiscate the unjust enrichment (t) from the opportunism, and impose a fine of *m* times the unjust enrichment (Cai, 2017; Cai & Zhou, 2016). $m\geq 0$ $m=\frac{\text{fine}}{\text{Amount of opportunism discovered}}$
Behavioral cost coefficient of regulation (w)	It refers to the coefficient of regulation cost of the public authority. $0<w<1$.
Calculation coefficient for regulation cost (b)	$b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$
Cost of regulation (C_r)	It refers to the behavior cost of regulation in the public authority (NDRC, 2007). $C_r=-wE_1p$ E_1 is a negative number.
Internal construction cost of the enterprise after the innovation and opportunism (C_3')	C' refers to the internal construction cost of the enterprise in the private partner (Professional Qualification Center of Ministry of Transport, 2020). It is information privately owned by the private partner and is not common knowledge. C_3' is the C' after private partner's technological innovation and opportunism.
Revenue after the innovation and opportunism (R_3)	R refers to the *revenue* that the private partner should obtain for the input of construction cost according to the PPP contract and the results of the performance evaluation.

Terms and Parameters	Meaning
	R_3 is the R after private partner's technological innovation and opportunism.
Payoff after the innovation and opportunism (E_3)	E refers to the payoff of the public authority and users, which only calculates the payment for construction cost and expenditure for project regulation services, and does not calculate revenue. E = -PUPC. E_3 is the E after public authority's incentives and regulation. E_3=- PUPC (contract price) - PUPC (contract changes due to technological innovation and opportunism) - PUPC (regulation cost) E_3 is a negative number.
Profit after the innovation and opportunism (F_3')	F' refers to the internal profit of the enterprise in the private partner. F_3' is the F' after private partner's technological innovation and opportunism.

The game process of Stage III is that in the construction stage, the public authority chooses the regulation strategy and the private partner chooses the opportunism strategy.

III-1, the intensity of regulation from the public authority (p). The public authority specifies the intensity of the regulation by issuing a regulatory system for the project (MOF, 2014).The public authority knows h, (α, β), k, (x, y), and predicts private partner's opportunism (t, e), and then decides on p. If p is too small, the proportion of checking and finding opportunism is too low, the private partner obtains more opportunistic profit, and the public authority spends more PUPC. If p is too large, the proportion of checking and finding opportunism is too high, although opportunism in the private partner can be well curbed, however, the public authority will thus payoff more regulation cost. Therefore, the value of p for the public authority should trade-off between "curbing opportunism" and "reducing regulation cost", and make the PUPC as small as possible.

III-2, opportunism from the private partner (t, e). The private partner analyzes the regulation strategy and the space for opportunism, and makes a decision on opportunism (Zhang, 2012). At this time, the private partner is at the terminal node of the game tree, and the decisions of all its predecessors are known, and the private partner makes the decision on (t, e) based on the known conditions. The private partner invests the behavior cost of hiding (C_h) that reduces the proportion of opportunism discovered (e), so the proportion of opportunism discovered is "p-e", and the proportion of opportunism not discovered is "1-(p-e)". If opportunism is detected, the private partner faces confiscation of the unjust enrichment (t) and a fine of mt. If it is not detected, it obtains the unjust enrichment (t). The expected value of the extra profit from opportunism can thus be calculated. Therefore, the private partner makes a decision on opportunism based on the expected value of the extra profit, and makes the internal profit of the enterprise (F') as large as possible.

The private partner's decision on e depends on whether it can earn extra profit (Ni, 2019). If

extra profit can be gained, the private partner will hide. However, if extra profit cannot be gained, the private partner will not engage in opportunism and will not need to hide.

3.3.4.4 Multi-stage game tree

The multi-stage game process is expressed with a game tree, as shown in Figure 3.2.

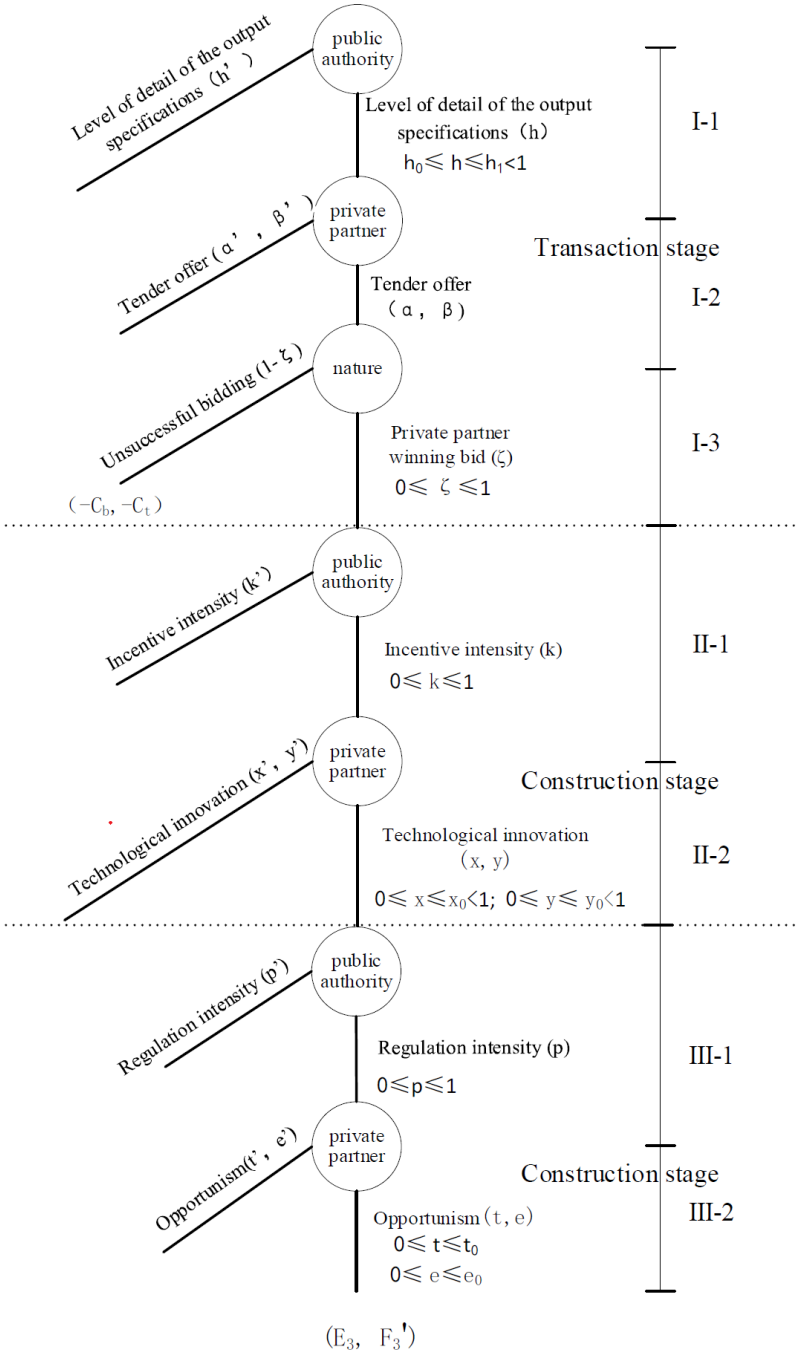


Figure 3.2 Overall game tree

The payoff vectors for the public authority and the private partner are noted below the terminal node of the above game tree, (Public authority and user's expenditures, Private partner's internal profit) = (E_3, F_3').

3.3.5 Inputs of mathematical modeling of game theory

All mathematical modeling exists in a certain scenario (Zhang, 2012). The mathematical modelling in this thesis has a total of 16 initial assumptions (inputs), as shown in Table 3.5. Among them, there are six initial assumptions that have a large amount of literature and the views of well-known scholars as their basis or source, and thus are directly formed as assumptions. The other 10 initial assumptions are based on a certain amount of literature as the basis or source, and are supported by the reality collected through structured interviews and the results of interview data analysis.

Table 3.5 Initial assumptions of mathematical modeling methods of game theory

NO.	Inputs for mathematical modeling method	Source/Basis
Initial assumption 1	The public authority and the private partner are both rational persons.	Structured interviews; H. J. Liu (2010); Meng (2019); Ni (2019)
Initial assumption 2	Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), there is room for savings for PUPC.	Structured interviews; CCEA (2018); Grimsey and Lewis (2016)
Initial assumption 3	In the transaction stage, all valid bidders that have passed pre-qualification are homogeneous bidders.	Structured interviews; J. T. Zhou et al. (2019); Weber et al. (2018)
Initial assumption 4	Transaction of the PPP project follows the market rules of "full competition and fair competition".	Structured interviews; MOF (2014); General Office of the State Council of the People's Republic of China (2023)
Initial assumption 5	The successful bidder of the PPP project transaction is determined according to the principle of "reasonably low price".	Structured interviews; MOF (2016)
Initial assumption 6	When tender offer is made in the private partner, the reservation profit rate of the works specified and unspecified in the output specifications is ≥0.	Structured interviews; S. Q. Wang and Wang (2017); ADB (2008)
Initial assumption 7	The results of design optimization (changes the output specifications) are shared between the public authority and the private partner.	Structured interviews; CCEA (2018); General Office of the State Council of the People's Republic of China (2023)
Initial assumption 8	The results of design deepening (without changing the output specifications) are exclusively enjoyed by the private partner.	Structured interviews; CCEA (2018); General Office of the State Council of the People's Republic of China (2023)
Initial assumption 9	If the private partner does not hide, the public authority can detect all opportunism among the targets of inspection.	Structured interviews; Ding (2016)
Initial assumption 10	The cost of regulation of the PPP project can meet: the cost of regulation ≤ the amount of fines and confession for maximum opportunism.	Structured interviews; NDRC (2007); Hemanta (2012)
Initial assumption 11	The dynamic game of complete information can be used to study the interest game between the public authority and the private partner.	Huang et al. (2009); L. Li et al. (2013); H. J. Liu (2010); Meng (2019); Ni (2019); Zhao (2016)
Initial	In the transaction stage, based on the output	Professional Qualification

NO.	Inputs for mathematical modeling method	Source/Basis
assumption 12	specifications from the public authority, the CS (construction cost calculated by Norm and Standard) for the PPP project can be calculated.	Center of Ministry of Transport (2020); MOF (2016); MOHURD (2013)
Initial assumption 13	Behavioral cost of design optimization in the private partner = $\frac{1}{2}\Phi_1 d_1 x^2$, where d_1 is the enterprise's internal construction cost of the works specified in the output specifications before design optimization, Φ_1 is the behavioral cost coefficient of design optimization, and x is the rate of construction cost savings due to design optimization.	Zhang (2012); H. J. Liu (2010); M. S. Li and Meng (2018); Y. L. Wang et al. (2016); China International Engineering Consulting Corporation (2021); J. Q. Wang (2018)
Initial assumption 14	Behavioral cost of design deepening in the private partner = $\frac{1}{2}\Phi_2 d_2 y^2$, where d_2 is the enterprise's internal construction cost of the works unspecified in the output specifications before design deepening, Φ_2 is the behavioral cost coefficient of design deepening, and y is the rate of construction cost savings due to design deepening.	Zhang (2012); H. J. Liu (2010); M. S. Li and Meng (2018); Y. L. Wang et al. (2016); China International Engineering Consulting Corporation (2021); J. Q. Wang (2018)
Initial assumption 15	Behavior cost of hiding = $\Phi_3 L$, where Φ_3 is the behavioral cost coefficient of hiding in the private partner. L is the amount of hidden opportunism due to the private partner's behavior of hiding.	Y. L. Yin et al. (2014); Y. L. Wang et al. (2016); Chen et al. (2014); J. Q. Wang (2018)
Initial assumption 16	The behavioral cost of regulation = $-wE_1p$, where w is the behavioral cost coefficient of regulation by the public authority, $-E_1$ is the expenditure of the public authority, and p is the intensity of regulation by the public authority.	NDRC (2007)

3.3.6 Analysis method for mathematical modeling of game theory

Based on construction cost theory and the aforementioned game tree, the payoff functions for the public authority and the private partner can be established. The principal-agent theory and backward induction method are used to solve the subgame perfect Nash equilibrium and derive the public authority's optimal utility function. Subsequently, the mathematical logic reasoning method is adopted to analyze the factors and trends influencing each decision variable and the public authority's optimal payoff (-PUPC), and explore the factors and paths for saving PUPC.

3.4 Focus group of experts

The results of the interview method and game theory modelling method may have some similarities and differences. In order to draw final research findings and increase the validity and reliability of this thesis, the focus group of experts will be used for evaluation.

The focus group of experts will conduct the evaluation in the following steps (Barnett, 2018): (1) Prepare evaluation materials and focus group guidelines. (2) Determine the setup of the focus

group and its participant numbers. According to the characteristics of intertwined interests within the PPP pattern, establish one focus group comprising nine industry experts. (3) Select evaluation experts and send out invitation letters. (4) Distribute evaluation materials. (4) The facilitator communicates with experts prior to the meeting to understand their familiarity with the evaluation materials and address any questions. (5) Organize video conferences with expert focus group, and form meeting minutes. (6) Summarize the evaluation conclusions of the focus group.

Based on the opinions of the focus group of experts and the actual research process of this thesis, the research findings of this thesis will be finally formed.

3.5 Summary

Interviews, game theory mathematical modelling, and focus groups of experts are the main research methods used in this thesis. These three research methods constitute a triangulation strategy.

Chapter 4: Data Analysis

This chapter will collect and organize the interview data, then conduct descriptive statistics and theme analysis on the structured interview data, and conduct coding analysis and descriptive statistics on the unstructured interview data. Finally, the data analysis results will be formed and a theoretical model will be established. The data analysis will be conducted using NVivo15 software and Microsoft Office 2021 (Excel).

4.1 Sample characterization

The interviewees in this thesis are seasoned practitioners in investment control or cost management within the PPP project. They possess a profound understanding of the economic management aspects in PPP practice. In this case, it is important to characterize the sample in order to ensure the quality and relevance of the obtained information. The sample characteristics of the interviewees are mainly reflected in five aspects: age, occupation, professional experience, judgment criteria, and familiarity with the questions for interview (Francisco, 2023).

4.1.1 Age

The PPP pattern is generally adopted in public service and infrastructure project, with relatively large investment amount (The State Council of the People's Republic of China, 2015); At the same time, in addition to the public authority and the private partner, the participants of the PPP pattern also include financing parties, contractors, subcontractors, raw material suppliers, professional operators, insurance companies, professional consulting firms, among others MOF (2014), involving a relatively broad social scope. Therefore, the PPP pattern requires professionals to have a certain level of social experience. Table 4.1 shows that 95.45% of the interviewees in this thesis are over 30 years old, and 4.55% are under 30 years old.

Table 4.1 Sample characterization

NO.	Variable	Category	Number of people	Percentage
1	Age	≤30 years old	1	4.54%
		30<age≤40 years old	15	68.18%
		40<age≤50 years old	5	22.73%
		50<age≤60 years old	1	4.55%
		>60 years old	0	0.00%
2	Occupation	Project representative from the public authority, or chief project leader from the private partner	9	40.91%
		Project investment manager from the public authority, or chief economist from the private partner	7	31.81%
		Project investment management staff from the public authority, or project cost management staff from the private partner	3	13.64%
		Chief project leader from the consulting agency commissioned by the public authority	3	13.64%
		Others	0	0.00%
3	Professional experience	≤5 years	0	0.00%
		5<years≤10	9	40.91%
		10<years≤15	8	36.36%
		15<years≤20	2	9.09%
		>20 years	3	13.64%
4	Basis for judgment	Theoretical analysis	5	22.73%
		Practical experience	16	72.73%
		Knowledge of relevant developments at home and abroad	1	4.54%
		Reference to domestic and foreign literature	0	0.00%
		Intuition	0	0.00%
4	Familiarity with the interview questions	Very familiar	4	18.18%
		Familiar	14	63.64%
		Relatively familiar	4	18.18%
		Not very familiar	0	0.00%
		Not familiar	0	0.00%

4.1.2 Occupation

The interviewees in this thesis are divided into five different occupational categories: project representative or chief project leader, project investment manager or chief economist, project investment or cost management staff, chief project leader from the consulting agency, and others. Table 4.1 shows that project representative or chief project leader accounted for 40.91%; project investment manager or chief economist accounted for 31.81%; project investment or cost management staff accounted for 13.64%; and chief project leader from the consulting agency accounted for 13.64%.

4.1.3 Professional experience

The professional experience (years of professional work experience) of the interviewees in this thesis is all above five years. Table 4.1 shows that personnel with five to ten years of professional experience account for 40.91%; 59.09% of the personnel have more than ten years of professional experience.

4.1.4 Basis for judgment

This thesis divides the interviewees' basis for judgement on the research questions into five different categories: theoretical analysis, practical experience, knowledge of relevant developments at home and abroad, reference to domestic and foreign literature, intuition. The purpose of the interview method in this thesis is to collect field experience, so the focus is on selecting interviewees with rich practical experience. Table 4.1 shows that 22.73% of the interviewees use "theoretical analysis" as the basis for judgment; 72.73% of the interviewees use "practical experience" as the basis for judgment; 4.54% of the interviewees use "knowledge of relevant developments at home and abroad" as the basis for judgment.

4.1.5 Familiarity level

To ensure the quality of the interview, interviewees are required to be familiar with the PPP pattern. Table 4.1 shows that 18.18% of the interviewees are "very familiar" with the interview questions; 63.64% are "familiar"; and 18.18% are "relatively familiar".

4.2 Data acquisition for structured interview

After obtaining the consent of the interviewees, the structured interview will be fully recorded, and then the interview recording materials will be transcribed into a word file. During the transcription process, the interview data was organized for ease of later data analysis without changing the meaning of the interviewees' words.

A total of 22 interview records were ultimately compiled. The interview materials of each interviewee are numbered (A1, B1, A2, B2...) in the order of interview, where A represents interviewees from the public authority and B represents interviewees from the private partner.

4.3 Data analysis result of structured interview

4.3.1 Descriptive statistics

For structured interview data, Microsoft Office 2021 (Excel) was used to conduct descriptive statistics on the core viewpoints of each interviewee on each interview theme (Fan et al., 2024). See Table C.1 in Annex C for details.

The descriptive statistics in this thesis are conducted according to the following approach:

1. Statistics on the selection results of the main questions.

The main questions of the interview outline are designed based on "multiple-choice questions + conversation and communication". The proposition corresponding to the main question is the initial assumption of the mathematical modeling method in game theory (see Section 3.3.5 of this thesis for specific details. Hereinafter referred to as "initial assumption"). Based on the statistical results of the main questions, the interviewees' support rate for the initial assumption is calculated based on "$\frac{\text{number of people supporting the initial assumption}}{\text{total number of people}}$".

For example, for main question 2.6: Both the public authority and the private partner are rational persons. Do you agree with this opinion?

The corresponding initial assumption: Both the public authority and the private partner are rational persons.

Using an excel spreadsheet for statistics, 18 out of 22 interviewees chose "agree" or "strongly agree", resulting in a support rate of 82%.

2. Statistics on "dissenting opinions" on the main questions.

During the interview process, if the interviewee holds neutral, negative, or completely negative opinions about the initial assumption, the interviewer communicated with the interviewees and asked them to provide a statement of reasons (hereinafter referred to as "dissenting opinions"). Descriptive statistics should be conducted on the dissenting opinions on each main question for later theme analysis.

For example, when interviewees select "neutral", "disagree", or "Strongly disagree" in response to the main question 2.6, they are required to provide their reasons in the corresponding cell of the descriptive statistics table and accurately describe their dissenting opinions.

3. Statistics on the judgment results of auxiliary questions.

The auxiliary questions are questions that the interviewer asks the interviewees from another perspective on the main questions.

Based on the interviewee's answers to the auxiliary questions, logical reasoning can be

employed to discern the interviewee's stance on the main question. This can verify whether the interviewee has accurately grasped the essence of the main question and facilitates a more comprehensive capture of information pertaining to the interview theme. The auxiliary questions in the interview outline are designed in the format of "true/false questions + conversation and communication". According to the statistical results of the interviewees' judgment on the auxiliary questions, the interviewees' support rate for the initial assumption is calculated based on "$\frac{\text{number of people supporting the initial assumption}}{\text{total number of people}}$". If the answers to the auxiliary questions help to support the validity of the initial assumption, it is called "supporting the initial assumption".

For example, for auxiliary question 2.6.1: Does the public authority care about the proper functioning of the PPP project and how much the public authority and user payment is? Using an excel spreadsheet to calculate the interviewees' answers to this question, all 22 interviewees answered "yes". According to logical reasoning, affirmative answers help support the validity of the initial assumption, therefore, the answer to the auxiliary question 2.6.1 has a 100% support rate for the initial assumption.

4. Statistics of "dissenting opinions" on auxiliary questions.

For auxiliary questions, the interviewer and interviewee engage in relatively broad conversations and exchanges. If the interviewee's answers show a neutral or negative viewpoint of the initial assumption, descriptive statistics should include the interviewee's statement of reasons (hereinafter referred to as "dissenting opinions") in the corresponding cell. This is for the purpose of later theme analysis.

For example, for auxiliary question 2.8.1: "2.8.1 When bidding for the PPP project, does the tender offer of the bidder who has passed the prequalification have a very significant impact on the probability of winning the bid?" Some interviewees judged it as "yes", while others judged it as "neutral". When interviewees judged "neutral" opinion to the initial assumption, they are required to provide their reasons in the corresponding cell of the descriptive statistics table and truthfully describe their dissenting opinions.

4.3.2 Theme analysis

Further theme analysis should be conducted for each initial assumption, according to the descriptive statistics derived from structured interviews. Table 4.6 presents the results of the theme analysis.

If the calculated support rate stands between 50%-60%, it is called "**very weak support**"; The calculated support rate of 60%-70% is called "**weak support**"; The calculated support rate

of 70%-80% is called "**general support**"; The calculated support rate of 80%-90% is called "**strong support**"; The calculated support rate of 90%-100% is called "**very strong support**". The degree of support that interviewees have for the initial assumption is assessed based on the support rate calculated by the descriptive statistics.

For each interview theme, a theme analysis is conducted according to the following approach:

1. Supporting and opposing opinions on the main questions. It includes the support rate for the main questions, as well as the classification and summary of the reasons for the "dissenting opinions" held by the opponents.

2. Supporting and opposing opinions on auxiliary questions. It includes the support rate for the auxiliary questions, as well as the classification and summary of the reasons for the "dissenting opinions" held by the opponents.

3. Theoretical analysis. A theoretical analysis is conducted on the "dissenting opinions" regarding the main and auxiliary questions, checking authenticity and rationality of the "dissenting opinions", and their influence on the initial assumptions. If the opponent's facts are clear and conclusive, and the reasons are well-founded and rigorous, and significantly influence the setup of the initial assumption, then the initial assumption should be comprehensively modified or canceled. If the facts are doubtful, the reasons lack rigor, or the influence on the initial assumption is not significant, a decision can be made to partially modify or not modify the initial assumption based on the specific circumstances.

4. Interpretation of the main questions by auxiliary questions. The main questions directly solicit the interviewee's opinion on the initial assumption, whereas auxiliary questions are designed to gather additional information about the theme from different perspectives. Based on interviewees' responses to auxiliary questions, it can be determined whether they've accurately understood the true meaning of the main questions. This deeper insight helps us understand their thought processes and logical perspectives on the initial assumption, making it easier to analyze and distinguish their supporting or opposing views. Therefore, through the analysis of interviews with auxiliary questions, it is possible to further understand the true thoughts of the interviewees and obtain their interpretation opinions on the main questions from the auxiliary questions.

5. Analysis results. Based on the above analysis, make a comprehensive judgment on whether the initial assumption needs to be modified. Specifically, it can be divided into "initial assumption not to be modified", "initial assumption requiring modification", and "initial assumption canceled".

6. Modify the initial assumption based on the analysis results. For those assumptions that need to be modified, based on the analysis of the interview theme, redefine the modified

assumptions.

Based on the analysis results, it was finally determined that six initial assumptions did not need to be modified, three initial assumptions needed to be modified, and one initial assumption was canceled. The theme analysis process is detailed in Table C.2 of Annex C, and the theme analysis results are shown in Table 4.2.

Table 4.2 Results of the theme analysis

Questions for Interview	Number of people supporting	Percentage	Theme analysis results
2.6 Both the public authority and the private partner are rational person. Do you agree with this view?	18	82%	The initial assumption will not be modified.
2.7 Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), is there any space for savings in the PUPC?	22	100 %	The initial assumption will not be modified.
2.8 In the transaction stage, all valid bidders that have passed pre-qualification are homogeneous bidders (each bidder has the same probability of winning the bid). Do you agree with this view?	15	68%	The initial assumption is modified to: In the transaction stage, the private partner acts as the representative of the winning bidder among all bidders.
2.9 The transaction of the PPP project should follow the market rules of "full competition and fair competition". Do you agree with this view?	22	100 %	The initial assumption will not be modified.
2.10 The successful bidder for a PPP project transaction is determined according to the principle of "reasonably low price". Do you agree with this view?	19	86%	The initial assumption needs to be modified to: The PPP project transactions follow the principle of "low price priority", i.e., the lower the tender offer, the higher the price score in the total score (except for tender offer lower than the cost)
2.11 When the private partner makes a tender offer, is the reservation profit rate for works specified and unspecified in the output specifications greater than or equal to 0?	19	86%	The initial assumption will not be modified.
2.12 Should the results of design optimization (changes to output specifications) be shared between the public authority and the private partner?	20	91%	The initial assumption will not be modified.
2.13 Should the results of design deepening (without changes to the output specifications) be reserved exclusively for the private partner?	20	91%	The initial assumption needs to be modified to: The results of design deepening (without changing the output specifications) should be exclusively enjoyed by the private partner (except for

Questions for Interview	Number of people supporting	Percentage	Theme analysis results
			excessive profit).
2.14 If the private partner does not hide, can the public authority detect all opportunism on the target of the inspection?	15	68%	The initial assumption has been canceled.
2.15 Do you think that the cost of regulation for the PPP project meets the condition: "Cost of regulation ≤ the amount of fines and confiscations for the maximum opportunism"?	20	91%	The initial assumption will not be modified.

4.4 Coding and category extraction of unstructured interview

Grounded theory, as a research method (Holton & Walsh, 2021), emphasizes the construction of theoretical frameworks through a systematic coding process starting from raw data. This thesis, based on the grounded theory method and NVivo 15.0 software, constructs a relevant theoretical model for saving PUPC in the public authority of the PPP project, providing guidance for practice. During the data analysis process, the researchers conducted open coding, axial coding, and selective coding.

4.4.1 The process of open coding

Open coding is the initial analysis of raw interview data, which is the process of mining basic information and initial concepts (C. X. Zhou, 2021). In the open coding stage, this thesis extracts initial concepts from interview data and creates nodes through the method of "continuous comparison". The main process is as follows:

Firstly, the researchers analyze and understands the interview content in its presented form. This is an operational process of breaking down raw data, assigning concepts, and then reassembling them in new ways. Secondly, the researchers compare the categories of different initial concepts, extract typical initial concepts based on property and dimensions, and name them (node names). It's best to use the original vocabulary (the interviewee's original words). This represents the prototype of open coding, as shown in Table D.1 of Annex D. Thirdly, the researchers proceed to read the subsequent textual materials, extract initial concepts, and consistently compare them with the established nodes. If there are identical concepts, use the existing node directly; If there are similar ones, fine-tune the existing node and use it together; If there are completely different ones, create a new node. Fourthly, by continuously comparing and coding, creating new nodes until all interview data has been processed, the conceptualization of interview data can be achieved. Fifth, the researchers inspect all the nodes that have been created

and conducts a systematic review and collation to ensure that each node (initial concept, open coding) conveys a distinct meaning.

This thesis has extracted the initial concepts from 22 sets of interview data and formed 77 open codings (a1-a77), covering various factors that affect public authority's PUPC savings and related decisions during the transaction and construction stages of the PPP project. These open codings reflect the interviewees' cognition, experience, and views on the relevant decisions to save PUPC, providing rich materials for further constructing theoretical frameworks. Due to space constraints, Table 4.3 only lists the names of the top 20 open codings and the number of their reference points. This thesis contains a total of 77 open codings, as detailed in Table D.2 of Annex D.

Table 4.3 Open codings and the number of their reference points

Open Coding	RP	Open Coding	RP	Open Coding	RP	Open Coding	RP
a1 Project scale (c1/c3/c4)	1+4+6	a6 Understanding of technology and the site	2	a11 Difference in the construction cost savings rates between the specified and unspecified engineering content	5	a16 Market maturity	4
a2 Complexity of project	7	a7 Risk allocation (c1/c2/c3)	2+10+4	a12 Difference in maximum construction cost savings rates between design optimization and design deepening	7	a17 Influence of level of detail of output specifications on PUPC	27
a3 Understanding level of project	4	a8 Deviation coefficient of quantities (c1/c2)	14+11	a13 Difference in tender profit rates between specified and unspecified engineering content	18	a18 Influence path of the level of detail of output specifications	15
a4 Preparation time	1	a9 Difference in behavioral cost coefficients between design optimization and design deepening	24	a14 Market competitiveness (c1/c2)	3+10	a19 Cost forecast	1
a5 Depth of preliminary work	3	a10 Expected value of construction cost	1	a15 Policies and regulations	4	a20 Scope of cooperation for project	2

Note: a21 to a77 are shown in Table D.2 of Annex D. RP is the abbreviation for the number of reference points.

Due to the large number of extracted initial concepts (open coding), in order to further aggregate the insights of various interviewees on the level of detail of output specifications, tender offer, intensity of incentives, technological innovation strategy, intensity of regulation, and opportunism strategy, this thesis extracted 32 subcategories (b1-b32) based on the initial

concepts. The process of extracting subcategories (C. X. Zhou, 2021) mainly involves:

Firstly, the initial concepts are divided into several categories based on the different implementation stages (transaction stage and construction stage) and different themes (six interview themes in the interview outline) of the PPP project. Then, the initial concepts that are interrelated within a category are aggregated together to form small groups. Thirdly, based on the conceptual characteristics of engineering cost management (such as revenue, cost, profit, environment) (Z. M. Wu, 2023), and in conjunction with the interviewees' intentions, the small groups are named to form subcategories. The relationship between subcategories and initial concepts is shown in Table 4.4.

Table 4.4 Relationship between subcategories and initial concepts

Subcategory	Open Coding
b01 Project characteristics and preparation	a1 Project scale$_{c1}$; a2 Complexity of project; a3 Understanding level of project; a4 Preparation time; a5 Depth of preliminary work; a6 Understanding of technology and the site
b02 Risk allocation principles	a7 Risk allocation$_{c1}$; a8 Deviation coefficient of quantities $_{c1}$
b03 Difference in the behavioral cost coefficient	a9 Difference in behavioral cost coefficients between design optimization and design deepening
b04 Difference in construction cost savings rate	a10 Expected value of construction cost; a11 Difference in the construction cost savings rates between the specified and unspecified engineering content; a12 Difference in maximum construction cost savings rates between design optimization and design deepening
b05 Difference in profit rate	a13 Difference in tender profit rates between specified and unspecified engineering content
b06 Market and industry factors	a14 Market competitiveness$_{c1}$; a15 Policies and regulations; a16 Market maturity
b07 Storyline of the level of detail of output specifications	a17 Influence of level of detail of output specifications on PUPC; a18 Influence path of the level of detail of output specifications
b08 Project CS	a19 Cost forecast; a20 Scope of cooperation for project; a21 Project characteristics; a22 Performance credit of the public authority; a23 CS / Investment scale
b09 Behavioral cost coefficient of technological innovation$_{c2}$	a24 Behavioral cost coefficient of design optimization$_{c2}$; a25 Behavioral cost coefficient of design deepening$_{c2}$
b09 Behavioral cost coefficient of technological innovation$_{c3}$	a40 Behavioral cost coefficient of technological innovation$_{c3}$; a26 Construction cost savings rate of specified engineering content / Construction cost savings rate of design optimization$_{c3}$
b09 Behavioral cost coefficient of technological innovation$_{c4}$	a40 Behavioral cost coefficient of technological innovation$_{c4}$; a24 Behavioral cost coefficient of design optimization$_{c4}$; a25 Behavioral cost coefficient of design deepening$_{c4}$
b10 Construction	a26 Construction cost savings rate of specified engineering content / Construction cost savings rate of design optimization$_{c2}$; a27 Construction cost savings rate of

Subcategory	Open Coding
cost savings rate	unspecified engineering content / Construction cost savings rate of design deepening
b11 Risk quotation coefficient	a7 Risk allocation$_{c2}$; a8 Deviation coefficient of quantities$_{c2}$
b12 Reservation profit rate	a14 Market competitiveness$_{c2}$; a28 Tender profit rate of the specified engineering content in the output specifications; a29 Tender profit rate of the unspecified engineering content in the output specifications; a30 Project return rate/ Internal rate of return / Expected return
b13 Productivity level	a31 Technological and management capability of the private partner; a32 Discount rate for productivity level in the private partner
b14 Storyline of tender offer	a33 Influence of tender offer on PUPC; a34 Influence path of tender offer
b15 Profit rate driven	a35 Potential return; a36 Tender profit rate
b16 Risk premium	a7 Risk allocation$_{c3}$; a37 Risk preference; a38 Technological progress / Technological maturity$_{c3}$; a39 Timeliness of fiscal fund payment
b17 Constraints from project characteristics	a41 Political factors or project's political sensitivity; a1 Project scale$_{c3}$
b18 Implementation conditions of policy	a42 Difficulty in implementing policy; a43 Identification of design optimization
b19 Storyline of intensity of incentives	a44 Influence of intensity of incentives on PUPC; a45 Influence path of intensity of incentives
b20 Corporate capability	a46 Private partner's ability for technological innovation; a47 Familiarity of technical strength with innovation / Project experience; a48 Standardization of corporate internal management; a49 Market competitiveness
b21 Incentives and benefit	a1 Project scale$_{c4}$; a50 Return mechanism of project; a51 Intensity of incentives; a52 Strategic expectation for long-term cooperation; a53 Efficiency boundary of design optimization
b22 External conditions	a38 Technological progress / Technological maturity$_{c4}$; a54 Limitation of external conditions
b23 Technological innovation storyline	a55 Influence of technological innovation on PUPC; a56 Influence path of technological innovation
b24 Regulatory mechanism and sensitivity	a57 Regulation cost; a58 Regulatory scope and responsibilities under contract; a59 Inspection intensity by superior authorities; a60 Standardization of management / Compliance risk; a61 Risk structure of contract; a62 Project characteristics / Project scale; a63 Social attention
b25 Proportion of hiding	a64 Proportion of hiding; a65 Maximum proportion of hiding opportunism
b26 Behavioral cost coefficient of hiding	a66 Behavioral cost coefficient of hiding$_{c5}$
b27 Punishment coefficient$_{c5}$	a67 Severity of punishment / Intensity of punishment / Punishment coefficient$_{c5}$
b27 Punishment coefficient$_{c6}$	a67 Severity of punishment / Intensity of punishment / Punishment coefficient$_{c6}$
b28 Storyline of	a68 Influence of intensity of regulation on PUPC; a69 Influence path of intensity

Subcategory	Open Coding
intensity of regulation	of regulation
b29 Expected net benefit	a70 Profitable return / Expected return / Potential return of opportunism; a66 Behavioral cost coefficient of hiding$_{c6}$
b30 Intensity of regulation	a71 Intensity of regulation; a72 Trends in regulation; a73 Deficiency in public authority's regulatory capacity
b31 Preference for corporate credibility	a74 Corporate credibility; a75 Moral hazard propensity
b32 Opportunism storyline	a76 Influence of opportunism on PUPC; a77 Influence path of opportunism

4.4.2 The process of axial coding

The axial coding in this thesis involves aggregating subcategories and establishing the inherent connections among different subcategories (Lu, 2022).

The main process of axial coding is as follows: Firstly, classify the subcategories that have already been formed. Because each interviewee's conversation consists of six different interview themes, and 32 subcategories are distributed among these six interview themes, subcategories can be classified according to interview themes. Secondly, analyze the aggregation connotation of subcategory. The subcategory is aggregated through "the specific decision-making actions and consequences of actions taken by the public authority and the private partner in a certain stage of PPP project implementation". Finally, determine the axial coding of the aggregated subcategories. These aggregated subcategories form interrelated relationships around a certain "main axis", which is the axial coding.

After refinement, this thesis identifies a total of six axial codings, specifically "c1 Optimal level of detail of output specifications"; "c2 Optimal tender offer"; "c3 Optimal intensity of incentives"; "c4 Optimal technological innovation strategy"; "c5 Optimal intensity of regulation"; "c6 Optimal opportunism strategy", as shown in Table 4.5. Each axial coding has a clear theoretical connotation (see "Terms" in the interview outline for details), covering the key elements of PPP project's PUPC during the transaction and construction stages.

Table 4.5 Relationship between axial coding and subcategory

Axial coding (main category)	Subcategory
c1 Optimal level of detail of output specifications	b01 Project characteristics and preparation; b02 Risk allocation principles; b03 Difference in behavioral cost coefficient; b04 Difference in construction cost savings rate; b05 Difference in profit rate; b06 Market and industry factors; b07 Storyline of the level of detail of output specifications
c2 Optimal tender offer	b08 Project CS; b09 Behavioral cost coefficient of technological innovation$_{c2}$; b10 Construction cost savings rate; b11 Risk quotation coefficient; b12

	Reservation profit rate; b13 Productivity level; b14 Storyline of tender offer
c3 Optimal intensity of incentives	b15 Profit rate driven; b16 Risk premium; b09 Behavioral cost coefficient of technological innovation$_{c3}$; b17 Constraints from project characteristics; b18 Implementation conditions of policy; b19 Storyline of intensity of incentives
c4 Optimal technological innovation strategy	b20 Corporate capability; b09 Behavioral cost coefficient of technological innovation$_{c4}$; b21 Incentives and benefit; b22 External conditions; b23 Technological innovation storyline
c5 Optimal intensity of regulation	b24 Regulatory mechanism and sensitivity; b25 Proportion of hiding; b26 Behavior cost of hiding; b27 Punishment coefficient$_{c5}$; b28 Storyline of intensity of regulation
c6 Optimal opportunism strategy	b29 Expected net benefit; b30 Intensity of regulation; b27 Punishment coefficient$_{c6}$ b31 Preference for corporate credibility; b32 Opportunism storyline

Take "optimal level of detail of output specifications" as an example to illustrate the intrinsic relationship between axial coding and subcategories. According to the coding analysis results, "c1 Optimal level of detail of output specifications" (axial coding) aggregates six subcategories: b01 Project characteristics and preparation; b02 Risk allocation principles; b03 Difference in the behavioral cost coefficient; b04 Difference in construction cost savings rate; b05 Difference in profit rate; b06 Market and industry factors. These six subcategories reflect the factors that need to be considered when making decisions on the level of detail in the output specifications of the public authority during the PPP project transaction stage. According to the interviewees' opinions, further statistics can be used to determine the impact (i.e., correlation) of the six subcategories on the axial coding.

Through the analysis of the relationship between the axial coding and the subcategories mentioned above, explore and construct the mechanism by which the axial coding (i.e., decision-making by the public authority or the private partner) is influenced by the subcategories (i.e., factors influencing decision-making). This theoretical framework, derived from the field experience of interviewees, lays the foundation for in-depth analysis of strategies for saving PUPC in the public authority.

4.4.3 The process of selective coding

Selective coding employs the logic of "drawing storyline" to identify core categories, construct theoretical models, and elucidate the interactive relationships among subcategories, axial coding, and core coding (Lu, 2022). The core category serves as the theoretical anchor, synthesizing the core property and research objectives of the storylines in interview data, while systematically linking the properties of axial codings and subcategories. The core category of this thesis is "strategies for saving PUPC by the public authority". This core category is influenced by six axial codings: optimal level of detail in output specifications, optimal tender offer, optimal

intensity of incentives, optimal technological innovation strategy, optimal intensity of regulation, and optimal opportunism strategy. See Figure 4.1 for details, due to space constraints in the figure, some codes with fewer reference points are not displayed.

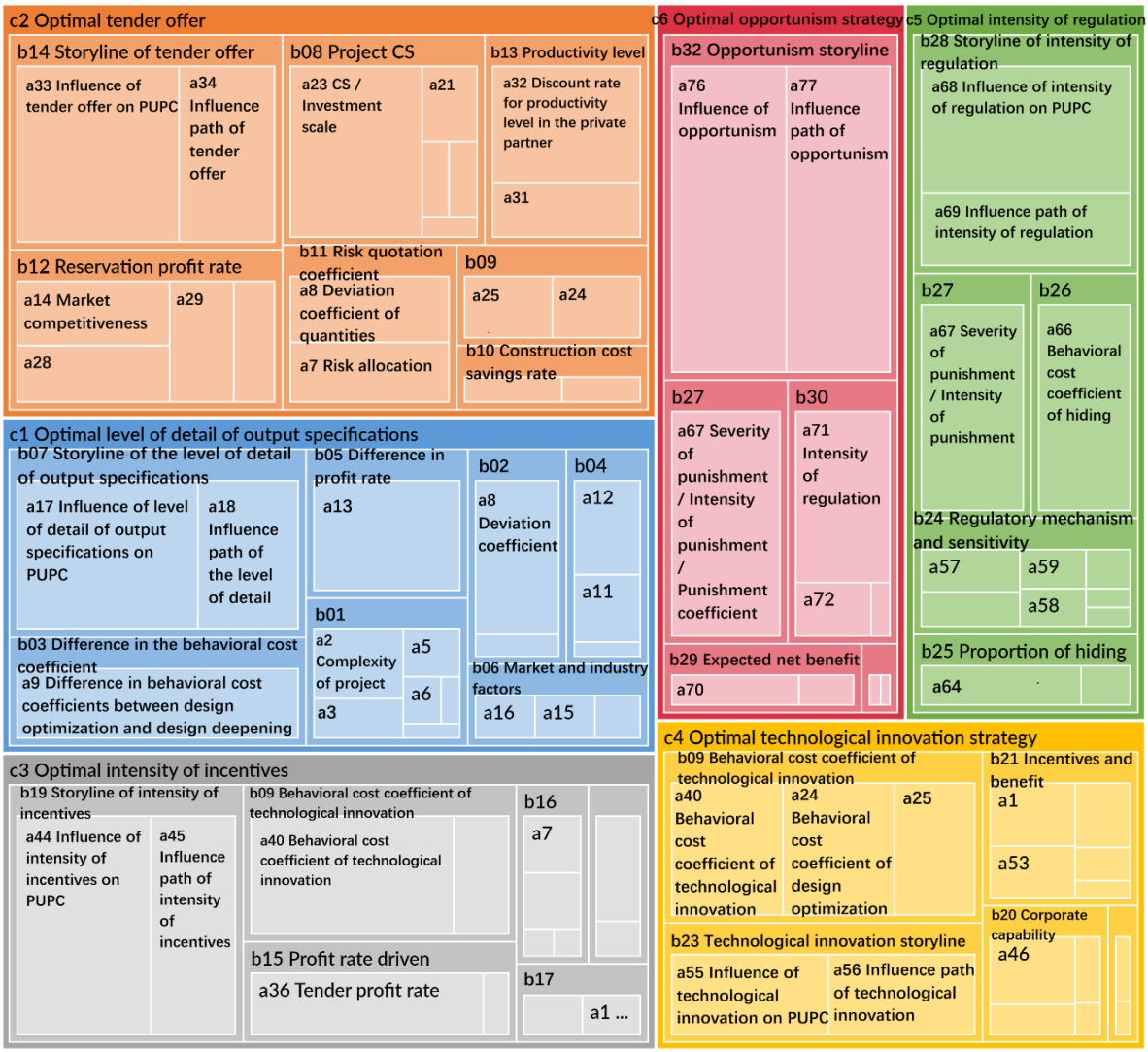


Figure 4.1 Hierarchical structure diagram among core categories, axial coding, and subcategories

Through repeated review of the initial concepts, subcategories, and axial coding of this thesis, the selective coding and storyline of interview data are presented (Lu, 2022): During the PPP project transaction and construction stage, the public authority selects the optimal level of detail of output specifications, optimal intensity of incentives, and optimal intensity of regulation based on the principle of minimizing PUPC, while the private partner selects the optimal tender offer, optimal technological innovation strategy, and optimal opportunism strategy based on maximizing its own profit; Among these optimal strategies, the strategy of the public authority is proactive and acts first, while the strategy of the private partner is interdependent with the strategy of the public authority and acts later; Then, the optimal strategies of both the public authority and the private partner influence the PUPC, jointly sketching the storyline of saving

PUPC.

4.4.4 Theoretical saturation test

The sampling method for qualitative research is different from quantitative research, which requires that the research results must be statistically significant (H. Z. Li, 2022). Therefore, qualitative research does not have specific requirements for sample size, but it needs to follow the principle of theoretical saturation.

At the end of each interview, the coders conducted a preliminary analysis or open coding of the interview content, and then decided how to select the next interviewee to supplement with more information (Tian, 2020). As the interviews progressed, after the 18th and 19th interviews, the interview data was imported into NVivo 15 software for coding analysis, and no new information was found.

To be cautious, the researchers organized the coding moderator and two coders to review the coding of the previous 19 interviews, repeatedly checking the accuracy of the initial concepts, subcategories, and axial coding to reduce the possibility of later modifications. After the review, detailed modifications and improvements were made. However, no new initial concepts or internal connections emerged from the 18th and 19th interviews.

The 20th, 21st, and 22nd interviews continued, but no new concepts or internal connections related to the research questions emerged. This indicates that the open coding, subcategories, and axial coding identified already covered the main aspects of the research object, and the data collection had reached theoretical saturation. At this point, the interviews ended (Fan et al., 2024; L. P. Yang et al., 2022).

4.4.5 Consistency check

In order to verify the validity and reliability of the coding analysis, two coders were assigned to independently code the interview data of 22 interviewees. Then, their coding result documents were given to the data analysis moderator, who imported them into NVivo 15 software for consistency checking. After importing into NVivo 15, the Kappa value was calculated in "Queries-Coding comparison" of the "Explore" menu. Table 4.6 shows the results of the consistency check.

Table 4.6 Consistency test result

Axial coding	Kappa coefficient
c1 Optimal level of detail of output specifications	0.9171
c2 Optimal tender offer	0.9105
c3 Optimal intensity of incentives	0.9330
c4 Optimal technological innovation strategy	0.9489
c5 Optimal intensity of regulation	0.9407
c6 Optimal opportunism strategy	0.9432

According to the consistency test, the Kappa coefficients of the six main categories are all above 0.8, indicating that the two coders have high consistency in the definition of all axial codings, which overall supports the accuracy and reliability of the research data (Chang, 2020), ensuring that the research results are grounded in accurate and reliable encoded data.

Forty-five days after the coding of this thesis had been completed, the coding moderator randomly sampled three interview materials from the 22 interview materials, and gave them to the two original coders to recode. After the coding was completed, the moderator imported the recoded files and their previous coded files into NVivo 15 to perform a "Coding comparison" operation and calculate the Kappa coefficient. The consistency (Kappa coefficient) of the codings at different times by coder 1 is 0.872, and the consistency of the codings at different times by coder 2 is 0.903, both of which meet the requirements.

Unlike data lists, the validity and reliability of the interview method do not have strict statistical indicators (H. Z. Li, 2022). This thesis mainly uses pre-interviews, pilot tests, theoretical saturation test, and consistency checks to ensure the validity and reliability of the interview method.

4.5 Data analysis result of unstructured interview

Based on the above coding analysis results, open coding, subcategory, axial coding, selective coding, and their inherent connections have been determined. In order to further explore their correlations (positive correlation, negative correlation, irrelevant) and the level of support from interviewees for these correlations, the researchers returned to all interview data to reconstruct the true meaning of the interviewees, excavate their expressions of correlation, and conduct statistical analysis. See Table D.3 in Annex D for details.

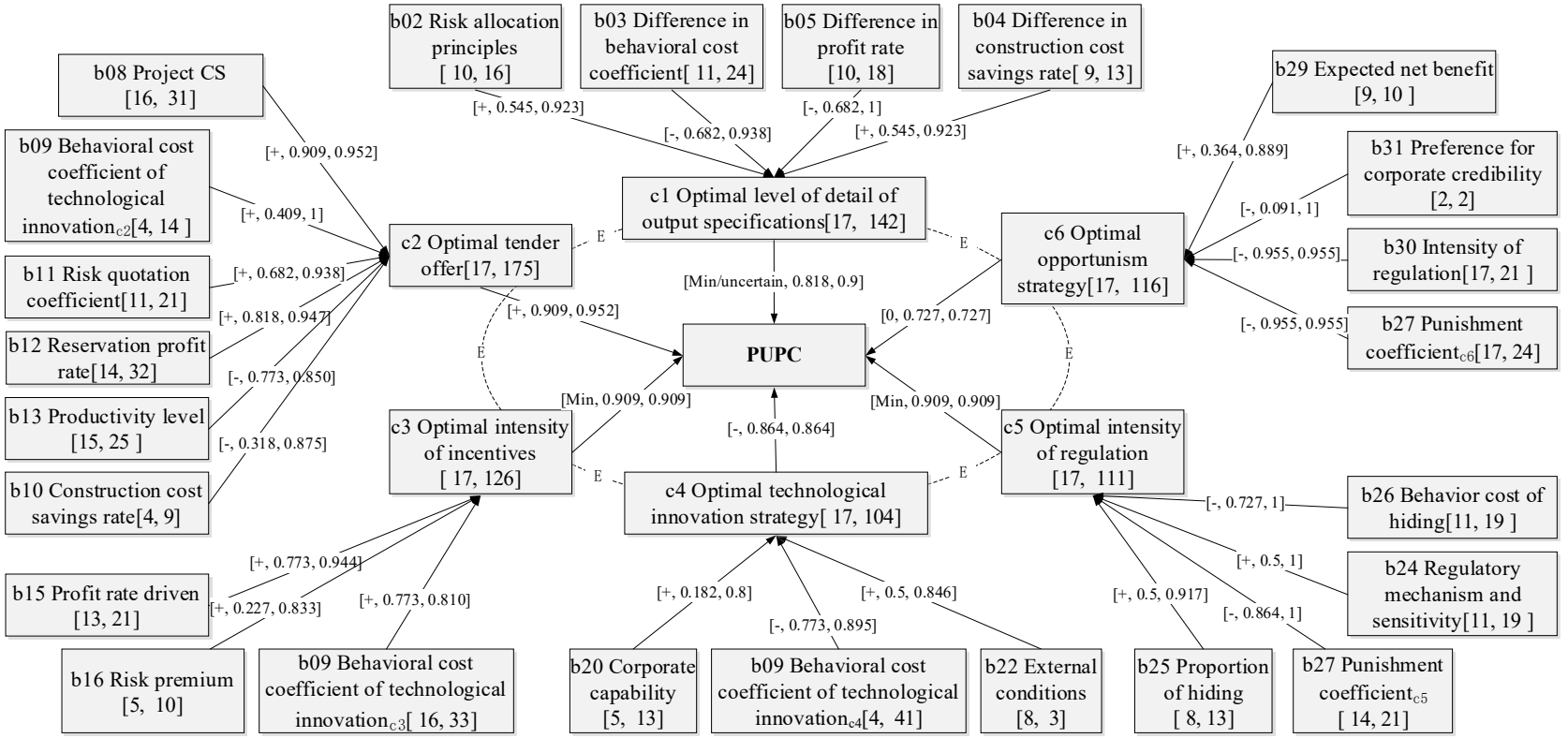
In the statistical process, "Blank" indicates that the interviewee did not mention the subcategory and its initial concepts; "N" indicates that the interviewee believes there is correlation between the subcategory and the corresponding axial coding, but is unsure or does not clearly indicate whether it is positively or negatively correlated; "0" indicates that the

interviewee believes that the subcategory is irrelevant to the corresponding axial coding; "+" indicates that the interviewee believes there is a positive correlation between the subcategory and the corresponding axial coding; "–" indicates that the interviewee believes there is a negative correlation between the subcategory and the corresponding axial coding; "Min" indicates that the interviewee believes that this subcategory minimizes the corresponding axial coding.

n_1 refers to the number of people who hold mainstream views divided by the total number of interviewees; n_2 refers to the number of people who hold mainstream views divided by the number of interviewees after excluding those who have not expressed their opinions ((i.e., those marked as "Blank"). The degree of support for mainstream views is represented by [n_1, n_2]. The following text only discusses the influencing factors where n_1 is greater than 50% or n_2 is greater than 80%.

4.5.1 Theoretical model

Based on the above data analysis results, it can be found how the six decision variables (axial codings) of the public authority and the private partner are influenced by 32 subcategories, and how these six decision variables affect the PUPC of the public authority. On this basis, the path of "32 subcategories → six axial codings → saving PUPC" was further clarified. The data analysis results can be presented through a theoretical model diagram (C. X. Zhou, 2021), as shown in Figure 4.2.



Explanation: 1. Meaning of [a1, a2] in the box: The first data (a1) represents the number of samples corresponding to the code, i.e., the number of samples that support the code; the second data (a2) represents the number of reference points corresponding to the code, i.e., the number of reference points that support the code.

2. Meaning of [symbol, n_1, n_2] on the line: The first data (symbol) indicates correlation; the second data (n_l) represents the proportion of mainstream views in the total number of people; the third data (n_2) represents the proportion of mainstream views after excluding people who did not express an opinion. "+ " indicates a positive correlation, "- " indicates a negative correlation, and "E " indicates an equilibrium correlation.

3. Due to space limitations, the above figure only lists subcategories where mainstream views account for a relatively large proportion.

Figure 4.2 Theoretical model of saving PUPC by the public authority

4.5.2 Factors influencing the optimal level of detail of output specifications

In the transaction stage, the decision on the level of detail of the output specifications from the public authority needs to tradeoff between "clarifying functional requirements and technical quality requirements" and "leaving sufficient space for technological innovation", and making PUPC as small as possible.

After statistical analysis, it was found that the "b05 Difference in profit rate ($\frac{the\ former}{the\ latter}$)" and "b03 Difference in behavioral cost coefficient ($\frac{the\ former}{the\ latter}$)" are negatively correlated with "c1 Optimal level of detail of output specifications", with the mainstream views accounting for [0.682, 1] and [0.682, 0.938], respectively. "b02 Risk allocation principles (risks borne by the private partner)" and the "b04 Difference in construction cost savings rate ($\frac{the\ former}{the\ latter}$)" are both positively correlated with "c1 Optimal level of detail of output specifications", and the proportion of mainstream views for both is [0.545, 0.923]. Therefore, it can be considered that the factors negatively correlated with the optimal level of detail of output specifications include: difference in profit rate ($\frac{the\ former}{the\ latter}$) and difference in behavioral cost coefficient ($\frac{the\ former}{the\ latter}$); The factors positively correlated with the optimal level of detail of output specifications include: risk allocation principles (risks borne by the private partner) and the difference in construction cost savings rate ($\frac{the\ former}{the\ latter}$).

The optimal tender offer and the optimal level of detail of output specifications are interdependent. The researchers have also conducted statistical analysis on the factors influencing optimal tender offer and their correlations. "b08 Project CS", "b12 Reservation profit rate", "b11 Risk quotation coefficient (risks borne by the private partner)", and "b09 Behavioral cost coefficient of technological innovation$_{c2}$" are all positively correlated with "c2 Optimal tender offer". The mainstream views account for [0.909, 0.952], [0.818, 0.947], [0.682, 0.938], and [0.409, 1], respectively. Both "b13 Productivity level" and "b10 Construction cost savings rate" are all negatively correlated with "c2 Optimal tender offer", with mainstream views accounting for [0.773, 0.850], [0.318, 0.875], respectively. Therefore, it can be considered that the factors positively correlated with the optimal tender offer include: project CS, reservation profit rate, risk quotation coefficient (risks borne by the private partner), and behavioral cost coefficient of technological innovation; The factors negatively correlated with the optimal tender offer include: productivity level and construction cost savings rate.

4.5.3 Factors influencing optimal intensity of incentives

During the construction stage, the decision on the intensity of incentives from the public authority needs to tradeoff between "stimulating the enthusiasm for technological innovation" and "reducing the cost of incentives", and make PUPC as small as possible.

After statistical analysis, "b15 Profit rate driven (reservation profit rate)", "b09 Behavioral cost coefficient of technological innovation$_{c3}$", and "b16 Risk premium" are all positively correlated with "c3 Optimal intensity of incentives", with mainstream views accounting for [0.773, 0.944], [0.773, 0.810], [0.227, 0.833], respectively. Therefore, it can be considered that the factors positively correlated with the optimal intensity of incentives include: profit rate driven (reservation profit rate), behavioral cost coefficient of technological innovation, and risk premium.

The optimal technological innovation strategy and the optimal intensity of incentives are interdependent. The researchers have also conducted statistical analysis on the factors influencing optimal technological innovation strategy and their correlations. "b09 Behavioral cost coefficient of technological innovation$_{c4}$" is negatively correlated with "c4 Optimal technological innovation strategy", with mainstream views accounting for [0.773, 0.895]. Both "b22 External conditions (External spatial value)" and "b20 Corporate capability (Capability value)" are positively correlated with "c4 Optimal technological innovation strategy", with mainstream views accounting for [0.5, 0.846] and [0.182, 0.8], respectively. Therefore, it can be considered that the factors negatively correlated with the optimal technological innovation strategy include: behavioral cost coefficient of technological innovation; The factors positively correlated with the optimal technological innovation strategy include: external conditions (external spatial value) and corporate capability (capability value).

4.5.4 Factors influencing optimal intensity of regulation

During the construction stage, the optimal intensity of regulation for the public authority needs to tradeoff between "curbing opportunism" and "reducing regulatory cost", and make PUPC as small as possible.

After statistical analysis, "b27 Punishment coefficient$_{c5}$" and "b26 Behavioral cost coefficient of hiding" are both negatively correlated with "c5 Optimal intensity of regulation", with the mainstream views accounting for [0.864, 1] and [0.727, 1], respectively. "b24 Regulatory mechanism and sensitivity (demand for regulation)" and "b25 Proportion of hiding" are both positively correlated with "c5 Optimal intensity of regulation", with mainstream views

accounting for [0.5, 1] and [0.5, 0.917], respectively. Therefore, it can be considered that the factors negatively correlated with the optimal intensity of regulation include: punishment coefficient, behavioral cost coefficient of hiding; The factors positively correlated with the optimal intensity of regulation include: regulatory mechanism and sensitivity (demand for regulation), and proportion of hiding.

The optimal opportunism strategy and optimal intensity of regulation are interdependent. The researchers have also conducted statistical analysis on the factors influencing optimal opportunism strategy and their correlations. "b30 Intensity of regulation", "b27 Punishment coefficient$_{c6}$", and "b31 Preference for corporate credibility" are all negatively correlated with "c6 Optimal opportunism strategy", with mainstream views accounting for [0.955, 0.955], [0.955, 0.955], and [0.091, 1], respectively. "b29 Expected net benefit" is positively correlated with "c6 Optimal opportunism strategy", with mainstream views accounting for [0.364, 0.889]. Therefore, it can be considered that the factors negatively correlated with the optimal opportunism strategy include: intensity of regulation, punishment coefficient, and preference for corporate credibility; The factors positively correlated with the optimal opportunism strategy include: expected net benefit.

4.5.5 Paths to save PUPC of the public authority

Based on the aforementioned coding analysis, this thesis has obtained six axial codings, namely the optimal level of detail of output specifications, optimal tender offer, optimal intensity of incentives, optimal technological innovation strategy, optimal intensity of regulation, and optimal opportunism strategy (hereinafter referred to as the "Six Optimal Strategies"). These axial codings run through the entire decision-making process of the "strategies for saving PUPC by the public authority" and have an impact on it. Based on the above coding analysis results and theoretical knowledge, the researchers returned to the original interview data to understand the true meaning of each interviewee. Then, further statistical analysis of the correlation was conducted, and the specific results are shown in Annex D and Table 4.7.

Table 4.7 Paths to save PUPC by the public authority

Relationship Paths	Relationship Structure and Connotation	Basis from Coding
Subcategory → The optimal level of detail of output specifications and optimal tender offer → Save PUPC	b05, b03, b02, and b04 affect the optimal level of detail of output specifications, which in turn aims to minimize PUPC (with uncertainty). b08, b12, b11, b09, b13, and b10 affect the optimal tender offer, which in turn affects PUPC (positive correlation) and forms a balance with public authority's decisions.	a17 Influence of level of detail of output specifications on PUPC; a18 Influence path of the level of detail of output specifications; a33 Influence of tender offer

Relationship Paths	Relationship Structure and Connotation	Basis from Coding
		on PUPC; a34 Influence path of tender offer.
Subcategory → Optimal strategy of intensity of incentives and technological innovation → Save PUPC	b15, b09, and b16 affect the optimal intensity of incentives, which in turn aims to minimize PUPC. b09, b22, and b20 affect the optimal technological innovation strategy, which in turn affects PUPC (negatively correlated) and forms a balance with public authority's decisions.	a44 Influence of intensity of incentives on PUPC; a45 Influence path of intensity of incentives a55 Influence of technological innovation on PUPC; a56 Influence path of technological innovation.
Subcategory → Optimal intensity of regulation and optimal opportunism strategy → Saving PUPC	b27, b26, b24, and b25 affect the optimal intensity of regulation, which in turn aims to minimize PUPC. b30, b27, b31, b29 affect the optimal opportunism strategy, which in turn affects PUPC (irrelevant) and forms a balance with public authority's decision-making.	a68 Influence of intensity of regulation on PUPC; a69 Influence path of intensity of regulation; a76 Influence of opportunism on PUPC; a77 Influence path of opportunism.

The statistical analysis shows that the optimal level of detail of output specifications by the public authority has an "Min/uncertain" impact on PUPC, with mainstream views accounting for [0.818, 0.9]. The optimal incentive intensity and optimal regulation intensity by the public authority all have a "Min" impact on PUPC, with mainstream views accounting for [0.909, 0.909]. In the transaction stage, the public authority, based on its own interests, strive to "minimize" PUPC when deciding on the level of detail of output specifications, but the final result is often "uncertain". Similarly, in the construction stage, the public authority, based on their own interests, strive to minimize PUPC when deciding on the optimal intensity of incentives and regulation.

The statistical analysis shows that the optimal tender offer of the private partner has a "positive correlation" impact on PUPC, with mainstream views accounting for [0.909, 0.952]. The optimal technological innovation strategy of the private partner has a "negative correlation" impact on PUPC, with mainstream views accounting for [0.864, 0.864]. The optimal opportunism strategy of the private partner has a "irrelevant" impact on PUPC, with mainstream views accounting for [0.727, 0.727]. According to the interviewees' views, it should be noted that if the regulation intensity and punishment strength in the public authority are tough enough, private partner's opportunism will not pay off. Hence, as long as there's no speculation, opportunism will not affect PUPC. In the transaction and construction stage, the private partner chooses the optimal strategies based on the principle of maximizing their own profit, taking into account various constraints, and these optimal strategies will ultimately affect PUPC.

Based on the correlation between the subcategories, axial coding, and selective coding mentioned above, the paths for the public authority to save PUPC can be summarized:

Firstly, from the perspective of reasonably reducing the contract price, the path to saving PUPC is "10 subcategories → the optimal level of detail of output specifications and the optimal tender offer → saving PUPC". In the project transaction stage, the public authority makes decisions on the optimal level of detail of output specifications, while the private partner makes decisions on the optimal tender offer, and then forms the most cost-effective PUPC contract price in the transaction.

Secondly, from the perspective of incentivizing positive behavior in the private partner, the path to saving PUPC is "6 subcategories → optimal intensity of incentives and optimal technological innovation strategy → saving PUPC". In the project construction stage, the optimal intensity of incentives is used to stimulate the private partner to carry out technological innovation, promote positive behavior of the private partner, and form the most cost-effective price adjustment outside the contract for PUPC.

Finally, from the perspective of regulating negative behavior in the private partner, the path to saving PUPC is "8 subcategories → optimal intensity of regulation and optimal opportunism strategy → saving PUPC". In the project construction stage, the optimal intensity of regulation is used to supervise opportunistic behavior in the private partner, curb negative behavior in the private partner, and ultimately avoid PUPC inflation caused by private partner's opportunism.

The path to saving PUPC accompanies the entire process of PUPC formation.

4.6 Summary

This chapter used descriptive statistics or Nvivo15 coding method to analyze the data from structured interviews and unstructured interviews, formed the data analysis results, and constructed a theoretical model.

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Chapter 5: Modelling Analysis of Game Theory

The game process is analyzed and the game tree is established in Chapter 3. This chapter further establishes the game's payoff functions, solves the subgame perfect Nash equilibrium, and derives the optimal utility function of the public authority. Then, the factors and trends influencing the equilibrium solutions (the optimal solutions of decision variables) and the optimal utility of the public authority are analyzed, and the factors and paths for saving PUPC are explored.

5.1 Assumptions (inputs)

Based on the results of the structured interviews in Chapter 4, the initial assumptions of the mathematical modelling of game theory are modified. The modified formal assumptions are as follows:

Assumption 1: The public authority and the private partner are both rational persons.

Assumption 2: Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), there is room for savings for PUPC.

Assumption 3: In the transaction stage, the private partner acts as the representative of the winning bidder among all bidders.

Assumption 4: Transaction of the PPP project follows the market rules of "full competition and fair competition".

Assumption 5: PPP project transactions follow the principle of "low price priority", i.e., the lower the tender offer, the higher the price score in the total score (except for tender offer lower than the cost).

Assumption 6: When tender offer is made in the private partner, the reservation profit rate of the works specified and unspecified in the output specifications is ≥ 0.

Assumption 7: The results of design optimization (changes the output specifications) are shared between the public authority and the private partner.

Assumption 8: The results of design deepening (without changing the output specifications) should be exclusively enjoyed by the private partner (except for excessive profit).

Assumption 9: The cost of regulation of the PPP project can meet: the cost of regulation $\leq$

the amount of fines and confession for maximum opportunism.

Assumption 10: The dynamic game of complete information can be used to study the interest game between the public authority and the private partner.

Assumption 11: In the transaction stage, based on the output specifications from the public authority, the CS (construction cost calculated by Norm and Standard) for the PPP project can be calculated.

Assumption 12: Behavioral cost of design optimization in the private partner = $\frac{1}{2}\Phi_1 d_1 x^2$, where d_1 is the enterprise's internal construction cost of the works specified in the output specifications before design optimization, Φ_1 is the behavioral cost coefficient of design optimization, and x is the rate of construction cost savings due to design optimization.

Assumption 13: Behavioral cost of design deepening in the private partner = $\frac{1}{2}\Phi_2 d_2 y^2$, where d_2 is the enterprise's internal construction cost of the works unspecified in the output specifications before design deepening, Φ_2 is the behavioral cost coefficient of design deepening, and y is the rate of construction cost savings due to design deepening.

Assumption 14: Behavior cost of hiding = $\Phi_3 L$, where Φ_3 is the behavioral cost coefficient of hiding in the private partner. L is the amount of hidden opportunism due to the private partner's behavior of hiding.

Assumption 15: The behavioral cost of regulation = $-wE_1p$, where w is the behavioral cost coefficient of regulation by the public authority, $-E_1$ is the expenditure of the public authority, and p is the intensity of regulation by the public authority.

5.2 Payoff functions (models) of the game

The payoff functions of the game are calculated in three stages. The payoff of the public authority is expressed by the expenditure of public authority and users, while the payoff of the private partner is expressed by internal profit of the enterprise.

5.2.1 Calculation of payoff for stage I game

1. Stage I: Private partner's cost

According to Assumption 11, the private partner can calculate C. From the definition of h, the CS for works specified in the output specifications is "hC", and the CS for works not specified in the output specifications is "(1-h)C".

The private partner can calculate the internal construction cost of the enterprise based on

CS, θ and δ. The internal construction cost of the enterprise for the works specified in the output specifications is "θhC", and the internal construction cost of the enterprise for the works unspecified in the output specifications is "θδ(1-h)C". Adding the two parts together gives the internal construction cost of the entire project for the private partner at the time of signing the PPP contract:

$$C_1'=\theta hC+\theta\delta(1-h)C \quad (5.1)$$

2. Stage I: Private partner's revenue and profit

From the definitions of α and β,the total tender offer for the PUPC from the private partner is α + β, and the private partner's expected revenue at the time of signing the PPP contract is:

$$R_1=\alpha+\beta \quad (5.2)$$

Profit = Revenue - Cost, from (5.1) and (5.2) above, the internal profit of the private partner at the time of signing the PPP contract is:

$$F_1'=\alpha+\beta-\theta hC-\theta\delta(1-h)C \quad (5.3)$$

3. Stage I: Public authority's expenditure

From the definition of E_1, E_1 (the public authority and user's expenditures) at the time of signing the PPP contract is:

$$E_1=-R_1=-\alpha-\beta \quad (5.4)$$

4. Stage I: Private partner wins the bid

After bidding and tendering, different bidding results occur.

The private partner acts as the representative of the winning bidder among all bidders, and the probability of winning the bid is ζ. If the private partner wins the bid, the payoffs for the public authority and the private partner are (E_3, F_3').

If the private partner does not win the bid, i.e., bidding is unsuccessful, the probability of unsuccessful bidding is 1-ζ, and the payoffs for the public authority and the private partner are $(-C_b,\ -C_t)$.

Expected value of the private partner payoff: $E = \zeta F_3'-(1-\zeta)C_t$

5.2.2 Calculation of payoff for stage II game

1. Stage II: Private partner's cost

(1) For the works specified in the output specifications

According to Assumption 12 and (5.1), the behavioral cost of design optimization $=\frac{1}{2}\Phi_1 d_1 x^2=\frac{1}{2}\Phi_1\theta hCx^2$

For the works specified in the output specifications, the CS before design optimization is

"hC", and according to the definition of x, the CS after design optimization is "hC(1-x)". After considering the discount rate of productivity level and the behavioral cost of design optimization, the internal construction cost of the enterprise after design optimization is $\theta hC(1-x) + \frac{1}{2}\Phi_1\theta hCx^2$.

(2) For the works unspecified in the output specifications

According to Assumption 13 and (5.1), the behavioral cost of design deepening $=\frac{1}{2}\Phi_2 d_2 y^2=\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2$.

For the works unspecified in the output specifications, the CS before design deepening is "δ(1-h)C", and according to the definition of y, the CS after design optimization is "δ(1-h)C(1-y)". After considering the discount rate of productivity level (θ) and the behavioral cost of design deepening, the internal construction cost of the enterprise after design deepening is $\theta\delta(1-h)C\ (1-y)+\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2$.

Adding the two parts above, the internal construction cost of the enterprise of the private partner after technological innovation is:

$$\boldsymbol{C_2'=\theta(1-x)hC+\theta\delta(1-y)(1-h)C+\frac{1}{2}\Phi_1\theta hCx^2+\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2} \qquad (5.5)$$

2. Stage II: Private partner's revenue and profit

(1) For the works specified in the output specifications

According to the definition of the quotation coefficient, the quotation coefficient (J) = $\frac{\text{tender offer}}{\text{CS}}$. The PUPC savings due to design optimization are expressed as $\Delta PUPC_1$, then:

$\Delta PUPC_1$ = quotation coefficient× savings in CS $=\frac{\alpha}{hC}(xhC)=\alpha x$

According to Assumption 7, the intensity of incentives for design optimization is k. If the PUPC savings due to design optimization are $\Delta PUPC_1$, then the private partner's share of $\Delta PUPC_1$ is k, and the public authority's share of $\Delta PUPC_1$ is 1-k.

Revenue after design optimization = $\alpha-(1-k)\alpha x=(1-x+kx)\alpha$

(2) For the works unspecified in the output specifications

The PUPC savings due to design deepening are expressed as $\Delta PUPC_2$.

According to Assumption 8, the intensity of incentives for design deepening is 100%. If the PUPC savings due to design deepening are $\Delta PUPC_2$, then $\Delta PUPC_2$ is shared entirely by the private partner.

Revenue after design deepening = Revenue before design deepening - $\Delta PUPC_2$ + $\Delta PUPC_2$ $=\beta$

Adding the two parts together, the expected revenue of the private partner after

technological innovation is:

$$R_2 = (1-x+kx)\alpha+\beta \quad (5.6)$$

Profit = Revenue - Cost, from (5.5) and (5.6) above, the internal profit of the private partner after technological innovation is:

$$F_2' = (1-x+kx)\alpha+\beta-\theta(1-x)hC-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_1\theta hCx^2-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2 \quad (5.7)$$

3. Stage II: Public authority's expenditure

After technological innovation, E_2 (the public authority and user's expenditures) is:

$$E_2 = -(1-x+kx)\alpha-\beta \quad (5.8)$$

5.2.3 Calculation of payoff for stage III game

1. Proportion of opportunism detected

The public authority carries out spot checks on opportunism based on its experience of regulation. The intensity of regulation (p) is the proportion of opportunism checked and detected by the public authority, assuming that the private partner has no hiding.

Furthermore, if the private partner hides, the proportion of hiding is e, and at this time, the proportion of opportunism discovered is p-e.

2. Consequences of opportunism detected

The opportunism studied in this thesis includes: overestimation and miscalculation of additional PUPC outside the contract, and concealment of savings from design optimization. It is well known that after such opportunistic behaviors are found, the cost of its rectification or rework cost is very little, so it is ignored.

If the public authority detects opportunism from the private partner, it will confiscate the unjust enrichment (t), and impose a penalty equal to m times the unjust enrichment ($m \geq 0$).

3. The cost of regulation and the cost of hiding

According to Assumption 14, Behavior cost of hiding (C_h) = $\Phi_3 et$, E_1 is negative.

According to Assumption 15, Cost of regulation (C_r) =$-wE_1p$.

4. Stage III: Public authority's expenditure and private partner's profit

Based on the proportion of opportunism that is detected and the proportion that is not, substitute into "expected value = $\sum$(payoff × proportion)", and calculate the public authority's expenditure and the private partner's actual profit. See Table 5.1 for details.

Table 5.1 Public authority's expenditure and private partner's actual profit in stage III of the game

State	Proportion	Public authority's expenditures	Private partner's profit
Detect	p-e	E_2+pwE_1-t+t+mt	F_2'+t-t-mt-etΦ_3
Not detect	1- (p-e)	E_2+pwE_1-t	F_2'+t-etΦ_3
Expected value =∑(payoff × proportion)		E_3=E_2+wpE_1+(pm+p-em-e-1)t	F_3'=F_2'+(em+e-pm-p+1-eΦ_3)t

According to Table 5.1, after "regulation + opportunism", the internal profit of the private partner:

$$\boldsymbol{F_3'=F_2'+(em+e-pm-p+1-e\Phi_3)t} \tag{5.9}$$

After "regulation + opportunism", E3 (the public authority and user's expenditures) is:

$$\boldsymbol{E_3=E_2+wpE_1+(pm+p-em-e-1)t} \tag{5.10}$$

5.2.4 The payoff functions of the game tree

After calculating the payoffs of the three-stage game, the payoff function of the public authority and the private partner can be obtained, where the payoff function of the public authority is "E_3" and the payoff function of the private partner is "F_3'".

Substituting (5.7) into (5.9), after "incentives + regulation + technological innovation + opportunism", the internal profit of the private partner is:

$$\boldsymbol{F_3'=(1-x+kx)\alpha+\beta-\theta(1-x)hC-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_1\theta hCx^2-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2+(em+e-pm-p+1-e\Phi_3)t} \tag{5.11}$$

Substituting (5.4) and (5.8) into (5.10), after "incentives + regulation + technological innovation + opportunism", the public authority's expenditures is:

$$\boldsymbol{E_3=-(1-x+kx)\alpha-\beta-wp(\alpha+\beta)+(pm+p-em-e-1)t} \tag{5.12}$$

5.3 Solution of the subgame perfect Nash equilibrium

5.3.1 Range of parameter values

According to the definition of parameters in Chapter 3, the range of value for each parameter is given in Table 5.2.

Table 5.2 Range of parameter values

NO.	Parameters	Range of values	NO.	Parameters	Range of values	NO.	Parameters	Range of values
1	h	$0<h_0\leq h\leq h_1<1$	7	k	$0\leq k\leq 1$	13	e	$0\leq e\leq e_0$
2	ζ	$0\leq\zeta\leq 1$	8	x	$0\leq x\leq x_0<1$	14	Φ_3	$0\leq\Phi_3\leq 1$, $0\leq\Phi_3 e\leq 1$
3	θ	$0<\theta\leq 1$	9	y	$0\leq y\leq y_0<1$	15	p	$0\leq p\leq 1$
4	δ	$\delta>0$	10	Φ_1, Φ_2	Φ_1, $\Phi_2>0$	16	m	$m\geq 0$
5	E_1, E_2, E_3	E_1, E_2, $E_3<0$	11	t	$0\leq t\leq t_0$	17	w	$0<w<1$
6	γ_1, γ_2	$\gamma_1\geq 0$; $\gamma_2\geq 0$	12	J	$J>0$	18	b	$1\leq b<2$

5.3.2 Method of solving

For solving the dynamic game of complete information, backward induction is generally used. With reference to the solution procedure of the *Stackelberg Model,* the order of solving equilibrium solution by backward induction is as follows: Stage III-2 (opportunism) → Stage III-1 (intensity of regulation) → Stage II-2 (technological innovation) → Stage II-1 (intensity of incentives) → Stage I-3 (winning the bid) → Stage I-2 (tender offer) → Stage I-1 (level of detail of output specifications).

5.3.3 Steps for solving

The steps for solving the subgame perfect Nash equilibrium solution in this thesis are as follows: (1) Solve for the optimal solution of opportunism (t, e), with results given in Proposition 1. (2) Solve for the optimal solution of intensity of regulation (p), with results given in Proposition 2. (3) Solve for the optimal solution of technological innovation (x, y), with results given in Proposition 3. (4) Solve for the optimal solution of the incentive intensity (k), with results given in Proposition 4. (5) Solve for the optimal solution of tender offer (α, β), with results given in Proposition 5. (6) Solve for the optimal solution of the level of detail of output specifications (h), with results given in Proposition 6. The detailed solving process is provided in Annex E.

5.3.4 Summary for the solution of subgame perfect Nash equilibrium

Following the solving of the subgame perfect Nash equilibrium in Annex E, the equilibrium solutions are obtained as shown in Table 5.3.

Table 5.3 Outcomes of the subgame perfect Nash equilibrium

NO.	Prerequisite	Outcomes of the subgame perfect Nash equilibrium
1	$x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$	$E_3=[\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta Ch^*+(\frac{1}{2\Phi_2}-1)(1+\gamma_2)\theta b\delta C$ $F_3'=(1-\frac{3}{8\Phi_1})\theta h^* C\gamma_1+(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C\gamma_2$
2		$h^*=h_0$ or h_1
3		$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta h^* C$; $\beta^*=(1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C$
4		$k^*=1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}$
5		$x^*=\frac{1}{2\Phi_1}$; $y^*=\frac{1}{\Phi_2}$
6		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$
7		$t^*=0$; $e^*=0$
8	$x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$	$E_3=[\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta Ch^*-(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C$ $F_3'=(1-\frac{3}{8\Phi_1})\theta h^* C\gamma_1+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C\gamma_2$
9		$h^*=h_0$ or h_1
10		$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta h^* C$; $\beta^*=(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C$
11		$k^*=1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}$
12		$x^*=\frac{1}{2\Phi_1}$; $y^*=y_0$
13		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$
14		$t^*=0$; $e^*=0$
15	$x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$	$E_3=[x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta Ch^*+(\frac{1}{2\Phi_2}-1)(1+\gamma_2)\theta b\delta C$ $F_3'=(1-x_0+\frac{1}{2}\Phi_1 x_0^2)\theta h^* C\gamma_1+(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C\gamma_2$
16		$h^*=h_0$ or h_1
17		$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2+\frac{1}{2}\Phi_1\gamma_1 x_0^2)\theta h^* C$; $\beta^*=(1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C$
18		$k^*=\frac{\Phi_1 x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$
19		$x^*=x_0$; $y^*=\frac{1}{\Phi_2}$
20		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$
21		$t^*=0$; $e^*=0$
22	$x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$	$E_3=[x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta Ch^*-(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C$ $F_3'=(1-x_0+\frac{1}{2}\Phi_1 x_0^2)\theta h^* C\gamma_1+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C\gamma_2$
23		$h^*=h_0$ or h_1
24		$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2+\frac{1}{2}\Phi_1\gamma_1 x_0^2)\theta h^* C$; $\beta^*=(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C$
25		$k^*=\frac{\Phi_1 x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$
26		$x^*=x_0$; $y^*=y_0$
27		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$
28		$t^*=0$; $e^*=0$

5.4 Influencing factors and trends of the optimal solution.

The optimal solution [t^*, e^*, p^*, x^*, y^*, k^*, α^*, β^*, h^*] of each decision node on the game tree forms the equilibrium path of the game. The optimal utility function (E_3) of the public authority is the equilibrium outcome, that is, the optimal solutions are the path, and the optimal utility function is the result. The mathematical models of the optimal solutions and optimal utility function have been obtained above. Next, it is necessary to analyze the factors and trends influencing the optimal solutions and optimal utility function based on the mathematical models. If the public authority understands the factors and trends influencing the optimal solutions and optimal utility function, it can generate significant value in the management of the PPP project.

5.4.1 Level of detail of the output specifications (h^*)

5.4.1.1 Result of analysis for h^*

According to Proposition 6, there are four discriminants for the value of h^*. By reasoning and analyzing these four discriminants, the factors influencing h^* and its trends can be obtained. The specific reasoning process is shown in Annex F.1. The result of the reasoning is as follows:

Result 1: h^* is related to the following factors:

(1) $\frac{\Phi_1}{\Phi_2}$ and $\frac{\gamma_1}{\gamma_2}$ are both negatively correlated with h^*, but in a staircase decrease. On the function graph of $h^*(\frac{\Phi_1}{\Phi_2})$, h^* takes high value to the left of the critical threshold of $\frac{\Phi_1}{\Phi_2}$, and low value to the right. The same applies to $\frac{\gamma_1}{\gamma_2}$.

(2) δ and $\frac{x_0}{y_0}$ (condition: $x_0 \leq \frac{1}{2\Phi_1}$ and $y_0 \leq \frac{1}{\Phi_2}$) are both positively correlated with h^*, but in a staircase increase. On the function graph of $h^*(\delta)$, h^* takes low value to the left of the critical threshold of δ, and high value to the right. The same applies to $\frac{x_0}{y_0}$.

(3) If multiple factors simultaneously influence h^*, use the positivity or negativity of Δ to determine the value of h^*. When $\Delta \leq 0$, h^* takes the low value (h_0); when $\Delta > 0$, h^* takes the high value (h_1).

5.4.1.2 The practical meaning of Result 1

1. The level of detail of output specifications (h^*) has many influencing factors and h^* is unstable.

In PPP practice, how does the public authority choose a reasonable level of detail of output specifications? Government documents only specify the basic level of detail of the output

specifications (MOF, 2014). Generally, the public authority aims to keep the level of detail as low as possible to expedite project implementation, while the private partner demands a higher level of detail to better understand the project and mitigate risks (J. T. Zhou et al., 2019). Experts and scholars usually suggest that the output specifications should clearly articulate the product and service outcomes while leaving room for technological innovation and management reform (S. Q. Wang, 2017). Why are the views of the parties so different? The underlying reason can be explained using Result 1.

According to Result 1, the factors influencing the level of detail of output specifications (h^*) are numerous, as are the discriminants. In reality, h^* is often influenced by multiple factors, and it is difficult to identify a single factor or observe the trend of a single factor's impact on h^*. Therefore, based on people's experience and impressions, h^* is volatile and unstable, which leads to different opinions on the level of detail of output specifications from the government, PPP project participants, industry experts, and scholars.

Result 1 reveals that the level of detail of output specifications (h^*) is inherently unstable, but that there are also some constant laws along with this turbulent change. The laws that the level of detail of output specifications (h^*) is affected by the behavioral cost coefficient of technological innovation, the reservation profit rate, the space for technological innovation, and the deviation coefficient of quantities are constant.

2. The influence of the cost coefficient (Φ) on the level of detail of output specifications.

Combining practice, the relationship between $\frac{\Phi_1}{\Phi_2}$ and h^* is explained. The level of detail of output specifications is expressed as "the proportion of the construction cost of the works specified in the output specifications to the total construction cost of the project", which is like a movable "slider" on a ruler, dividing the works of the PPP project into two parts: those that have been clearly specified in the output specifications and those that have not. The higher (lower) the level of detail of the output specifications, the more (fewer) works are included in the former part and the fewer (more) works are included in the latter part. The cost coefficient of technological innovation for the former is ϕ_1, while that for the latter is ϕ_2. When $\frac{\Phi_1}{\Phi_2}$ increases to above the critical threshold, in order to reduce the construction cost and save PUPC, the public authority will naturally reduce the engineering content of the former and increase the engineering content of the latter, that is h^* takes a low value. Conversely, when $\frac{\Phi_1}{\Phi_2}$ decreases to below the critical threshold, h^* takes a high value.

Take Δ_1 (see Proposition 6) as an example. If δ=1, b=1, and γ_1=γ_2, then: when $\frac{\Phi_1}{\Phi_2}\geq$0.75,

$h^*=h_0$; when $\frac{\Phi_1}{\Phi_2}<0.75$, $h^*=h_1$.

3. The influence of the reservation profit rate (γ) on the level of detail of the output specifications.

Combining practice, the relationship between $\frac{\gamma_1}{\gamma_2}$ and h^* is explained. As mentioned above, the former of the "slider" is the works specified in the output specifications, while the latter is the works not specified in the output specifications.

When $\frac{\gamma_1}{\gamma_2}$ increases to above the critical threshold, in order to guide the private partner to reasonably reduce its tender offer and save PUPC, the public authority will naturally reduce the engineering content of the former and increase the engineering content of the latter, that is h^* takes a low value. Conversely, when $\frac{\gamma_1}{\gamma_2}$ decreases to below the critical threshold, h^* takes a high value.

Take Δ_1 (see Proposition 6) as an example. If δ=1, b=1, and $\phi_1=\phi_2=\phi$, then: when $\gamma_1 \geq \gamma_2 - \frac{\gamma_2+1}{8\phi-3}$, $h^*=h_0$; when $\gamma_1<\gamma_2 - \frac{\gamma_2+1}{8\phi-3}$, $h^*=h_1$.

4. The influence of the space for technological innovation (x_0, y_0) on the level of detail of output specifications.

Combining practice, the relationship between $\frac{x_0}{y_0}$ and h^* is explained. As described above, the former of the "slider" is the works specified in the output specifications, while the latter is the works not specified in the output specifications. When $\frac{x_0}{y_0}$ decreases to below the critical threshold, in order to reduce construction cost and save PUPC, the public authority will naturally reduce the engineering content of the former and increase the engineering content of the latter, that is h^* takes a low value. Conversely, when $\frac{x_0}{y_0}$ increases to above the critical threshold, h^* takes a high value.

Take Δ_4 (see Proposition 6) as an example. If δ=1, b=1, $\gamma_1=\gamma_2$, and $\phi_1=\phi_2$, then: when $\frac{x_0}{y_0}\leq 1$, $h^*=h_0$; when $\frac{x_0}{y_0}>1$, $h^*=h_1$.

5. The influence of the deviation coefficient of quantities (δ) on the level of detail of output specifications.

Combining practice, the relationship between δ and h^* is explained. The more detailed the information provided by the public authority on engineering surveys and construction conditions, the lower the risk of quantity deviation (δ) by the private partner. When δ decreases to below the critical threshold, h^* takes a low value. Conversely, when δ increases to above the

critical threshold, h^* takes a high value.

Take Δ_1 (see Proposition 6) as an example. If b=1, $\gamma_1=\gamma_2$, and $\phi_1=\phi_2=\phi$, then: when $\delta\leq\frac{8\phi-3}{8\phi-4}$, $h^*=h_0$; when $\delta>\frac{8\phi-3}{8\phi-4}$, $h^*=h_1$.

When the level of detail of output specifications is influenced by two or more factors simultaneously, such as the cost coefficient of technological innovation, the reservation profit rate, the space for technological innovation, and the deviation coefficient of quantities, the value of h needs to be determined using the discriminant (Δ).

In special cases, if $\gamma_1=\gamma_2$, $\phi_1=\phi_2$, $x_0=y_0$, b=1, and δ=1, then: $h^*=h_0$. The practical significance of this theoretical result is that, if the difference between design optimization and design deepening, as well as the regulation cost and the risk of deviation of quantities, are not considered, then the PPP pattern itself tends towards output specifications that can clearly define public demands but are relatively rough. This might be where the application value of the PPP pattern lies.

5.4.2 Tender offer (α^*, β^*)

5.4.2.1 Result of analysis for α^* and β^*

According to Table 5.3 (subgame perfect Nash equilibrium solution), the expressions of α^* and β^* can be obtained. By reasoning with these mathematical expressions, the factors and trends influencing α^* and β^* can be obtained. The specific reasoning process is shown in Annex F.2. The result of the reasoning is as follows:

Result 2: The tender offer ($\alpha^*+\beta^*$) of the private partner is influenced by the following factors:

(1) C, δ, θ, γ_1, γ_2, ϕ_1 ($x_0>\frac{1}{2\Phi_1}$) and ϕ_2 are positively correlated with the tender offer.

(2) x_0 ($x_0\leq\frac{1}{2\Phi_1}$) and y_0 ($y_0\leq\frac{1}{\Phi_2}$) are negatively correlated with the tender offer.

(3) The tender offer is influenced by $h_0(h_1)$, but the trend of influence needs to be determined through discriminant calculation.

5.4.2.2 The practical meaning of Result 2

The factors influencing the tender offer of the private partner are: C, θ, γ, ϕ, δ, x_0, y_0, $h_0(h_1)$. Combining practice, the meaning of Result 2 can be explained. First, C, θ, δ, ϕ_1 ($x_0>\frac{1}{2\Phi_1}$), ϕ_2, and γ are the components of the private partner's internal construction cost and internal profit. The larger they are, the higher the private partner's forecasted tender offer will naturally be.

Second, x_0 ($x_0 \leq \frac{1}{2\Phi_1}$) and y_0 ($y_0 \leq \frac{1}{\Phi_2}$) reflect the space for technological innovation of the engineering content of the two parts (the former and the latter) of the PPP project. The greater the space for technological innovation, the greater the potential for cost savings, which is more conducive to lowering the forecasted construction cost for the private partner and, in turn, lowering the tender offer.

Finally, the level of detail of output specifications (h^*) undoubtedly influences tender offer ($\alpha^*+\beta^*$), while the trend of h^* on $\alpha^*+\beta^*$ needs to be determined through discriminants.

In special cases, if $\gamma_1=\gamma_2$, $\phi_1=\phi_2$, $x_0=y_0$, $b=1$, and $\delta=1$, then h^* is positively correlated with ($\alpha^*+\beta^*$). In other words, when the differences between different technological innovation are not considered, there are no costs of regulation, and there is no risk of deviations in quantities, then reducing the level of detail of the output specifications will encourage the private partner to reduce the tender offer.

5.4.3 Intensity of incentives (k^*)

5.4.3.1 Result of analysis for k^*

According to Table 5.3 (subgame perfect Nash equilibrium solution), the expression of k^* can be obtained. By reasoning these expressions, the factors and trends influencing k^* can be obtained. The specific reasoning process is shown in Annex F.3. The result of the reasoning is as follows:

Result 3: J_1, Φ_1, and γ_1 are all positively correlated with k^*, and J_1 is an intermediate variable affecting k^*.

5.4.3.2 The practical meaning of Result 3

This thesis assumes that the result of design deepening should be exclusively owned by the private partner, that is, the incentive intensity for design deepening is 100%, so there is no need for discussion. However, the incentive intensity (k^*) for design optimization needs to be discussed.

Combining practice, the meaning of Result 3 can be explained. First, incentives for the private partner to carry out design optimization need to satisfy the participation constraint: "result obtained by the private partner through design optimization - behavioral cost of design optimization itself ≥ reservation profit corresponding to the construction cost being optimized if it is not optimized". Here, the "result obtained by the private partner through design optimization" can be expressed as the incentive intensity (k^*) and savings rate of construction

cost (x^*); The "behavioral cost of design optimization" can be expressed as the cost coefficient (Φ_1); The "reservation profit corresponding to the construction cost being optimized if it is not optimized" can be expressed as the reservation profit rate (γ_1). Obviously, as Φ_1 and γ_1 become greater, the incentive intensity ($k^{*)}$ needs to be greater.

Second, in PPP practice, in order to incentive technological innovation, the public authority will provide stronger incentives when behavior cost of technological innovation is higher for the private partner.

Finally, technological innovation is characterized by risk and a technological premium, so the profit rate of technological innovation is generally higher than the industry's average social profit rate (X. L. Liu, 2014). Such a demand from the private partner ultimately feeds back into the value of the incentive intensity. Therefore, the linkage between incentive intensity and reservation profit rate is also understandable.

Take the equation for k^* in (E.34) as an example. When Φ_1=1.5 and γ_1=20%, then k^*=53%. This trial calculation result is basically consistent with PPP practice.

5.4.4 construction cost savings rate (x^*, y^*)

5.4.4.1 Result of analysis for (x^*, y^*)

According to Table 5.3 (subgame perfect Nash equilibrium solution), the expressions of x^* and y^* can be obtained. Through observation, the factors and trends influencing x^* and y^* can be obtained as follows:

Result 4: (1) x^* is correlated with the following factors: when $x_0 \leq \frac{1}{2\Phi_1}$, x_0 is positively correlated with x^*; when $x_0 > \frac{1}{2\Phi_1}$, Φ_1 is negatively correlated with x^*. (2) y^* is correlated with the following factors: when $y_0 \leq \frac{1}{\Phi_2}$, y_0 is positively correlated with y^*; when $y_0 > \frac{1}{\Phi_2}$, Φ_2 is negatively correlated with y^*.

5.4.4.2 The practical meaning of Result 4

According to Result 4 and Table 5.3, x^*=MIN (x_0, $\frac{1}{2\Phi_1}$). Similarly, y^*=MIN (y_0, $\frac{1}{\Phi_2}$).

$x^*=\frac{1}{2\Phi_1}$ and $y^*=\frac{1}{\Phi_2}$ are the most economical construction cost savings rates for the private partner when there are no external constraints.

Combining practice, the meaning of Result 4 can be explained. "The payoff of design optimization in the private partner = net increase of engineering profit – behavior cost of design

optimization". The engineering profit of the private partner increases linearly with the construction cost saving rate (x), while the behavior cost of design optimization increases rapidly parabolically with x. Therefore, the payoff of design optimization in the private partner should have a maximum value at a stationary point. x_0 is the maximum construction cost saving rate that the private partner can achieve, affected by exogenous conditions such as engineering technology and the environment. When the stationary point is within the range of x_0, x^* takes the value of the stationary point; when the stationary point is outside the range of x_0, x^* takes x_0. Similarly, the construction cost saving rate (y^*) for design deepening can also be understood in this way.

According to Table 5.3, if $x_0>\frac{1}{2\Phi_1}$, $y_0>\frac{1}{\Phi_2}$ and $\phi_1=\phi_2$, then $y^*=2x^*$. In other words, when the space for design optimization and design deepening is large enough, and their behavioral cost coefficients are the same, the private partner's effort in design deepening will be twice that of design optimization. This theoretical result also explains why, under the same conditions, the private partner is more willing to save construction cost through design deepening than through design optimization.

Additionally, taking x^* as an example, when $\Phi_1=1.5$ and $x_0=25\%$, then $x^*=25\%$. These show that technological innovation is not only affected by incentive compatibility constraint, but also affected by exogenous conditions.

5.4.5 Intensity of regulation (p^*)

5.4.5.1 Result of analysis for (p^*)

By observing the mathematical expression of p^* in Table 5.3 (subgame perfect Nash equilibrium solution), the factors and trends influencing p^* can be obtained as follows:

Result 5: p^* is correlated with the following factors: e_0 is positively correlated with p^*; ϕ_3 and m are all negatively correlated with p^*.

5.4.5.2 The practical meaning of Result 5

According to Result 5 and Table 5.3, the regulation intensity (p^*) needs to cover the largest hidden space (e_0), while also having some redundancy ($\frac{1-e_0\Phi_3}{m+1}$). Increasing e_0 will cause p^* to increase; increasing ϕ_3 or m will cause p^* to decrease.

Combining practice, the meaning of Result 5 can be explained. Firstly, the regulation intensity (p) is the proportion of opportunism detected when the private partner does not hide, while the proportion of hiding (e_0) is, due to hiding, the reduction of the proportion of

opportunism detected. Therefore, to punish and curb opportunism, the regulation intensity should exceed the proportion of hiding. That is to say, the larger e_0 is, the greater p^* will naturally become.

Secondly, raising ϕ_3 or m will increase opportunism expenditure and reduce the expected value of the net benefits of opportunism. Therefore, raising ϕ_3 or m can also have the effect of curbing opportunism. Furthermore, it can be deduced that, given the same effect of curbing opportunism, when ϕ_3 or m is increased, the intensity of regulation (p^*) can be appropriately reduced.

In special case, if $e_0 = 0$, then $p^*=\frac{1}{m+1}$. That is to say, when the private partner cannot hide, the public authority only needs to decide the intensity of regulation according to the punishment coefficient (m). When m=0, p^*=100%; when m=5%, p^*=95%. This theoretical result can be used to explain some phenomena in the regulation of domestic PPP pattern. For example, at present, when the public authority reviews the additional investment outside the contract of the PPP project, even if it finds that the private partner has overestimated and miscalculated, it generally does not impose a penalty. At the same time, the public authority conducts 100% spot checks (reviews) of additional investment.

In practice, if there is the potential for hiding by the private partner, the public authority must activate the punishment mechanism, otherwise opportunism cannot be curbed. This phenomenon can also be explained using the above theory. According to Proposition 2, $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$. That is to say, when $e_0>0$, m^* must be greater than 0, which means that the punishment mechanism should be activated. If $e_0>0$ and $m^*=0$, then the case of (E.5) in Table E.1 arises, i.e. the regulation by the public authority is 100% and the opportunism by the private partner is also 100%.

5.4.6 Opportunism (t^*, e^*)

5.4.6.1 Result of analysis for (t^*, e^*)

By observing the mathematical expression of (t^*, e^*) in Table 5.3 (subgame perfect Nash equilibrium solution), the factors and trends affecting t^* and e^* can be obtained as follows:

Result 6: When the strategy of regulation by the public authority is (p^*, m^*), the private partner does not engage in opportunism and does not hide.

5.4.6.2 The practical meaning of Result 6

According to Table 5.3 (subgame perfect Nash equilibrium), when $p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$ and

$m^* \geq \frac{e_0(1-\Phi_3)}{1-e_0}$, then the private partner does not engage in opportunism, conversely, the private partner engages in opportunism.

Combining practice, the meaning of Result 6 can be explained. First, the public authority should accurately grasp the e_0 and ϕ_3 of the private partner, and ensure that the intensity of regulation and the punishment coefficient reach or exceed the stipulated values, so as to prevent the private partner from engaging in opportunism.

Second, How should the phenomenon be understood where "regulation by the public authority is underway, while opportunism by the private partner has not stopped"? The public authority derives a regulation strategy (p, m) based on the forecasted parameters, and then the regulatory body organizes the implementation. Does the (p, m) that is finally implemented meet the requirements of p^* and m^* in Table 5.3? The answer is "not necessarily", for the following reasons: (1) It is difficult for the public authority to accurately grasp the private partner's e_0 and ϕ_3. If the forecasted value of e_0 is too low or the forecasted value of ϕ_3 is too high, this will result in the forecasted values of p and m also being too low. (2) The forecasted strategies of p and m from the public authority are not actually implemented during actual implementation (note: they are reduced). (3) After the private partner knows the regulation strategies (p, m) from the public authority, it adjusts its strategies of opportunism (e_0, ϕ_3), increases e_0 and decreases ϕ_3, so that opportunism is still profitable. Therefore, the regulation strategies of the public authority need to be continuously revised in practice, in order to meet the conditions of (p^*, m^*). When the conditions are met, the public authority regulation and the private partner opportunism form a balance, but this balance is transient and dynamic. After a period of time, if the private partner adjusts its strategy of opportunism, the balance will be broken, and the public authority will need to readjust its strategy of regulation.

5.4.7 PUPC

5.4.7.1 Result of analysis for PUPC

According to Table 5.3 (subgame perfect Nash equilibrium solution), the mathematical expression of the utility function (E_3) of the public authority can be obtained. Since PUPC = -E_3, the mathematical expression of PUPC is as follows:

1. When $x_0 > \frac{1}{2\Phi_1}$ and $y_0 > \frac{1}{\Phi_2}$,

$$\mathbf{PUPC = [(1+\gamma_1)b - \frac{b+3\gamma_1 b+2}{8\Phi_1} - (1- \frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta C h^* + (1-} \quad (5.13)$$

$$\frac{1}{2\Phi_2})(1+\gamma_2)\theta b\delta C$$

2. When $x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$,

$$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta C h^*+(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C \quad (5.14)$$

3. When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$,

$$PUPC=[(1+\gamma_1)b-x_0(b\gamma_1+1)-\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)-(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta C h^*+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\theta b\delta C \quad (5.15)$$

4. When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$,

$$PUPC=[(1+\gamma_1)b-x_0(b\gamma_1+1)-\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)-(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta C h^*+(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C \quad (5.16)$$

After the intermediate variables (α^*, β^*, k^*, x^*, p^*, t^*, e^*) are substituted, the optimal payoff functions between the independent variables and the PUPC are derived.

After reasoning, the factors and trends influencing the PUPC of the public authority are obtained. The specific reasoning process is shown in Annex F.4. The result of the reasoning is as follows:

Result 7： PUPC of the public authority is correlated with the following factors:

(1) C, δ, w, e_0, θ, Φ_1, Φ_2, γ_1, γ_2 are all positively correlated with PUPC.

(2) m and Φ_3 are negatively correlated with PUPC.

(3) When $\Delta\leq 0$, h_0 is positively correlated with PUPC; when $\Delta>0$, h_1 is negatively correlated with PUPC.

(4) When $x_0\leq\frac{1}{2\Phi_1}$, x_0 is negatively correlated with PUPC.

(5) When $y_0\leq\frac{1}{\Phi_2}$, y_0 is negatively correlated with PUPC.

5.4.7.2 The practical meaning of Result 7

In combination with practice, the meaning of Result 7 can be explained.

First, the construction cost calculated by Norm and Standard, the discount rate of productivity level, the reservation profit rate, the behavioral cost coefficient of technological innovation, the deviation coefficient of quantities, the maximum proportion of hiding, and the regulation cost coefficient are positively correlated with PUPC. At the same time, the

behavioral cost coefficient of hiding and the punishment coefficient are negatively correlated with PUPC. This theoretical result can also explain why in reality the public authority chooses large enterprise with high productivity level, low technological innovation cost, weak profit-making attribute, strong public welfare attribute, strong risk resistance ability, and good corporate credibility as the private partner of the PPP project.

Second, the practical significance of $x_0 \leq \frac{1}{2\Phi_1}$ or $y_0 \leq \frac{1}{\Phi_2}$ is that the space for technological innovation limits the ability of the private partner to perform. In this case, the size of the space for technological innovation will be fed back to PUPC and will be negatively correlated with PUPC. The technological innovation space of the private partner is not only related to the characteristic of the project itself, but also to external conditions of engineering construction. The greater the innovation space of the private partner, the more PUPC is likely to be saved.

Furthermore, the correlation between the level of detail of output specifications and PUPC is unstable and should be determined based on specific situations. When $\Delta \leq 0$, then $h^* = h_0$; when $\Delta > 0$, then $h^* = h_0$. The positive and negative nature of Δ is analyzed in Result 1.

Finally, most people often focus on the tender offer ($\alpha+\beta$), incentive intensity (k), and the cost saving rate of technological innovation (x and y), regulation intensity (p) and opportunism (t) in PPP project investment management. In fact, these are only intermediate variables and means of controlling PUPC, not the essential factors that determine PUPC.

5.5 Summary of analysis results

5.5.1 Influence of independent variables on PUPC

According to (5.13) to (5.16), the independent variables affecting PUPC are: C, θ, $h_0(h_1)$, δ, γ_1, γ_2, w, m, Φ_1, Φ_2, Φ_3, x_0, y_0, and e_0.

According to Result 7, the independent variables have the following influence on PUPC:

(1) C, δ, w, e_0, θ, Φ_1, Φ_2, $\boldsymbol{\gamma_1}$, and $\boldsymbol{\gamma_2}$ are positively correlated with PUPC.

(2) m, Φ_3, x_0 (when $x_0 \leq \frac{1}{2\Phi_1}$), and y_0 (when $y_0 \leq \frac{1}{\Phi_2}$) are negatively correlated with PUPC.

(3) The correlation between $h_0(h_1)$ and PUPC is unstable, and is determined based on the positive or negative value of Δ.

5.5.2 Influence of intermediate variables on PUPC

According to the definition of E_3 in Chapter 3, PUPC = $-E_3$. On an equilibrium path, (5.12) can

be transformed as follows:

$$\mathbf{PUPC= (1-x^*+k^*x^*)\alpha^*+\beta^*+wp^* (\alpha^*+\beta^*)+(1+e^*+e^*m-p^*m-p^*)t^*} \quad (5.17)$$

Comparing function (5.17) with functions (5.13) to (5.16), it can be seen that α^*, β^*, k^*, x^*, y^*, p^*, t^*, and e^* are intermediate variables.

The influence of intermediate variables on the dependent variable (PUPC) is as follows:

(1) According to the incentive compatibility constraint of the optimal solutions, the strategies (h^*, k^*, p^*) of the public authority are all committed to minimizing PUPC.

(2) The factor (α^*, β^*) is an intermediate variable in the game, and it is intrinsically connected to other intermediate variables (h^*, k^*, x^*, y^*, p^*), but the specific correlation is uncertain.

(3) Substituting (E.22) and (E.23) into (5.13) to (5.16), it can be obtained that x^* is negatively correlated with PUPC; substituting (E.18) and (E.19) into (5.13) to (5.16), it can be obtained that y^* is negatively correlated with PUPC, so (x^*, y^*) is negatively correlated with PUPC.

(4) According to the reasoning process in Result 7 in Annex F, it is known that $b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$ and b is positively correlated with PUPC. Since $p^*= e_0+\frac{1-e_0\Phi_3}{m+1}$, p^* is positively correlated with b. Furthermore, p^* is positively correlated with PUPC.

(5) Since t^* and e^* are 0, (t^*, e^*) is irrelevant to PUPC.

5.5.3 Influence of independent variables on intermediate variables

The influence of the independent variables on the intermediate variables is shown in Results 1 to 6 above.

5.5.4 The path of saving PUPC by the public authority

The independent variables [C, θ, $h_0(h_1)$, δ, γ_1, γ_2, Φ_1, Φ_2, Φ_3, x_0, y_0, e_0] influence the intermediate variables [h^*, (α^*, β^*), k^*, (x^*, y^*), p^*, (t^*, e^*)], and then the intermediate variables influence the dependent variable (PUPC), ultimately forming the path that influences PUPC, as shown in Figure 5.1.

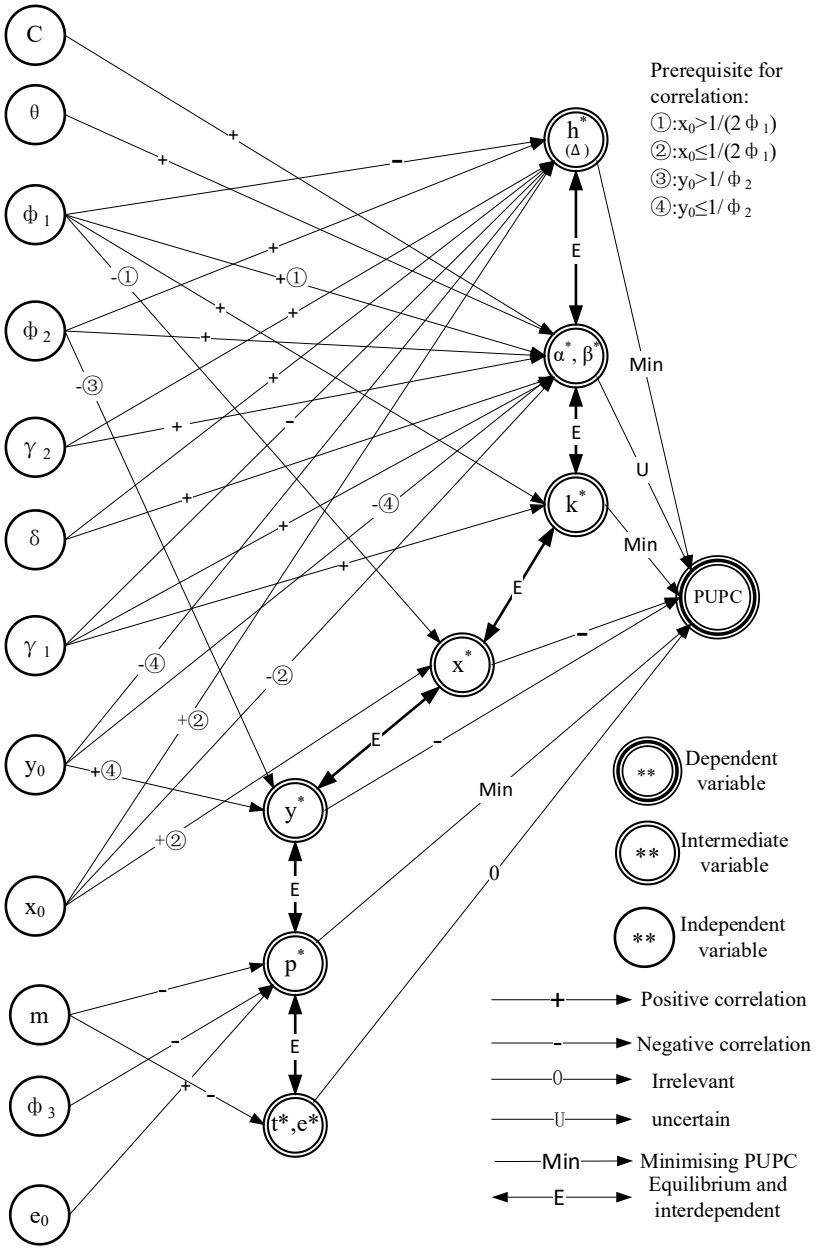


Figure 5.1 Path for the public authority to save PUPC

The independent variables are the characteristic parameters (private information) of the project itself, the public authority, and the private partner. The intermediate variables are the decision variables of the public authority and the private partner in the transaction and construction stages. Observing Figure 5.1 from a vertical perspective, when the intermediate variables take their optimal solutions, [h^*, (α^*, β^*), k^*, (x^*, y^*), p^*, (t^*, e^*)] form the equilibrium path of the game. Then, observing Figure 5.1 from a horizontal (population) perspective, the path "independent variable → optimal solutions of intermediate variables → PUPC" is the path that minimizes PUPC for the public authority.

5.6 Summary

This chapter firstly established the payoff functions of the game. Subsequently, it solved for the optimal solution of each decision in the game and the optimal payoff function of the public authority, and analyzed the factors and trends influencing them. Finally, it derived the correlations among the independent variables, intermediate variables, and PUPC, and summarized the factors and paths for the public authority to save PUPC.

Chapter 6: Findings and Discussion

After completing the data analysis based on the interview method and mathematical modeling of game theory, this chapter would compare the results corresponding to the two research methods, and evaluate them using the focus group method. Subsequently, in light of the research questions posed in Chapter 1 of the thesis, it would discuss new findings from the research and engage in debate and commentary.

6.1 Comparison of results from two research methods

Using the research questions and topic of this thesis as the focal points for comparative analysis, Table 6.1 compares and summarizes both the similarities and differences in the research results obtained through the interview method and mathematical modeling of game theory.

Table 6.1 Comparison table of research results from interview method and mathematical modelling method of game theory

NO.	Research themes	Comparison of the results of the two research methods (+ indicates a positive correlation with the research theme, - indicates a negative correlation with the research theme. Interview method is abbreviated as "IM", mathematical modelling method of game theory is abbreviated as "MM")	
1	Optimal level of detail of output specifications	Similarities	1.1 Difference in the behavioral cost coefficient of technological innovation (-), difference in reservation profit (-), size of risk allocation (+), and difference in construction cost savings rate (+).
		Differences	1.2 Difference in space for technological innovation (IM: not mentioned; MM: +). 1.3 The level of detail of output specifications is inherently unstable (IM: not mentioned; MM: yes).
2	Optimal tender offer	Similarities	2.1 Project construction cost calculated by Norm and Standard (+), productivity level (-), construction cost savings rate (-), behavioral cost coefficient of technological innovation (+), deviation risk coefficient of quantities (+), reservation profit rate (+).
		Differences	2.2 Space for Technological Innovation (IM: Not mentioned; MM: -).
3	Optimal intensity of incentives	Similarities	3.1 Behavioral cost coefficient of technological innovation (+), profit rate driven (+).
		Differences	3.2 Risk premium (IM: +; MM: not mentioned).
4	Optimal technological innovation strategy	Similarities	4.1 When the space for technological innovation is sufficiently large, the behavioral cost coefficient of technological innovation (–); When the space for technological innovation is not sufficiently large, the space

NO.	Research themes	Comparison of the results of the two research methods (+ indicates a positive correlation with the research theme, - indicates a negative correlation with the research theme. Interview method is abbreviated as "IM", mathematical modelling method of game theory is abbreviated as "MM")	
			for technological innovation (+).
		Differences	4.2 Corporate capability (IM: +; MM: not mentioned).
5	Optimal intensity of regulation	Similarities	5.1 Maximum ratio of hiding (+), the behavioral cost coefficient of hiding (-), and the punishment coefficient (-).
		Differences	5.2 Regulation mechanisms and sensitivity [demand for regulation] (IM: +; MM: not mentioned). 5.3 Optimal intensity of regulation can only be effective when used in conjunction with punishment coefficients (IM: not mentioned; MM: yes).
6	Optimal opportunism strategy	Similarities	6.1 Regulation intensity (–), punishment coefficient (–), expected net benefit (+).
		Differences	6.2 Preference for corporate credibility (IM: -; MM: not mentioned).
7	Factors influencing PUPC and their correlations	Similarities	7.1 The factors influencing PUPC include: construction cost calculated by Norm and Standard, discount rate of productivity level (or productivity level), reservation profit rate, behavioral cost coefficient of technological innovation, deviation coefficient of quantities, maximum ratio of hiding, behavioral cost coefficient of hiding, punishment coefficient, external conditions (space for design optimization, space for design deepening), and regulation cost coefficient.
		Differences	7.2 For IM, the factors influencing PUPC also include: construction cost savings rate, risk premium, corporate capability, regulation mechanisms and sensitivity (demand for regulation), expected net benefit, regulation intensity, and preference for corporate credibility. 7.3 For MM, the following can be derived: (1) Factors positively correlated with PUPC include construction cost calculated by Norm and Standard, discount rate of productivity level, reservation profit rate, behavioral cost coefficient of technological innovation, deviation coefficient of quantities, maximum ratio of hiding, and regulation cost coefficient; (2) Factors negatively correlated with PUPC include behavioral cost coefficient of hiding, punishment coefficient, space for design optimization (when $x_0 \leq \frac{1}{2\Phi_1}$), and space for design deepening (when $y_0 \leq \frac{1}{\Phi_2}$). 7.4 For MM, actively adjusting or optimally selecting exogenous variables that affect PUPC is the basis for the public authority to save PUPC.
8	Paths to save PUPC	Similarities	8.1 The optimal intensity of incentives and the optimal intensity of regulation aim to minimize PUPC. 8.2 The optimal construction cost savings rate is negatively correlated with PUPC. 8.3 The optimal opportunism strategy is uncorrelated with PUPC. 8.4 The six optimal strategies constitute the equilibrium

NO.	Research themes	Comparison of the results of the two research methods (+ indicates a positive correlation with the research theme, - indicates a negative correlation with the research theme. Interview method is abbreviated as "IM", mathematical modelling method of game theory is abbreviated as "MM")	
			path of the game, and they are in equilibrium with each other.
			8.5 "Independent variable (or subcategory) → six optimal strategies → PUPC" is the path that minimizes PUPC for the public authority.
		Differences	8.6 Optimal level of detail of output specifications aims to minimize PUPC (IM: minimize/uncertain; MM: minimize).
			8.7 Relationship between the optimal tender offer and PUPC (IM: +; MM: uncertain).

For the comparative analysis results presented in Table 6.1, several clarifications are warranted: (1) Based on Result 1 and Proposition 6 from the mathematical modelling method of game theory, it is shown from mathematical reasoning that h^* takes low value to the left of the critical threshold of $\frac{x^*}{y^*}$ and high value to the right. Therefore, for the mathematical modelling method of game theory, the difference in construction cost savings rate is positively correlated with optimal level of detail of output specifications, but exhibits a staircase increase. (2) For the mathematical modelling method of game theory, according to the expressions for optimal construction cost savings rate and optimal tender offer in Chapter 5, it can be deduced that "the construction cost savings rate is negatively correlated with the optimal tender offer". (3) For the interview method, during the data analysis of technology innovation space and technology innovation strategy, the subcategory "b22 External conditions (External spatial value)" refers to the technology innovation space. (4) For the interview method, the relationship between regulation cost coefficient and PUPC can be inferred through the following chain: "a57 Regulation cost → b24 Regulatory mechanism and sensitivity → PUPC". (5) For mathematical modeling method of game theory, "expected net benefit" serves as the decision criterion for opportunism in the private partner. According to the participation constraint in Section E.1.1, it can be inferred that the expected benefit of the private partner is positively correlated with opportunism amount.

6.2 Focus group evaluation

6.2.1 Expert selection

There are nine experts in the focus group. Six well-known PPP experts have been invited from the PPP expert pool of China National Association of Engineering Consultants. They were

selected by "random selection + personal willingness" from the list of expert pool members in July 2025. Among them, three are from the public authorities or engineering consulting agencies commissioned by the public authorities, and the other three come from the private partners.

Then, researchers searched Baidu for "Industry influence ranking of PPP research institutions" and, based on the "search results + personal willingness", invited two scholars from well-known research institutions.

Finally, researchers invited an independent expert who was recommended by the industry association from the PPP Professional Committee of the China National Association of Engineering Consultants. As of January 2025, projects in the fields of transportation, urban construction, environmental protection engineering, and water conservancy on the National PPP Information Platform of the NDRC account for 96.1%, with participating experts coming from these four fields.

6.2.2 Evaluation materials and focus group guidelines

Prior to the focus group meeting, researchers prepared evaluation materials and focus group guidelines, which were distributed to all experts in advance. The evaluation materials include research background information, research questions, research scope, evaluation objective, terms, and activity procedure. In order to control the research risks, the experts should only make judgments, supplements and improvements to the existing research results, and should not add brand-new viewpoints, concepts or internal connections. The focus group guidelines list the similarities and differences in research results between two methods along distinct research themes; while explicitly specifying the discussion questions the facilitator plans to address during the meeting. The discussion questions are designed with the following lines of thought:

1. Request experts to judge the similarities of research results between the two methods (do you agree?), and to supplement or improve them (are there still any shortcomings?).

2. Request experts to judge the differences in research results between the two methods (which result do you favor?), to supplement or improve them (if you endorse one of the results, do you have any suggestions for improvement?), and to comment (if you do not endorse either result, what suggestions do you have for improvement?).

Following the above question design lines, the focus group guidelines comprise a total of 22 questions under eight themes. See Annex G for details.

6.2.3 Pilot test

To detect operational issues during focus group implementation, researchers conducted a pilot test to resolve them before formal meeting. The pilot test covered the entire workflow: invitation distribution/acceptance, meeting scheduling, pre-meeting communication, the formal meeting and recording, audio file transcription and organization, and conclusion of focus group.

This thesis selected two volunteers from invited experts to participate in the pilot test. The facilitator, volunteers, and note-taker jointly conducted a one-day pilot test. Through the pilot test, researchers have identified many issues during focus group implementation, improved the focus group guidelines, and refined the requirements for focus group activities. To sum up, it primarily consists of the following aspects.

1. During the pilot test, it was found that the meeting duration might be insufficient due to the large number of discussion questions and experts involved. To save time and enhance efficiency, all experts are required to submit written preliminary opinions about the 22 questions to the facilitator no later than four days prior to the formal meeting. Subsequently, the facilitator will gather the opinions from all experts on each question, and feed back the gathered preliminary opinions to all experts. During the formal meeting, experts are not required to present their preliminary opinions but should focus on providing supplementary comments after reviewing the gathered feedback from all experts. Simultaneously, the total meeting duration will be extended from 120 to 150 minutes. All experts will be notified in advance that each participant is allocated around 15-20 minutes for their total speaking time.

2. During the pilot test, volunteers emphasized the necessity of clarifying the detailed speaking schedule well in advance of the meeting. Therefore, researchers specified the speaking sequence for the formal meeting in the evaluation materials, ensuring that all experts were informed of the detailed process well in advance.

3. During the pilot test, volunteers suggested modifying the questioning approach for some questions to enable experts to accurately provide the information required by researchers. The researchers replaced the original broad questions with progressive questions. For example, the original question "What is the relationship between the space for technological innovation of the PPP project and the optimal tender offer?" was replaced with "Does the space for technological innovation of the PPP project has an impact on the optimal tender offer? If so, what is the relationship?"

4. During the pilot test, volunteers presented the concept of the "six optimal strategies" with ambiguous meaning. Researchers thus added a definition of this concept to the "terms" section

of the evaluation materials.

5. During the pilot test, researchers considered the possibility that a few experts might be unable to attend the on-site meetings. To address this, researchers specifically added online meeting arrangements, including: video conferencing software and meeting equipment.

6. During the pilot test, researcher-volunteer communications revealed that volunteers' grasp of evaluation materials was insufficient, thereby impeding test progress. Consequently, detailed requirements were added for the facilitator to communicate with each expert prior to the meeting, to ensure that experts are thoroughly familiar with the content of the evaluation materials and focus group guidelines.

The pilot test have enhanced the preliminary preparations for focus group activities, refined the requirements for the implementation process, and optimized the scheduling of the meeting times, thereby laying the groundwork for the successful execution.

6.2.4 Data organization

After the focus group meeting, the research team members transcribed the audio recordings into Word documents, then integrated the experts' preliminary opinions, supplementary comments, and Q&A from the discussion to compile the meeting minutes. The meeting minutes are categorized by research theme and presented with a clear, logical structure. At the end of each theme in the minutes, the discussion results of the expert focus group are summarized. Any content agreed upon by seven or more of the nine experts shall be included in the focus group's discussion results.

6.2.5 Focus group's discussion results

The focus group discusses eight themes, which directly correspond to the four research questions outlined in Chapter 1 of this thesis. The discussion results of the focus group will be fully explicated in the subsequent findings and discussion, and thus are not reiterated here.

6.3 How to select the optimal level of detail of output specifications

6.3.1 New findings on the optimal level of detail of output specifications and dialogue with literature

Grimsey and Lewis (2016) believe that output specifications should allow sufficient space and incentives for introducing design innovations, thereby enhancing efficiency. S. Q. Wang (2017)

believes that output specifications must explicitly define governmental and public requirements for facilities or services to ensure their availability, but too detailed output specifications may limit the space for technological innovation. S. Q. Wang and Wang (2017) believes that not every project requires detailed specifications for all components of output specifications; instead, these can be reasonably arranged according to public demand and practical needs. These scholars have qualitatively discussed the level of detail of output specifications, arguing that the level of detail of output specifications should fall within a reasonable range. However, in reality, managers need specific strategies to guide the level of detail of output specifications for practice. This thesis provides an approach from both qualitative and quantitative perspectives, revealing distinct levels of detail of output specifications across different scenarios.

According to the previous research and focus group's discussion, the optimal level of detail of output specifications in the public authority is inherently unstable. The difference in the behavioral cost coefficient of technological innovation and the difference in the reservation profit rate is both negatively correlated with the optimal level of detail of output specifications. The difference in the space for technological innovation (when $x_0 \leq \frac{1}{2\Phi_1}$, $y_0 \leq \frac{1}{\Phi_2}$) and the risk allocation of quantity deviation is positively correlated with the optimal level of detail of output specifications. Therefore, the greater the difference in the behavioral cost coefficient of technological innovation, the greater the difference in reservation profit rate, the smaller the difference in the space for technological innovation, and the smaller the risk allocation of quantity deviation in the private partner, then the rougher the output specifications selected by the public authority; conversely, the public authority will select more detailed output specifications.

From the perspective of maintaining its own cost-effectiveness, the public authority adopts the above optimal level of detail of output specifications during the transaction stage, which is in line with the public's interest demand. Public products or services pursue efficiency in the use of public fund and competitive pricing (GIH, 2019; Grimsey & Lewis, 2016). Under certain conditions, it is undoubted that they will select solutions with low construction cost and small investment expenditure. However, if the research scenario is changed, and the schedule objective within the project's triangular objective is taken as the most important assessment factor (Ding, 2016), the results may change. Once the time taken to prepare the output specifications is considered and the time factor of project schedule is translated into project revenue, cost, and net profit, it will present a new issue worth exploring.

The optimal level of detail of output specifications in the public authority exists under certain conditions. Lam and Javed (2015) believe that when external conditions change, changes in the pre-set terms of the output specifications are inevitable. Javed et al. (2011) believe that output specifications are flexible and should adapt to future changes. GIH (2019) believes that the output specifications can be further improved through procurement negotiations. Therefore, when the environment changes, the public authority needs to promptly adjust the optimal strategy for level of detail of output specifications according to the theoretical model in this thesis.

6.3.2 New findings of optimal tender offer and dialogue with literature

Professional Qualification Center of Ministry of Transport (2020) believes that tender offer should comprehensively consider internal construction cost of the enterprise, construction plan, design deepening, design optimization, market price fluctuation, financing cost, and profit level. The MOT's document states that the tender offer shall be prepared based on the market and business operation conditions, and shall not be lower than the project cost (MOT, 2016). MOHURD's document states that the tender offer should be determined based on the design document, internal construction cost of the enterprise, construction plan, and market price, and should not be lower than the project cost (MOHURD, 2013). Z. M. Wu (2023) stated that bidders should determine their tender offers based on the bidding document, as well as their own circumstances and the external environment. These studies discuss that C, θ, Φ_1, Φ_2, γ_1, γ_2, x_0, y_0 correlate with the tender offer, but the specific correlation between them is not clear. This thesis further reveals the influencing factors, correlations, and optimal strategies of the private partner's tender offer based on PPP project cost management practice.

According to the previous research and focus group's discussion, the project *CS*, the discount rate of productivity level, behavioral cost coefficient of technological innovation, the deviation coefficient of quantities, and the reservation profit rate are positively correlated with the optimal tender offer. The space for technological innovation (when $x_0 \leq \frac{1}{2\Phi_1}$, $y_0 \leq \frac{1}{\Phi_2}$) is negatively correlated with the optimal tender offer. Therefore, the higher the *CS*, the greater the discount rate of productivity level, the higher the behavioral cost coefficient of technological innovation, the higher the deviation coefficient of quantities, the greater the reservation profit rate, and the smaller the space for technological innovation, then the higher the tender offer selected by the private partner; conversely, the private partner will select a lower tender offer.

From the perspective of enhancing the probability of winning the bid and ensuring adequate

profitability, the private partner adopts the aforementioned optimal tender offer strategy during the transaction stage to align with its internal management requirements. When conducting PPP project transaction, the private partner makes the optimal tender offer based on the average social construction cost of the project, combined with its internal competitiveness and external competitive environment. Q. Yang et al. (2021) believe that with the increasing maturity of the PPP market and the growing standardization of competition, the private partner must conduct repeated calculations for its quotation. Therefore, it is generally believed that the private partner can only ensure the appropriateness of tender offer through multi-factor and multi- plan calculations. Xu et al. (2019) believe that the private partner's tender profit rate and deviation coefficient of quantities must be dynamically adjusted in response to external conditions. Consequently, the optimal tender offer should be iteratively calculated using the theoretical model presented in this thesis, accounting for changes in influencing factors, to enhance applicability.

6.4 How to select the optimal intensity of incentives

6.4.1 New findings on optimal intensity of incentives and dialogue with literature

Fang et al. (2018) believe that the intensity of incentives should be set as the average of the reservation profit rate in the public authority and the level of effort in the private partner. Han (2023) believe that the private partner should be rewarded with a certain proportion of the net benefit after fully compensating for the cost of technological innovation. M. S. Li and Meng (2018) believe that the public authority should offer proportional additional incentives (αT_1) to the private partner to stimulate technological innovation. X. L. Liu (2014) believes that the rate of return on technological innovation should converge with the rate of return on technological risk. Their research has clarified that intensity of incentives is related to reservation profit rate, behavioral cost of technological innovation, and risk premium. However, the specific correlation between them remains ambiguous, and managers need specific strategies of incentive intensity to guide practical implementation. This thesis adopts a method that runs through the transaction and construction stages to study the influencing factors, correlations, and optimal strategies of the intensity of incentives in the public authority.

According to the previous research and focus group's discussion, the behavioral cost coefficient of technological innovation, the reservation profit rate, and the risk premium all exhibit positive correlations with the optimal intensity of incentives. Therefore, the higher the

behavioral cost coefficient of technological innovation, the higher the reservation profit rate, and the higher the risk premium, then the higher the intensity of incentives selected by the public authority; conversely, the public authority will select a lower intensity of incentives.

From the perspective of saving PUPC and enhancing capital utilization efficiency (General Office of the State Council of the People's Republic of China, 2023; Han, 2023), the public authority incentivizes technological innovation in the private partner, which aligns with the requirements of public value management. The public authority's principal-agent management of the PPP project inevitably involves incentivizing positive behavior. Such revenue incentives generally compensate for the behavioral cost of technological innovation in the private partner and provide a certain risk-return rate (Fang et al., 2018; S. M. Huang, 2020; Z. X. Liu, 2018), aligning with conventional incentive mechanism. However, it is worth noting that this thesis adopts a perspective of revenue-based incentives, whereas real-world PPP incentives are often multidimensional and flexible. S. M. Huang (2020) summarized that PPP incentives include fiscal and tax policies, concession period, risk allocation, and rights of control. Even some scholars consider honor, commendation and financing consolation letters as incentives (Han, 2023). Therefore, the public authority can adopt various incentives. However, if the public authority adopts a revenue distribution approach for incentives, the theoretical model in this thesis can provide some guidance.

6.4.2 New findings on optimal technological innovation strategy and dialogue with literature

Technological innovation in the private partner mainly primarily aims to enhance project quality and cost-effectiveness through project design, engineering construction, and cost management (M. S. Li & Meng, 2018). Through technological innovation, the private partner can reduce construction cost and save PUPC during the construction stage. As Kline and Rosenberg (1986) stated, the primary objective of technological innovation is to enhance the commercial value of projects, which ultimately manifests in revenue and cost. Later, Holmström and Milgrom (1987), M. S. Li and Meng (2018), and J. Q. Wang (2018) further proposed, for technological innovation, that the relationship between its cost and the effort level follows a quadratic function, while the relationship between its revenue and the effort level follows a linear function. Their research has provided a theoretical foundation for the study of technological innovation within the PPP pattern. In recent years, H. J. Liu (2010), M. S. Li and Meng (2018), and J. Q. Wang (2018) have further studied the relationship among the revenue

of technological innovation, the effort level, and ability of technological innovation. However, their research did not place technological innovation throughout the transaction, construction, and other stages of the PPP, thereby limiting their practical applicability. Therefore, it is necessary to integrate technological innovation into the external conditions of various stages of the PPP pattern, conduct comprehensive research, explore its influencing factors and optimal strategies, and apply them to practice. This thesis uses the "construction cost savings rate" to represent the effort level of technological innovation, and reveals the influencing factors, correlations, and optimal strategies of technological innovation.

According to the previous research and focus group's discussion, when the space for technological innovation (i.e., maximum construction cost savings rate) is sufficiently large, the behavioral cost coefficient of technological innovation is negatively correlated with the construction cost savings rate of technological innovation; When the space for technological innovation is not large enough, the space for technological innovation is positively correlated with the construction cost savings rate of technological innovation. The enterprise's capacity for reducing cost and enhancing efficiency is positively correlated with the optimal construction cost savings rate. Therefore, the smaller the behavioral cost coefficient of technological innovation (when $x_0>\frac{1}{2\Phi_1}$, $y_0>\frac{1}{\Phi_2}$), the larger the space for technological innovation (when $x_0\leq\frac{1}{2\Phi_1}$, $y_0\leq\frac{1}{\Phi_2}$), and the higher the enterprise's capacity for reducing cost and enhancing efficiency. then the higher the construction cost savings rate selected by the private partner; conversely, the private partner will select a lower construction cost savings rate.

From the perspective of increasing internal profit of the enterprise, the private partner adopts the aforementioned optimal technological innovation strategy during the construction stage, which aligns with the requirements of change management and the enterprise's own interests. Mowery and Rosenberg (1983) believe that technological advancements and market demand interactively drive technological innovation. In today's era of rapid development in science and technology, technological innovation is an inevitable choice for the private partner to achieve sustainable development. The external driving force for technological innovation in the private partner is incentives from the public authority, while its internal driving force is the need for the private partner to maintain competitiveness in tender offer (Grimsey & Lewis, 2016). The measuring functions for revenue and cost of technological innovation in this thesis derive from the general summaries of previous research. The revenue and cost of specific project or specific enterprise may not necessarily conform to these functions. Therefore, the

private partner needs to make adjustments based on its own conditions, and identify the optimal technological innovation strategy that best fits its own characteristics.

6.5 How to select the optimal intensity of regulation

6.5.1 New findings on optimal intensity of regulation and dialogue with literature

S. Q. Wang and Wang (2017) and Z. X. Liu (2018) believe that regulation of the PPP project by the public authority is essential. Rahel (2020) believes that regulation can reduce opportunism and suggests that regulation and punishment should be combined. Y. L. Wang et al. (2016) believe that increasing the amount of reward or punishment does not necessarily induce private partner's behavioral shift toward "high effort"; only appropriate reward and punishment can effectively motivate such effort. S. M. Huang (2020) believes that punishment mechanism can curb opportunism only when the punishment amount only when the punishment amount exceeds the potential additional benefits from opportunism. However, punishment mechanism must be cautious and should not indiscriminately adopt severe punishment measures. Most scholars believe that regulation and punishment are necessary, and the intensity of regulation and the punishment amount should be set within a reasonable range. However, in reality, managers need specific intensity of regulation strategies to guide practice. This thesis adopts a method that runs through the transaction and construction stages to study the influencing factors, correlations, and optimal strategies of intensity of regulation in the public authority.

According to the previous research and focus group's discussion, the maximum proportion of hiding and demand for regulation are positively correlated with optimal intensity of regulation. The behavior cost coefficient of hiding and punishment coefficient are negatively correlated with optimal intensity of regulation. The optimal intensity of regulation should be employed in conjunction with the punishment coefficient to effectively curb opportunism. Therefore, the larger the maximum proportion of hiding, the stronger the demand for regulation, the lower the cost coefficient of hiding, and the smaller the punishment coefficient, then the stronger the regulation selected by the public authority; conversely, the public authority will select a weaker regulation.

From the perspective of preventing artificially inflated PUPC and ensuring the authenticity and validity of PPP consideration, the public authority regulates the opportunism of the private partner (Z. X. Liu, 2018), which aligns with the regulative requirements of public value. The

public authority's principal-agent management of PPP project inevitably involves regulating negative behavior. As stated by Chen et al. (2014), public authority's regulation strategy generally drives up opportunistic expenditures, making opportunistic behavior unprofitable. In addition, the public authority should actively respond to the demand for regulation from superior administrative department, the public, and the media (S. Q. Wang & Wang, 2017). Although some theoretical progress has been made regarding the intensity of regulation, it should also be recognized that in reality, regulation is often multi-dimensional (Han, 2023), including access, payment, performance, quality and safety, exit, public demand, and information disclosure. The payment regulation studied in this thesis is only one aspect of it. Meanwhile, Ni (2019) mentioned that in addition to taking punishment measures to curb opportunism, both parties should also initiate contract renegotiation to fundamentally reduce the motivation for opportunism. These studies essentially open another door for addressing opportunism.

6.5.2 New findings of optimal opportunism strategy and dialogue with literature

Rahel (2020) believes that opportunism can lead to reducing efficiency, suppressing competition, and harming the public interest. Owusu-Manu et al. (2018) believe that the moral hazard in the PPP project can lead to reducing competitiveness, increasing transaction cost, diminishing project profitability, and decreasing contract enforceability. Therefore, the public authority should curb opportunism. Essentially, the means to curb opportunism involve rendering opportunism unprofitable (Chen et al., 2014). Furthermore, it is necessary to analyze the cost and revenue generated by opportunism. M. S. Li and Meng (2018), J. Q. Wang (2018) and Y. L. Wang et al. (2016) studied the measurement methods of cost and revenue of opportunism. However, their research did not place opportunism into the external conditions of transaction and construction stages of the PPP, rendering their theoretical results difficult to implement in practice. Therefore, it is necessary to integrate opportunism into the real-world environment, explore its influencing factors and optimal strategies, and apply them to guide practice.

According to the previous research and focus group's discussion, the comparison of intensity of regulation, punishment coefficient, and preference for corporate credibility are all negatively correlated with the optimal opportunism amount. Therefore, if the intensity of regulation and punishment coefficient from the public authority are sufficiently high, the opportunism from the private partner becomes unprofitable. In such cases, the private partner

will not implement opportunism and thus will not hide; conversely, the private partner will engage in opportunism. The stronger the private partner's preference for corporate credibility, then the weaker the motivation to implement opportunism.

The purpose of opportunism in the private partner is to obtain unjust enrichment, which conflict with the interests of the public authority. Therefore, the private partner generally observes the intensity of regulation and punishment coefficient from the public authority, implement the behavior of hiding when necessary (Campbell, 2013). Without a doubt, the preference for corporate credibility will affect decision-making on opportunism from the perspective of the enterprise's overall strategy. The theoretical model in this thesis provides some reference for decision-making on opportunism, but it should be noted that opportunism in the private partner exhibits dynamic features. As stated by Y. L. Yin et al. (2014) the maximum proportion of hiding and difficulty of hiding of the private partner may be dynamically changing. Therefore, the public authority should adjust regulation strategy in a timely manner according to the theoretical model in this thesis, otherwise regulation will become ineffective.

6.6 What are the factors and trends influencing PUPC and what are the paths to save PUPC

6.6.1 Factors and trends influencing PUPC

J. T. Zhou et al. (2019) believe that the tender offer of PUPC is positively correlated with the private partner's internal construction cost, reasonable profit rate, and internal rate of return. Professional Qualification Center of Ministry of Transport (2020) indicates that internal construction cost is positively correlated with *CS* of project and discount rate of productivity level. Therefore, the correlation of PUPC in the transaction stage with the CS of project, discount rate of productivity level, and reasonable profit rate is clear. M. S. Li and Meng (2018) and Y. L. Wang et al. (2016) believe that technological innovation in the private partner incurs behavioral cost while also generating revenue, with the public authority sharing a proportion of the revenue according to contractual agreement. This also indicates that the technological innovation of the private partner during the construction stage can reduce PUPC. Chen et al. (2014) and S. M. Huang (2020) believe that regulation incurs behavioral cost and increases PUPC; However, regulation can curb opportunism and avoid the artificial inflation of PUPC. Therefore, the public authority's regulation undoubtedly saves more PUPC than no regulation.

These scholars have studied the partial factors that affect PUPC in a certain stage of the PPP pattern, but in practice, some factors often influence both the transaction and construction stages of the PPP pattern, such as the construction cost savings rate from technological innovation, which influences both the tender offer of PUPC in the transaction stage (Xiao & Zhang, 2020) and the out-of-contract adjustment of PUPC in the construction stage (General Office of the State Council of the People's Republic of China, 2023). Based on the above, it is necessary to adopt a method that runs through the transaction and construction stages to study PUPC. Consequently, this thesis studies the influencing factors and equilibrium results of PUPC from both qualitative and quantitative perspectives.

Based on the previous research and focus group's discussion, the factors and trends influencing PUPC can be summarized as follows: the *CS* of project, discount rate of productivity level, reservation profit rate, behavioral cost coefficient of technological innovation, deviation coefficient of quantities, maximum proportion of hiding, regulation cost coefficient, risk premium, regulatory mechanism and sensitivity (demand for regulation) are positively correlated with PUPC; The cost coefficient of hiding, punishment coefficient, enterprise's capacity for reducing cost and enhancing efficiency, space for design optimization (when $x_0 \leq \frac{1}{2\Phi_1}$), and space for design deepening (when $y_0 \leq \frac{1}{\Phi_2}$) are negatively correlated with PUPC. Therefore, the public authority should actively adjust or optimally select exogenous variables (characteristic parameters) that influence PUPC, establishing the foundational conditions for saving PUPC. Firstly, the public authority should select the private partner with high productivity level, low reservation profit rate, low demand for risk premium, low behavioral cost coefficient of technological innovation, small maximum proportion of hiding, high cost coefficient of hiding, and strong enterprise's capacity for reducing cost and enhancing efficiency as partners. Secondly, the public authority should actively adjust its own characteristic parameters, including appropriately reducing the cost coefficient of regulation, moderately increasing the penalty coefficient, and minimizing the demand for regulation. Thirdly, the public authority should take measures to adjust the characteristic parameters of the PPP project, including by reducing the project's *CS*. Fourthly, the space for technological innovation and the deviation risk of quantities have dual attributes (characteristics of the private partner and characteristics of the project itself), and the public authority should take dual measures to expand the space for technological innovation and reduce the deviation risk of quantities.

Once the public authority masters the influencing factors and trends of PUPC, it can seize

favorable factors and advantageous trends to control and save PUPC. Thus, this constitutes a strategy for saving PUPC, termed the "factor strategy". S. Q. Wang and Wang (2017) believe that the core principle of the PPP pattern is "emphasizing on integrating all stages and forming performance". The aforementioned exogenous variables ultimately integrate to form the PUPC outcome, while in practice these exogenous variables may change over time. Therefore, if the characteristic parameters of the private partner, the public authority, or the project itself in the PPP pattern change, the corresponding optimal strategies and PUPC will also change. However, in this process, the model of the six optimal strategies and the factor strategy of saving PUPC remain unchanged, and the game between the two sides will achieve re-equilibrium through re-game.

6.6.2 Paths to save PUPC

Ding (2016) that a project is an unconventional, non-repetitive, one-off task with defined objectives and constraints, where specific objectives include quality, schedule, and cost. The Chartered Institute of Building defines project management as the process of achieving project objectives through project planning and project control from the beginning to the completion of the project, which includes objective management and path management. Consequently, for the PPP project to realize savings PUPC, practicable paths must be established. This thesis studies paths to save PUPC based on the construction cost formation process (transaction and construction) of the PPP project, which are rarely discussed in previous literature.

Based on the previous research and focus group's discussion, the public authority may select the equilibrium path during project implementation. The equilibrium path is the most PUPC-saving and practicable solution. During the transaction and construction stages, the public authority and the private partner engage in the game of decision-making regarding six aspects, which correspond to six decision variables (intermediate variables). These decision variables, under the joint influence of other decision variables and exogenous variables (independent variables), form six optimal strategies. After the game between the two sides, among the six optimal strategies form an interdependent and stable equilibrium relationship that neither side wishes to change. Connecting these optimal strategies forms the equilibrium path. The six optimal strategies serve as intermediate variables, with one side linked to exogenous variables (independent variables), and the other side linked to PUPC (dependent variable). Their relationship with exogenous variables is detailed in the research findings of the first three research questions of the thesis. While their relationship with PUPC is as follows:

the public authority's optimal level of detail of output specifications, the optimal intensity of incentives, and the optimal intensity of regulation all aim to minimize PUPC; the relationship between the private partner's optimal tender offer and PUPC is uncertain; the optimal strategy of technological innovation is negatively correlated with PUPC; and the optimal opportunism strategy is irrelevant to PUPC.

Once the public authority masters the equilibrium path of the game decisions (see Figure 5.1), saving PUPC will have an action route. This constitutes another strategy for saving PUPC, termed the "path strategy". For the public authority, the "factor strategy" does not naturally promote PUPC savings; rather, it requires the "path strategy" as a bridge to achieve the goal. Zhang (2012) believes that Nash equilibrium is a set of strategy combinations, which is composed of the optimal strategies of all participants, without any individual participant having a motivation to select other strategies under the premise that exogenous variables remain unchanged. Due to this equilibrium effect, in the transaction stage of the project, through the optimal level of detail of output specifications and the optimal tender offer, the most PUPC-saving contract price is formed; In the construction stage of the project, through optimal incentive intensity to motivate positive behavior from the private partner, and optimal regulation intensity to supervise negative behavior from the private partner, the most PUPC-saving contract price adjustment is ultimately formed.

6.7 Chapter summary

This chapter compares the research results of two research methods and discusses these results using the expert focus group method. Subsequently, in response to the four research questions posed in the thesis, it compares the previous literature with the new findings presented herein, following which it debates and comments on the new findings.

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Chapter 7: Conclusions, Applications, Limitations and Suggestions

Based on the research findings and discussions in the previous sections, this chapter will summarize the research conclusions and practical applications, analyze the limitations of the research, and offer the suggestions for future research.

7.1 Research conclusion

This thesis studies the optimal strategies for three sets of decisions closely related to the PUPC, along with the factors and paths for the public authority to save the PUPC. Based on the research scenario and methodology employed, the conclusions are drawn through induction, comparison, focus, and discussion.

7.1.1 How to select the optimal level of detail in output specifications, optimal incentive intensity, and optimal regulation intensity

After playing out the game between the public authority and the private partner, three sets of decision variables— the level of detail of output specifications and the tender offer, the intensity of incentives and the technological innovation strategy, and the intensity of regulation and the opportunism strategy—ultimately form six optimal strategies. These strategies, influenced by exogenous variables (independent variables), constitute crucial decisions for realizing PUPC savings.

The optimal level of detail of output specifications is the first decision point on the public authority's equilibrium path. The difference in the behavioral cost coefficient of technological innovation and the difference in reservation profit rate is both negatively correlated with the optimal level of detail of output specifications; the risk allocation of quantity deviation and the difference in space for technological innovation (when the space for technological innovation is not sufficiently large) are both positively correlated with the optimal level of detail of output specifications. The optimal level of detail of output specifications in the public authority is inherently unstable. The optimal tender offer in the private partner is an equilibrium strategy interdependent with the level of detail of output specifications in the public authority. The

project's CS, the private partner's discount rate of productivity level, the behavioral cost coefficient of technological innovation, the deviation coefficient of quantities, and the reservation profit rate are positively correlated with the optimal tender offer. The space for technological innovation (when the space for technological innovation is not sufficiently large) is negatively correlated with the optimal tender offer.

The optimal intensity of incentives is the second decision point on the public authority's equilibrium path. The behavioral cost coefficient of technological innovation, the reservation profit rate, and the risk premium are all positively correlated with the optimal intensity of incentives. The optimal technological innovation strategy (optimal construction cost savings rate) in the private partner is an equilibrium strategy interdependent with the optimal intensity of incentives in the public authority. When the space for technological innovation is sufficiently large, the behavioral cost coefficient of technological innovation is negatively correlated with the optimal construction cost savings rate; when the space for technological innovation is not sufficiently large, the space for technological innovation is positively correlated with the optimal construction cost savings rate. The enterprise's capacity for reducing cost and enhancing efficiency is positively correlated with the optimal construction cost savings rate.

The optimal intensity of regulation is the third decision point on the public authority's equilibrium path. The maximum proportion of hiding and the demand for regulation are positively correlated with the optimal intensity of regulation. The behavior cost coefficient of hiding and the punishment coefficient are negatively correlated with the optimal intensity of regulation. The optimal intensity of regulation should be employed alongside the punishment coefficient to effectively curb opportunism. The optimal opportunism strategy in the private partner is an equilibrium strategy interdependent with the optimal intensity of regulation in the public authority. comparison of the regulation intensity, the punishment coefficient, and the preference for corporate credibility are all negatively correlated with the optimal amount of opportunism.

The aforementioned six optimal strategies may be determined based on their corresponding influencing factors and their correlations. When an optimal strategy is simultaneously influenced by multiple factors, the mathematical model in this thesis may be employed to simulate calculations and derive reference value for the optimal strategy.

7.1.2 Factor strategy and path strategy for saving PUPC

The first strategy for saving PUPC (factor strategy) is that from the perspective of the factors

influencing PUPC, the public authority actively adjusts or optimally selects the exogenous variables (characteristic parameters) influencing PUPC, thereby establishing the foundational conditions for saving PUPC.

Firstly, the public authority should optimally select the partner through competitive methods such as invitations, announcements, pre-qualification, and bidding. The selected partner should be a private partner with high productivity level, low reservation profit rate, low demand for risk premium, low behavioral cost coefficient of technological innovation, small maximum proportion of hiding, high cost coefficient of hiding, and strong enterprise's capacity for reducing cost and enhancing efficiency.

Secondly, the public authority should actively adjust its own characteristic parameters, including appropriately reducing the cost coefficient of regulation, moderately increasing the penalty coefficient, and minimizing the demand for regulation wherever possible.

Thirdly, the public authority should implement measures to adjust the characteristic parameters of the PPP project itself, including reducing the project's *CS*.

Fourthly, the space for technological innovation and the deviation risk of quantities are related to not only the project's itself characteristics but also those of the private partner, possessing dual attributes, therefore, the public authority should adopt dual measures to expand the space for technological innovation (when the space for technological innovation is not sufficiently large) and reduce the deviation risk of quantities. The public authority should adopt a dual approach to expand space for technological innovation (when such space is insufficient) and mitigate the deviation risk of quantities. Firstly, improving the external conditions for technological innovation aims to expand the scope for technological innovation of projects; strengthening project site surveys aims to reduce the deviation risk of quantities. Secondly, the public authority should select a private partner which possesses strong capabilities of technological innovation and strong resistance to risks.

The second strategy for saving PUPC (path strategy) is that from the perspective of the path to save PUPC, the public authority selects the equilibrium path in the strategic game of project implementation. The equilibrium path is the most PUPC-saving and practicable solution. For the public authority, the "factor strategy" does not naturally promote savings of PUPC; rather, it requires the "path strategy" as a bridge to achieve the goal.

In the transaction stage, the public authority makes the decision on the level of detail of the output specifications, while the private partner makes the decision on the tender offer. In the construction stage, the public authority makes the decisions on the intensity of incentives and the intensity of regulation, while the private partner makes the decisions on the technological

innovation strategy and the opportunism strategy. The action strategies of the public authority and the private partner constitute decision variables (intermediate variables). Engaging in a dynamic game between the two sides, these decision variables generate six optimal strategies under the combined influence from other decision variables and exogenous variables (independent variables). Following the game, these six optimal strategies form an interdependent and stable equilibrium relationship, which is connected to the equilibrium path.

The six optimal strategies serve as intermediate variables, with one side connected to exogenous variables (independent variables) and the other side to PUPC. Their relationship with exogenous variables (independent variables) is detailed in Section 7.1.1, while their relationship with PUPC is as follows: the optimal level of detail of output specifications, optimal intensity of incentives, and optimal intensity of regulation in the public authority all aim to minimize PUPC. The relationship between the private partner's optimal tender offer and PUPC is uncertain, the optimal technological innovation strategy (optimal construction cost savings rate) is negatively correlated with PUPC, and the optimal opportunism strategy is irrelevant to PUPC. The private partner's decisions are the result of considering self-interest and game equilibrium.

7.2 Practical applications

7.2.1 Three sets of decisions for the PPP project

1. Optimal level of detail of output specifications

The theoretical models and research conclusion of this thesis can be used to make decisions on the optimal level of detail of output specifications. Output specifications are core documents of the PPP project drafted by the public authority (GIH, 2019; Javed, 2013). The optimal level of detail of output specifications is inherently unstable, yet it follows some rules (the conclusion of this thesis). In order to determine the optimal level of detail of output specifications, the public authority needs to investigate the difference in the behavioral cost coefficient of technological innovation, the difference in reservation profit rate, and the difference in the space for technological innovation of potential bidders through inquiries, clarifications, market stress tests among others, during the transaction stage. At the same time, it is also necessary to conduct on-site surveys to understand the objective deviation risk of quantities. On this basis, the public authority formulates the optimal level of detail of output specifications based on the information gathered from the majority of potential bidders and the characteristics of the project itself, and

implements it during the transaction stage.

2. Optimal tender offer

The theoretical models and research conclusion of this thesis can be used to make decisions on optimal tender offer. Tender offer is an important business activity for the private partner participating in the PPP project (Professional Qualification Center of Ministry of Transport, 2020). The private partner determines the optimal tender offer by investigating and analyzing both internal competitiveness and the external competitive environment, combined with the output specifications and bidding documents issued by the public authority. The internal competitiveness of the enterprise includes the productivity level of the private partner, the behavioral cost coefficient of technological innovation, and the reservation profit rate; the external competitive environment includes the *CS*, the space for technological innovation, and the deviation coefficient of quantities. In order to obtain accurate and reliable parameter information, the private partner not only collect information provided by the public authority and review historical data of similar projects, but also familiarize itself with the construction conditions of the project through site surveys and scheme design demonstrations. During the transaction stage, the private partner formulates the optimal tender offer and implements it.

To increase their probability of winning bids in market competition or to obtain higher profits with the same quotation, the private partner should take corresponding measures. Firstly, the private partner needs to improve productivity level, reduce the behavioral cost coefficient of technological innovation, and increase the reservation profit rate. Secondly, the private partner needs to strive for more external conditions conducive to technological innovation. Finally, the private partner needs to obtain as much survey data and project information as possible to make the deviation coefficient of quantities close to actual circumstances.

3. Optimal intensity of incentives

The theoretical models and research conclusion of this thesis can be used to make decisions on the optimal intensity of incentives. Incentives are a common management tool in the PPP project (Han, 2023; Laffont & Martimort, 2002). The public authority can reasonably determine the optimal intensity of incentives through the behavioral cost coefficient of technological innovation, the reservation profit rate, and the risk premium of technological innovation of the private partner. In the transaction stage, in order to make accurate decisions, the public authority needs to conduct investigations, forecast the aforementioned parameters of most potential bidders, and formulate a preliminary plan of optimal intensity of incentives for use in PPP project bidding. In the construction stage, after the private partner who wins the bids is confirmed, the aforementioned parameters and information should be verified again. The

optimal intensity of incentives shall then be adjusted and amended in combination with the published output specifications and the tender offer that have been confirmed, and subsequently be implemented.

4. Optimal technological innovation strategy

The theoretical models and research conclusion of this thesis can be used to make decisions on optimal technological innovation strategy. Technological innovation strategy is commonly used measures by the private partner to reduce cost and increase efficiency (M. S. Li & Meng, 2018). The private partner reasonably determines the optimal technological innovation strategy by investigating and analyzing the behavioral cost coefficient of technological innovation, the space for technological innovation, and the enterprise's capacity for reducing cost and enhancing efficiency. In the transaction stage, the private partner combines the enterprise's own capabilities, project characteristics, and site survey data to forecast the aforementioned parameters and formulate a preliminary plan of optimal technological innovation strategy for use in PPP project tendering. In the construction stage, after the public authority has determined the optimal intensity of incentives to be implemented, the aforementioned parameters and information are verified again. The optimal technological innovation strategy shall then be adjusted and amended in combination with the output specifications, tender offer, and intensity of incentives that have been published or determined, and subsequently be implemented.

5. Optimal intensity of regulation

The theoretical models and research conclusion of this thesis can be used to make decisions on the optimal intensity of regulation. Regulation is commonly used measures by the public authority to curb opportunism (Owusu-Manu et al., 2018; J. Q. Wang, 2018). The public authority reasonably determines the optimal intensity of regulation through the maximum proportion of hiding, the behavioral cost coefficient of hiding, the demand for regulation, and the punishment coefficient. In the transaction stage, in order to make accurate decisions, the public authority needs to conduct investigations, forecast the aforementioned parameters of most potential bidders, and formulate a preliminary plan for optimal intensity of regulation for use in PPP project bidding. In the construction stage, after the private partner has determined the optimal technological innovation strategy to be implemented, the aforementioned parameters and information should be verified again. The optimal intensity of regulation shall then be adjusted and amended in combination with the output specifications, tender offer, intensity of incentives, and technological innovation strategy that have been published or determined, and subsequently be implemented.

The public authority should strengthen the management of internal control processes,

ethical discipline, and regulation techniques (Chen et al., 2014). This will prevent loopholes and deficiencies in the internal management of the public authority from providing opportunities for the private partner. Through this, the maximum proportion of hiding from the private partner can be indirectly reduced, and the difficulty of hiding for the private partner can be increased.

According to the conclusion of this thesis, the intensity of regulation should be combined with the punishment coefficient (S. Q. Wang & Liu, 2014) to avoid a situation where "the public authority imposes stringent regulation, but the private partner still engages in opportunism". If the regulatory resources of the public authority are indeed constrained, the intensity of regulation can be reduced by appropriately increasing the punishment coefficient and raising the difficulty of hiding for the private partner.

According to the conclusion of this thesis, the optimal intensity of regulation and punishment coefficient calculated by the public authority based on the forecasted parameters need to be continuously revised in practice. If, after regulation by the public authority, opportunism from the private partner still persists, the public authority needs to analyze the causes. These reasons may include: firstly, the actual maximum proportion of hiding is higher than the public authority's projection, and the actual cost of hiding is lower than the public authority's projection, resulting in the public authority's predetermined intensity of regulation and punishment coefficient being too low. Secondly, the public authority's predetermined intensity of regulation and punishment coefficient may not be truly implemented in the actual enforcement process (F. Gao, 2017).

6. Optimal opportunism strategy

The theoretical models and research conclusion of this thesis can be used to make decisions on optimal opportunism strategy. Opportunism is something that the private partner must face in PPP project management (Y. L. Yin et al., 2014). The private partner reasonably determines the optimal opportunism strategy by investigating and analyzing the intensity of regulation, punishment coefficient, and preference for corporate credibility. During the transaction stage, the private partner combines their own credit preference with the intensity of regulation and punishment coefficient specified in the bidding documents, to formulate a preliminary plan for the optimal opportunism strategy for use in PPP project tendering. In the construction stage, after the public authority has determined the optimal intensity of regulation to be implemented, the aforementioned parameters and information are verified again. The optimal opportunism strategy is adjusted and amended in combination with the output specifications, tender offer and intensity of incentives, technological innovation strategy, and intensity of regulation that

have been published or determined, and subsequently be implemented.

7.2.2 Actively adjusting or optimally selecting characteristic parameters conducive to saving PUPC

The public authority may actively adjust or optimally select the characteristic parameters of the private partner, the public authority, and the project itself based on the conclusion of this thesis, thereby establishing foundational conditions for saving PUPC.

The public authority optimally selects the characteristic parameters of the private partner. In the transaction stage, the public authority preferentially selects a private partner as the partner that exhibits high productivity level, low reservation profit rate, low demand for risk premium, low behavioral cost coefficient of technological innovation, small maximum proportion of hiding, high cost coefficient of hiding, and strong enterprise's capacity for reducing cost and enhancing efficiency. The public authority allows suppliers that meet the conditions of the project to register and prepare for competition through market research, invitations, and public announcements (CCEA, 2018), this is the first selection. Then through prequalification and market stress tests, the public authority admits suppliers with favorable characteristic parameters who successfully registered to enter the formal tendering process as potential bidders (MOF, 2014), this is the second selection. Finally, through bidding, the public authority selects the best from among the potential bidders and determines the final successful bidder (WBG, 2017), this is the third selection.

The public authority actively adjusts its characteristic parameters. Firstly, through competitive means, it selects third-party regulatory agencies and reduces the cost coefficient of regulation (Chen et al., 2014). Secondly, it selects a punishment coefficient based on the maximum proportion of hiding (ability of hiding) and the cost coefficient of hiding (difficulty of hiding) of the private partner (Owusu-Manu et al., 2018). For the private partner with stronger ability of hiding and easier to hide, a higher punishment coefficient should be selected; conversely, a lower punishment coefficient should be chosen. Thirdly, the demand for regulation from superior departments and public users should be reduced by promptly disclosing as much project information as possible.

The public authority adjusts the characteristics of the project itself. Prior to the PPP project transaction, the public authority selects the scheme with the lower *CS* through scheme comparison, economic analysis, and expert argumentation.

The space for technological innovation and the deviation coefficient of quantities have dual

characteristics; consequently, the public authority should adopt dual measures. In addition to taking strong capability for technological innovation and risk resistance as important conditions for selecting the private partner, the public authority should also take measures to adjust the characteristics of the project itself. For example: the public authority may approve changes to the location of construction sites proposed by the private partner, provide temporary construction sites, or supply supporting infrastructure, or others, to change the external conditions of project construction and provide more space for technological innovation (Y. L. Wang et al., 2016). Another example: the public authority should carry out the necessary engineering surveys and construction condition investigations, grasp the geological situation and construction conditions of the project sites, fully disclose project information, and reduce the private partner's expectation of the deviation risk of quantities (S. Q. Wang & Wang, 2017) .

7.2.3 Organizing and implementing the PPP project along the equilibrium path

The public authority mastering the path to the most PUPC-saving can yield significant application value in PPP project management. Once the characteristics of the public authority, the private partner, and the project itself are stable, the public authority can prepare a plan to save PUPC, according to the optimal strategies and equilibrium path, and organize its implementation throughout the project management process.

In PPP practice, if a decision variable deviates from the optimal strategy due to mistakes or other reasons, and this deviation becomes a fait accompli, then the subsequent decision variables will be recalibrated to form a new equilibrium path (Ni, 2019). "Recalibration" is based on the decision behaviors that has already occurred and the theoretical models of this thesis, including propositions 1 to 6 of the game-theoretical modelling method. It involves re-determining the optimal strategies for all subsequent decision nodes following the deviated decision node, and formulating a new plan to save PUPC, so that the economic management of the PPP project can return to a new equilibrium path.

7.3 Theoretical contribution

Regarding "Research Question 1", this thesis employs a quantitative method to study the optimal level of detail of output specifications and explores their impact on tender offer and technological innovation. S. Q. Wang (2017) and Javed et al. (2011) have employed a qualitative method to study the level of detail of output specifications. Currently, few studies employ quantitative method on this topic, and this thesis represents progress upon prior research.

Regarding "Research Question 2", this thesis studies optimal incentive strategy based on construction cost savings rate and reservation profit rate, representing a new development in previous PPP research. H. J. Liu (2010), M. S. Li and Meng (2018), Y. L. Wang et al. (2016), and J. Q. Wang (2018) studied incentive strategies based on the positive relationship between revenues obtained from technological innovation and the investment in such innovation. In practice, PPP project incentives focus more on the results of technological innovation (result-oriented) rather than on the investment in innovation. This thesis introduces the construction cost savings rate to address this issue.

Regarding "Research Question 3", this thesis studies optimal regulation strategy based on unjust enrichment and proportion of hiding, representing a new development in previous PPP research. M. S. Li and Meng (2018), Y. L. Wang et al. (2016), and Chen et al. (2014) studied regulation strategies based on the positive relationship between the return generated by opportunism and the degree of opportunistic effort. In practice, PPP project regulation focuses more on preventing losses (result-oriented) than on the degree of opportunistic effort. This thesis introduces unjust enrichment and proportion of hiding, thereby enriching the regulation theory of the PPP.

Regarding "Research Question 4", this thesis constructs both a qualitative theoretical model and a quantitative mathematical model for saving PUPC, providing an operational path for achieving this objective. In qualitative research, the coding method of grounded theory and descriptive statistics have been employed to construct a qualitative theoretical model. In quantitative research, mathematical modelling method of game theory has been employed to derive a quantitative theoretical model (path diagram). Then, based on the results of both qualitative and quantitative research, through expert group focus, theoretical achievements guiding practice of saving PUPC have been formed.

Throughout this research, this thesis integrates the transaction and construction stages of the PPP pattern' game to study saving PUPC, which is a new development in previous research. J. T. Zhou et al. (2019), Nisar (2007), Frederic et al. (2006) and others have mainly focused on a certain stage of the PPP project to study PUPC. Grimsey and Lewis (2016), Fang et al. (2018), Weber et al. (2018) did not distinguish between different stages of the PPP pattern, instead employing an overall abstracted game of interests to study PUPC. This thesis, using the game between the public authority and the private partner during the transaction and construction stages as its scenario, derives research conclusion on how the public authority can save PUPC, thereby providing a theoretical basis for enhancing the efficiency of the PPP pattern.

Throughout this research, this thesis employs the cost-plus method to calculate construction

cost and applies it to game theory, which is closer to the practice of PUPC management and further enhances the applicability of the research conclusion. The cost model proposed by Xu et al. (2019) is grounded in the asset pricing model; the cost model proposed by Almaaz et al. (2020) is grounded in transaction cost economic theory; the cost model proposed by Hemanta (2012) is grounded in construction risk of time and cost. The construction cost model in this thesis is fully consistent with the national standard of construction cost management in China (CCEA, 2018), and is also similar to the bill of quantities pricing pattern from the UK quantity surveying industry (Z. M. Wu, 2023). It is based on industry norm and standard or corporate rate, combined with the productivity level of the enterprise and the market prices of the production factors, to calculate the direct construction cost. Then, on this basis, profit, statutory fee, and tax are calculated to form the final construction cost of the project. This deep integration of the cost-plus method of construction cost with the mathematical modelling of game theory reflects the combination of theory and practice.

7.4 Limitations

The thesis uses interviews and mathematical modeling of game theory to obtain strategies and paths for public authority savings PUPC. However, looking back over the entire research process, there are still some limitations:

1. Although in-depth interviews can better capture the real views of interviewees, this thesis only invited 22 professionals for in-depth interviews. The sample size may be insufficient (H. Z. Li, 2022), perhaps inadequate for inferring the views of the majority.

2. The mathematical modeling method of game theory in this thesis is based on the dynamic game of complete information. The "dynamic game of complete information" is a relatively common and representative scenario (F. Gao, 2017), but it cannot represent all scenarios of the PPP project. In reality, there may also be scenario of "dynamic games of incomplete information" between the public authority and the private partner (Science Popularization in China & Baidu, 2023), which is not covered in this thesis.

3. The mathematical modelling of game theory in this thesis is based on the assumption that both the public authority and the private partner act as rational persons. However, the game studied in this thesis runs through the transaction and construction stages of the PPP model, and the path of the game is relatively long, so sometimes both parties may exhibit irrational behavior (S. Y. Xie, 2021). This is not covered in this thesis.

4. The mathematical modelling of game theory in this thesis is based on the assumptions

that "The results of design deepening should be exclusively enjoyed by the private partner (except for excessive profit)" and "the cost of regulation ≤ the amount of fines and confession for maximum opportunism". Although these assumptions have been verified through interviews and are consistent with the actual situation of most PPP projects, in practice, there will be a small number of PPP projects that do not conform these assumptions. If the private partner cannot exclusively enjoy the results of design deepening, or if the cost of regulation is greater than the amount of fines and confession for maximum opportunism, the results of the mathematical modelling of game theory should be revised.

5. This thesis assumes that the usage and operation performance of the PPP project are normal, and on this basis, it studies how to save PUPC without considering the impact of project operation on PUPC. In reality, there is also an overall payment reduction strategy (Frederic et al., 2006). This strategy refers to measures taken by the public authority in the transaction stage and in the construction stage, whereby, although PUPC increases, the total value of PUPO and PUPA decreases more significantly. After deducting the reduction in (PUPO + PUPA), PUPC is effectively reduced. This thesis does not cover the impact of operation on PUPC or the overall payment reduction strategy.

6. This thesis uses a quadratic function model for the behavioral cost of technological innovation, and a linear function model for the regulation cost and the cost of hiding. These cost models follow previous research (described in the literature review), which is consistent with the actual situation of most PPP projects (J. Q. Wang, 2018; Y. L. Wang et al., 2016). However, it cannot be ruled out that some PPP projects may not conform to these cost models; this thesis does not cover such special circumstances. If this happens, the corresponding research results should be adjusted based on the actual cost models and the research methodology of this thesis.

7. This thesis studies the trade-off between the private partner's probability of winning bid and its tender offer. The factors affecting the private partner's probability of winning bid are complex and numerous. Because bidding and tendering itself constitutes a broad research topic, based on the focus of this study, the mathematical modelling of game theory in this thesis does not directly investigate the mathematical model between the probability of winning bid and tender offer, but instead makes a simplification. The simplification is that the private partner, whilst ensuring "reservation profit", submits tender offer according to the principle of "low price priority under equal conditions". This simplification does not reveal the quantitative relationship between the probability of winning bid and the tender offer.

8. The mathematical modelling of game theory in this thesis defines the "proportion of

hidden opportunism (e)" as "by hiding, the private partner reduces the proportion of opportunism that is discovered, this reduction is the proportion of hidden opportunism". Since the public authority checking for opportunism is generally random, only if private partner's behavior of hiding is assumed to be uniformly distributed across opportunism, the proportion of hiding corresponding to different random checks can be a stable value, and a mathematical model can thus be established. However, in reality, behavior of hiding may not be uniformly distributed across opportunism, and the proportion of hiding for different opportunistic events may be different, which is not covered in this thesis.

7.5 Prospects for future research

Reflecting upon the above limitations, this thesis proposes the following prospects for future research:

1. Future research, if time and resources are sufficient, could increase the types and number of interview samples to obtain more comprehensive and accurate insights from PPP professionals regarding strategies for the public authority to save on PUPC.

2. In practice, some PPP projects may also exhibit the situation of "dynamic game of incomplete information". Future research could further enrich the strategies for the public authority to save PUPC from the perspective of dynamic game of incomplete information.

3. The public authority and the private partner may occasionally exhibit irrational behavior. Irrational behavior from either party in the game may lead to a deviation from the equilibrium path, and even cause the "dynamic game" to transform into an "evolutionary game" (Lei & Zhao, 2018). Future research may try this research direction.

4. In the future, research may integrate the three stages of the PPP pattern - transaction, construction, and operation. In this way, not only the impact of operation on PUPC can be studied, but also the strategy for overall payment reduction. if there is any progress in this research direction, it will further enrich the theory of the PPP pattern.

5. This thesis studies the factors influencing PUPC and various decision variables, but does not analyze the sensitivity of these factors. Future research could further carry out sensitivity analysis based on this study to obtain more research findings.

6. Considering the correlation between the probability of winning bid and the tender offer, future research can separately explore the quantitative relationship between the probability of winning bid and the tender offer in the PPP pattern. This is a very important topic

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Annex A: Interview Outline

Informed consent for individual interviews

The public authority and users use the public products or services provided by the PPP project, so they need to pay. Public authority and user payment (PUP) consists of three parts: payment for construction (PUPC), payment for operation (PUPO) and payment for all other matters (PUPA). PUPC is the main component of PUP, so researching saving PUPC while ensuring the functionality of the PPP project is of great significance for the stable and prolonged development of the PPP pattern.

The research objectives of this thesis are, from the perspective of public authority and users, in order to save PUPC, to seek the optimal level of detail of output specifications in the transaction stage, as well as the optimal strategies of incentives and regulation in the construction stage, and ultimately explore the influencing factors of PUPC and the path for saving PUPC.

Through this interview, it is hoped to understand the interviewee's views on the optimal level of detail of output specifications, the optimal strategy of incentives and regulation from the public authority, explore the influencing factors of PUPC, and summarize effective ways to save PUPC.

In order to ensure the authenticity of the research, the content of the interviews will be audio recorded and stored, then converted into text for analysis. The interviewer solemnly promises the interviewee that when the interviewer publishes the research results, the identity of the interviewee will be kept strictly confidential and no personal information about the interviewee will be made public. If the interviewee is willing to be interviewed, please sign below. The interview is expected to last 90 minutes. The interviewer would like to express his sincere gratitude to the interviewee for his or her support!

The interviewee has read the above carefully and volunteered to participate in the research.

Many thanks to the interviewee for taking the time to participate.

Interviewee's signature:_____

Interviewer's signature:_____

Date:_____

Dear Respondent:

Hello!

Thank you very much for your participation in the interview for the thesis "Strategies for Saving Public Authority and User Payment for Construction of China's PPP Project: Output Specifications, Incentives and Regulation" (hereinafter: this thesis).

The interview outline consists of three parts: Background, Structured Interview, and Unstructured Interview. It will take about 90 minutes of your time, thank you again for your support!

Part I Background

1.1 Research questions

1. In the project transaction stage, how does the public authority choose the optimal level of detail of output specifications to save PUPC?

2. In the project construction stage, how does the public authority choose the optimal intensity of incentives and regulation to save PUPC?

3. What are the factors influencing PUPC and the path to saving PUPC?

Note: PUPC is an abbreviation for "Public Authority and User Payment for Construction". The public authority in this thesis is the government side. The private partner is the social capital side.

1.2 Scope of the research

The research in this thesis is made specifically from the public authority's perspective, instead of the private partner.

The research in this thesis is centered around saving PUPC. The research does not deal with payment for operation and payment for all other matters. This thesis studies how to save PUPC in the transaction and construction stages, rather than the operation stage. Except for the responsibilities and risks borne by the public authority as agreed in the contract, the risks of construction investment shall be borne by the private partner.

When project financing, usage and operational performance are normal:

1. If no risks and responsibilities (rights) borne by the public authority occur during construction, the private partner obtains the PUPC at a fixed cost, which will not be adjusted due to changes in the actual construction cost.

2. If risks and responsibilities (rights) borne by the public authority occur during construction (e.g. design optimization), PUPC = a fixed cost + adjustment amount for Contract changes.

1.3 Purpose of the interview

The purpose of structured Interview is to provide support for some assumptions in the mathematical modeling of game theory. For some of the assumptions (inputs) in the mathematical modeling of game theory, if a basis or source cannot be found in the literature of Chapter 2, the reality will be collected through the interview, and the corresponding results will be used as the basis for these assumptions (inputs).

The purpose of unstructured interview is to seek answers to the research questions of this thesis. For the research questions of this thesis, the interview method is used to find the answers to the research questions and obtain research results.

1.4 Terms

1.4.1 PUPC

The public authority and user payment (PUP) refers to the **public** authority and **user payment** in the PPP project according to the performance evaluation results and the contract, abbreviated as "PUP". PUP consists of three parts: Public authority and user payment for construction (PUPC), public authority and user payment for operation (PUPO), and public authority and user payment for all other matters (PUPA).

PUPC refers to the **public** authority and the **user payment** for **construction** cost of the private partner and project regulation services according to the performance evaluation results and the PPP contract.

1.4.2 Construction cost calculated by norm and standard for the entire project (C)

Construction Cost Calculated by Norm and Standard, abbreviated as CS.

CS refers to the project construction cost calculated by Norm and Standard of the country, province or industry. It is the project construction cost with the social average productivity level.

Construction Cost Calculated by Norm and Standard for the Entire Project (C) refers the *CS* for the entire project.

1.4.3 Discount rate of productivity level (θ)

The construction cost calculated by Norm and Standard for the Entire Project (C) reflects

the social average productivity level, the private partner as an individual of the society, its level of project management and engineering technology will be generally higher than the social average productivity level (in general, only large enterprises or investors with strong strength can participate in the construction of the PPP project), and this advancement of the project management and engineering technology will be ultimately reflected in the reduction of the construction cost (*the private partner's internal construction cost is lower than C*), therefore, the enterprise's internal construction cost will be appropriately discounted on the basis of C. This discount rate is called **discount rate of productivity level (θ)**. The higher the level of productivity, the lower discount rate of productivity level.

1.4.4 Level of detail of the output specifications (h)

The level of detail of output specifications is expressed as the proportion of *CS* of the works specified in the output specifications to *C*.

The works specified in the output specifications refers to the works in the output specifications whose quantities can be accurately calculated.

1.4.5 Deviation coefficient of quantities (δ)

In the transaction stage of the PPP project, for works unspecified in the output specifications, the private partner forecasts the conventional estimated quantities according to the available information. There will be a deviation between these conventional estimated quantities and the corresponding quantities of future design drawings, which is usually expressed by **the deviation coefficient (δ)**.

$$\delta=\frac{\text{CS corresponding to quantities for the first set of design drawings}}{\text{CS corresponding to regular estimated quantities}}$$

1.4.6 Reservation profit rates (γ1 and γ2)

Reservation profit rates (γ_1 and γ_2) refer to the profit rates that the private partner calculates separately for the works specified and unspecified in the output specifications when submitting the tender offer of the PPP project.

1.4.7 Tender offer (α, β)

The tender offer from the private partner consists of two parts: the tender offer for PUPC of works specified in the output specifications (α) and the tender offer for PUPC of works unspecified in the output specifications (β).

1.4.8 Intensity of incentives (k)

Intensity of incentives (k): The percentage of PUPC savings that are shared with the private partner in order to incentivize design optimization.

1.4.9 Technological innovation (x, y)

Technological innovation: The private partner carries out design optimization and design deepening on the basis of the output specifications provided by the public authority.

Design optimization: It refers to the private partner modifies and improves the design of engineering contents that have been specified in the output specifications during the construction stage, so as to enhance the value of the project, which is characterized by the private partner's modification of the output specifications agreed in the contract. The level of effort of design optimization is expressed as "construction cost saving rate due to design optimization (x)".

Design deepening: It refers to the private partner supplements and refines the design of engineering contents that have not been specified in the output specifications during the construction stage, so as to meet constructability and enhance the value of the project, which is characterized by the private partner's ability not to modify output specifications agreed in the contract. The level of effort of design deepening is expressed as "construction cost saving rate due to design deepening (y)".

Behavioral cost coefficient of design optimization (Φ_1): If the behavioral cost of design optimization from the private partner is $\frac{1}{2}\Phi_1 d_1 x^2$, then d_1 is the enterprise's internal construction cost of specified work in the output specifications before design optimization. Φ_1 is the behavioral cost coefficient of design optimization. x is the saving rate of construction cost for design optimization.

Behavioral cost coefficient of design deepening (Φ_2): If the behavioral cost of design deepening from the private partner is $\frac{1}{2}\Phi_2 d_2 y^2$, then d_2 is the enterprise's internal construction cost of not specified work in the output specifications before design deepening. Φ_2 is the behavioral cost coefficient of design deepening. y is the saving rate of construction cost for design deepening.

1.4.10 Intensity of regulation (p)

Intensity of regulation (p): The proportion of checking and finding opportunism by the public authority, assuming that the private partner does not hide.

Behavioral cost coefficient of regulation (w): The proportion of the behavioral cost of

regulation by the public authority to the regulated cost expenditure.

Punishment coefficient (m): If opportunism by the private partner is detected, the public authority will confiscate the unjust enrichment (*t*) from the opportunism, and impose a fine of *m* times the unjust enrichment, where *m* is the punishment coefficient.

1.4.11 opportunism amount (t)

Opportunism amount (t): It refers to the overestimation and miscalculation of additional PUPC outside the contract, or the concealment of savings from design optimization that have already occurred, by the private partner in the construction stage.

Proportion of hidden opportunism (e): By hiding, the private partner reduces the proportion of opportunism that is discovered. This proportion of reduction is e.

Maximum amount of opportunism (t_0): influenced by exogenous conditions except for regulation, the private partner's opportunism can reach a maximum.

Maximum proportion of hidden opportunism (e_0): the maximum proportion of hidden opportunism by the private partner that can be achieved under the influence of exogenous conditions and regulation.

Behavior cost coefficient of hiding (Φ_3): The proportion of the behavioral cost of hiding to the amount of undetected opportunism.

Part II: Structured interview

Explanation: There are 15 questions below, each with a single-choice question and an accompanying short-answer question, where **the short-answer question is an extended description of the single-choice question, and the interviewee is required to first make a "yes" or "no" judgment, and then provides an explanation in one or two sentences.**

Some of the research assumptions (inputs) in this thesis cannot be supported or sourced from the literature review. Through interviews with the following questions, the reality of the situation is collected and the relevant data is analyzed. The relevant results serve as the basis and verification of these assumptions (inputs).

Name of interviewee (signature):_____ Date:_____

2.1 Your age is ( ).

A. ≤30 years old

B. 30<age≤40 years old

C. 40<age≤50 years old

D. 50<age≤60 years old

E. >60 years old

2.2 Your occupation is ( ).

A. Project representative from the public authority, or chief project leader from the private partner

B. Project investment manager from the public authority, or chief economist from the private partner

C. Project investment management staff from the public authority, or project cost management staff from the private partner

D. Chief project leader from the consulting agency commissioned by the public authority

E. Others

2.3 How many years of professional experience do you have? ( )

A. ≤5 years

B. 5<years≤10

C. 10<years≤15

D. 15<years≤20

E. >20 years

2.4 Your judgment of the interview questions is based on ( ).

A. Theoretical analysis

B. Practical experience

C. Knowledge of relevant developments at home and abroad

D. Reference to domestic and foreign literature

E. Intuition

2.5 Your familiarity with the interview questions is ( ).

A. Very familiar

B. Familiar

C. Relatively familiar

D. Not very familiar

E. Not familiar

2.6 Both the public authority and the private partner are rational person. Do you agree with this view?

Please choose an answer ( ): A. Strongly agree. B. Agree. C. Neutral. D. Disagree. E. Strongly disagree.

2.6.1 Does the public authority care about the proper functioning of the PPP project and the

public authority and user payment?

2.6.2 Does the private partner care about the proper functioning of the PPP project and the SPV's profitability?

2.7 Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), is there any space for savings in the PUPC?

Please choose an answer ( ): A. There is a lot of space for savings. B. There is room for savings. C. Neutral. D. There is no space for savings. E. There is no room for savings at all.

2.7.1 Does the public authority take any measures in the transaction stage to reduce the contract price of the PPP project?

2.7.2 Does the public authority take any measures in the construction stage to reduce future payment for construction cost?

2.8 In the transaction stage, all valid bidders that have passed pre-qualification are homogeneous bidders (each bidder has the same probability of winning the bid). Do you agree with this view?

Please choose an answer ( ): A. Strongly agree. B. Agree. C. Neutral. D. Disagree. E. Strongly disagree.

2.8.1 When bidding for the PPP project, does the tender offer of the bidder who has passed the prequalification have a very significant impact on the probability of winning the bid?

2.9 The transaction of the PPP project should follow the market rules of "full competition and fair competition". Do you agree with this view?

Please choose an answer ( ): A. Strongly agree. B. Agree. C. Neutral. D. Disagree. E. Strongly disagree.

2.9.1 Do you think there are any deficiencies in market competition in the PPP pattern?

2.9.2 Do you think "full competition, fair competition" is important for PPP project transaction?

2.10 The successful bidder for a PPP project transaction is determined according to the principle of "reasonably low price". Do you agree with this view?

Please choose an answer ( ): A. Strongly agree. B. Agree. C. Neutral. D. Disagree. E. Strongly disagree.

2.10.1 When evaluating bids for the PPP project, does the lower the price, the higher the score of the quotation (except if below cost)?

2.11 When the private partner makes a tender offer, is the reservation profit rate for works specified and unspecified in the output specifications greater than or equal to 0?

Please choose an answer ( ): A. Definitely yes. B. Yes. C. Neutral. D. No. E. Definitely no.

2.11.1 Have you come across any PPP projects in which the tender profit rate for the private partner's construction investment is negative?

2.12 Should the results of design optimization (changes to output specifications) be shared between the public authority and the private partner?

Please choose an answer ( ): A. Definitely yes. B. Yes. C. Neutral. D. No. E. Definitely no.

2.12.1 Does design optimization require joint decision-making by the public authority and the private partner? If so, would it be more motivating for both parties if they could share the corresponding results?

2.13 Should the results of design deepening (without changes to the output specifications) be exclusively enjoyed by the private partner?

Please choose an answer ( ): A. Definitely yes. B. Yes. C. Neutral. D. No. E. Definitely no.

2.13.1 Does design deepening require the public authority participation in decision-making?

(Note: This thesis assumes that "the public authority records the design deepening drawings submitted by the private partner" does not constitute the public authority participation in the decision-making of design deepening.)

2.13.2 If not, would it be more appropriate for the private partner to exclusively enjoy the corresponding results?

2.14 If the private partner does not hide, can the public authority detect all opportunism on the target of the inspection?

Please choose an answer ( ): A. Definitely yes. B. Yes. C. Neutral. D. No. E. Definitely no.

2.14.1 Are there any bottlenecks in the current inspection technology or methods that lead to opportunism not being fully detected?

2.15 Do you think that the cost of regulation for the PPP project meets the condition: "Cost of regulation ≤ the amount of fines and confiscations for the maximum opportunism"?

Please choose an answer ( ): A. Definitely yes. B. Yes. C. Neutral. D. No. E. Definitely no.

2.15.1 Have you encountered PPP projects in which, in the construction stage, the regulation cost by the public authority exceeded "the losses to the public authority due to opportunism resulting from the absence of regulation + penalties for opportunism"?

Part III: Unstructured interview

Explanation: The following is an open-ended interview. Regarding the research question of this

thesis, through interviews with the following questions, real-life situations are collected, relevant data are analyzed, answers to the research questions are sought, to obtain research results.

3.1 Research Question: In the project transaction stage, to save PUPC, how does the public authority choose the optimal level of detail of output specifications?

3.1.1 Background information of the interview theme (theme 1 and theme 2): Level of detail of output specifications and tender offer

1. Level of detail of output specifications (h)

The level of detail of output specifications (h) is expressed in this thesis as the proportion of the construction cost of works specified in the output specifications to the total construction cost of the project. The level of detail of the output specifications is like a movable "slider" on a scale that divides the works of a PPP project into two parts: the works specified in the output specifications and the works not specified, with the higher level of detail of the output specifications, the more works are in the former and the less works are in the latter.

The optimal level of detail of the output specifications from the public authority (h^*). Which level of detail of the output specifications is optimal? For the public authority, $h^*=\left\{ h \middle| \min_h(\text{PUPC}) \right\}$. The decision on the optimal level of detail of output specifications for the public authority needs to tradeoff between "specifying detailed functional requirements and technical quality indicators' and 'leaving sufficient space for technological innovation".

In the transaction stage, the decision process for the level of detail of the output specifications from the public authority. In the PPP project construction stage, the private partner conducts design optimization for the engineering contents specified in the output specifications, and design deepening for the engineering contents not specified in the output specifications. Design optimization and design deepening both belong to technological innovation, with the aim of saving construction cost. They have both their own behavioral cost and the benefits generated by saving construction cost. In the PPP project transaction stage, the private partner forecasts the internal construction cost of the enterprise and makes tender offer, taking into account the construction cost of the project itself and the savings of construction cost due to technological innovation at a later stage (during the construction stage). Through setting a reasonable level of detail of output specifications, the public authority reduces the projected value of bidders' internal construction cost and the amount of their tender offers, which in turn reduces the PUPC.

The higher (or lower) level of detail of output specifications, the larger (or smaller) the engineering scope of design optimization, and the smaller (or larger) the engineering scope of design deepening. Corresponding to the works specified in the output specifications are: construction cost saving rate of design optimization, maximum construction cost saving rate of design optimization, retained profit rate for the works specified, behavioral cost coefficient of design optimization. Corresponding to the works not specified in the output specifications are: construction cost saving rate of design deepening, maximum construction cost saving rate of design deepening, retained profit rate for the works not specified, behavioral cost coefficient of design deepening, and deviation coefficient of quantities. The public authority obtains information on these characteristic parameters through market testing before issuing bidding documents.

Comparing the construction cost savings rate, maximum construction cost savings rate, reservation profit rate, behavioral cost coefficient, and deviation coefficient of quantities between the engineering content specified and not specified in the output specifications, select the appropriate level of detail of the output specifications, based on the principle of "lowering the projected value of the bidder's tender offer".

2.Tender offer (α, β)

Optimal tender offer from the private partner (α^*, β^*). What is the optimal tender offer? For the private partner,

$(\alpha^*, \beta^*) = \{ \min(\alpha), \min(\beta) | \text{Forecast profit rate} \geq \text{retained profit rate} \}$.

The decision on the optimal tender offer for the private partner needs to tradeoff between "an appropriately high tender offer that realizes the enterprise's reservation profit" and "an appropriately low tender offer that increases the probability of winning the bid".

In the transaction stage, the private partner makes a decision on the tender offer. Firstly, for the works specified and unspecified in the output specifications, the CS, θ, and δ are calculated separately, and the construction cost savings in the later stage (construction stage) are forecasted, so as to obtain the internal construction cost of the enterprise. Then, based on the characteristics of the PPP project and the operation situation of the private partner, the reservation profit rate is determined. Finally, the private partner increases the probability of winning the bid through reasonably low prices, and determines the tender offer.

3.1.2 Questions for interview

Interview Question 1: In the project transaction stage, what are the factors and trends influencing the optimal level of detail of output specifications (h^*) for the public authority?

Interview Question 2: In the project transaction stage, what are the factors and trends influencing the optimal tender offer (α^*, β^*) for the private partner?

3.2 Research Question: In the project construction stage, how can the public authority choose the optimal intensity of incentives to save PUPC?

3.2.1 Background information of the interview theme (theme 3 and theme 4): Intensity of incentives and technological innovation

1. Intensity of incentives (k)

The intensity of incentives (k) is, in the construction stage, the proportion of the results of technological innovation that should be shared with the private partner to incentivize technological innovation (design optimization and design deepening) from the private partner. This thesis believes that the results of design deepening should be exclusively enjoyed by the private partner, so the intensity of incentives for design deepening (100%) does not need to be discussed. What needs to be discussed is the intensity of incentives for design optimization (k).

Optimal intensity of incentives from the public authority (k^*). What is the optimal intensity of incentives? For the public authority,

$$k^*=\left\{ k \middle| \min_k(\text{PUPC})\ ;\ \text{Profit after design optimization} \geq \text{Profit before design optimization} \right\}$$

The decision on the optimal intensity of incentives for the public authority needs to tradeoff between "incentivizing technological innovation" and "reducing PUPC".

In the construction stage, the decision-making process for the intensity of incentives from the public authority. Firstly, the private partner will carry out design optimization only if the net profit after design optimization is greater than the net profit before design optimization. The net profit after design optimization of the private partner should consider the reduction in the private partner's revenue due to the public authority's sharing of the results (related to k), the construction cost savings resulting from the design optimization, and the behavioral cost of the design optimization. The net profit before design optimization should consider the reservation profit (or profit rate) of the original tender. From this, the constraints on the intensity of incentives can be derived. Next, the value of the intensity of incentives is calculated when the PUPC is as small as possible. The intensity of incentives is announced by the public authority in the PPP's bidding documents after market research and testing.

2. Technological innovation strategy (x, y)

Technological innovation strategy (x, y): x is the saving rate of construction cost resulting from design optimization. y is the saving rate of construction cost resulting from design

deepening.

Optimal strategy of technological innovation from the private partner (x^*, y^*). What is the optimal technological innovation strategy? For the private partner,

$$(x^*, y^*)=\left\{ (x,\ y) \middle| \max_{x,y}(\text{Private partner's profit})\ ;\ \text{Profit after technological innovation}\ \geq\ \text{Profit before technological innovation} \right\}.$$

The decision on the optimal technological innovation strategy for the private partner needs to tradeoff between "increasing the behavioral cost due to technological innovation" and "decreasing the construction cost due to technological innovation".

In the construction stage, the decision-making process for technological innovation from the private partner. The public authority's incentives generally satisfy the condition that "the profit after technological innovation by the private partner ≥ the profit before technological innovation". As the saving rate of construction cost continues to increase, the behavioral cost of technological innovation will also become higher and higher (in a parabolic relationship). When the saving rate reaches a certain level, the loss from technological innovation will outweigh the gain (which does not meet the above constraint).

3.2.2 Questions for interview

Interview Question 3: In the project construction stage, what are the factors and trends influencing the optimal intensity of incentives (k^*) for the public authority?

Interview Question 4: In the project construction stage, what are the factors and trends influencing the optimal strategy of technological innovation (x^*, y^*) for the private partner?

3.3 Research Question: In the project construction stage, how can the public authority choose the optimal intensity of regulation to save PUPC?

3.3.1 Background information of the interview theme (theme 5 and theme 6): Intensity of regulation and opportunism

1. Intensity of regulation (p)

The intensity of regulation refers to the proportion of spot checks carried out by the public authority on regulated targets.

Optimal intensity of regulation for the public authority (p^*). What is the optimal intensity of incentives? For the public authority, $p^*=\left\{ p \middle| \min_{p}(\text{PUPC}) \right\}$. The decision on the optimal intensity of regulation for the public authority needs to tradeoff between "curbing opportunism" and "reducing regulation cost".

In the construction stage, the decision-making process for the intensity of regulation from

the public authority. Firstly, to curb opportunism by the private partner, the proportion of spot checks by the public authority should exceed the proportion of maximum hidden opportunism by the private partner. Secondly, the strength of punishment is also an indispensable means for the public authority to curb opportunism. Finally, the cost coefficient (difficulty) of the private partner's hidden opportunism also affects the decision-making on the intensity of regulation.

2. Opportunism strategy (t, e)

The opportunism strategy (t, e): t is the opportunism amount. e is the proportion of hidden opportunism.

The optimal strategy of opportunism for the private partner (t^*, e^*). What is the optimal strategy of opportunism? For the private partner, (t^*, e^*) $=\left\{(t,\ e)\middle|\ \max_{t,e}(\text{Private partner's profit})\right\}$. The decision on the optimal opportunism strategy for the private partner is based on the expected value of extra profit.

In the construction stage, the decision-making process for opportunism from the private partner. The private partner decides the amount of opportunism to implement based on the intensity of regulation, the strength of punishment, and the ease of hidden opportunism. When the forecasted opportunism is not profitable, the motivation to engage in opportunism diminishes.

3.3.2 Questions for interview

Interview Question 5: In the project construction stage, what are the factors and trends influencing the optimal intensity of regulation (p^*) for the public authority?

Interview Question 6: In the project construction stage, what are the factors and trends influencing the optimal strategy of opportunism (t^*, e^*) for the private partner?

3.4 Research Question: What are the influencing factors of PUPC? What are the paths to save PUPC?

3.4.1 Background information of the interview theme (theme 7 and theme 8): Methods and paths for PUPC saving

PUPC is the consideration that the public authority and users should pay for the construction cost invested by the private partner. This thesis assumes that PPP project financing, usage, and operational performance are in a normal state. PUPC consists of two parts: "contract price (winning price)" and "adjustment of contract changes due to risks and responsibilities (rights) to be borne by the public authority".

1. Cost characteristics of the project itself

Before the transaction of the PPP project, feasibility study should be conducted, including investment estimation (or budget estimate) and economic evaluation. Investment estimation or budget estimate (referred to as "construction cost calculated by Norm and Standard for the entire project" in this thesis, abbreviated as "*C*") is prepared based on the scheme design and national or industry estimation index (or budget estimation norm and standard). *C* reflects the cost characteristics of the PPP project from the perspective of the average level of social productivity.

2. Strategies of the public authority

In order to save PUPC, the public authority promotes reasonably low tender offer in the project transaction stage by adopting a fair market competition mechanism and appropriate *level of detail of output specifications*. It promotes cost reduction and efficiency improvement in the construction stage by adopting *incentive measures*, and at the same time curbs inflated PUPC due to opportunism by adopting *regulation measures*. When implementing these measures, the public authority needs to make decisions on h, k, and *p* based on the previous "Themes 1 to 6".

3. Strategies of the private partner

In order to obtain greater profit for the enterprise, in the project transaction stage, the private partner increases the probability of winning the bid by submitting a reasonably low *tender offer*, while guaranteeing a reasonable profit rate. In the construction stage, the private partner actively reduces cost and increases efficiency through *design optimization and design deepening*, and at the same time strengthens the enterprise's management of *opportunism* to prevent losses from fines and confiscation. When implementing these measures, the private partner needs to make decisions on (α, β), (x, y) and (t, e) based on previous "Themes 1 to 6".

3.4.2 Questions for interview

Interview Question 7: Summarize and think about the factors and paths influencing PUPC. According to the analysis of the paths influencing PUPC, among the factors influencing PUPC, which are the most original factors influencing PUPC (independent variables)? Which are the intermediate factors influencing PUPC (intermediate variables)? What are the trends influencing PUPC (positive or negative correlation with PUPC)?

Interview Question 8: What are the paths to save PUPC?

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Annex B: Figures and Tables Appended to the Literature Review

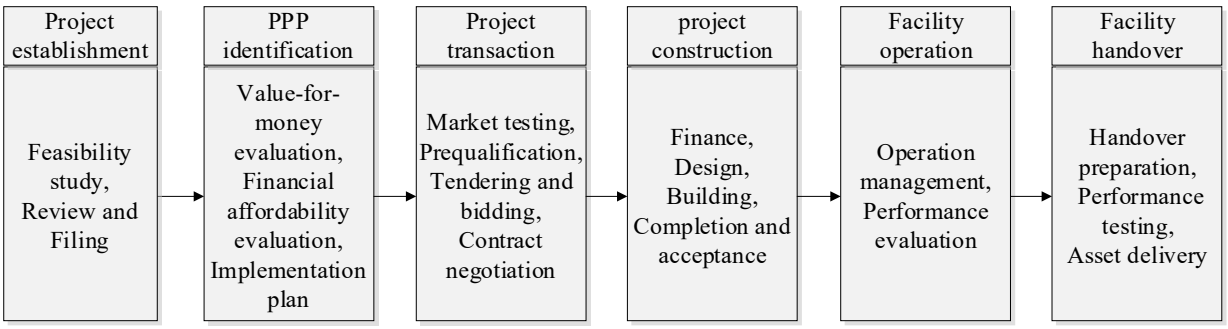


Figure B.1 The six stages of the PPP pattern

Source: MOF(2014); NDRC (2019)

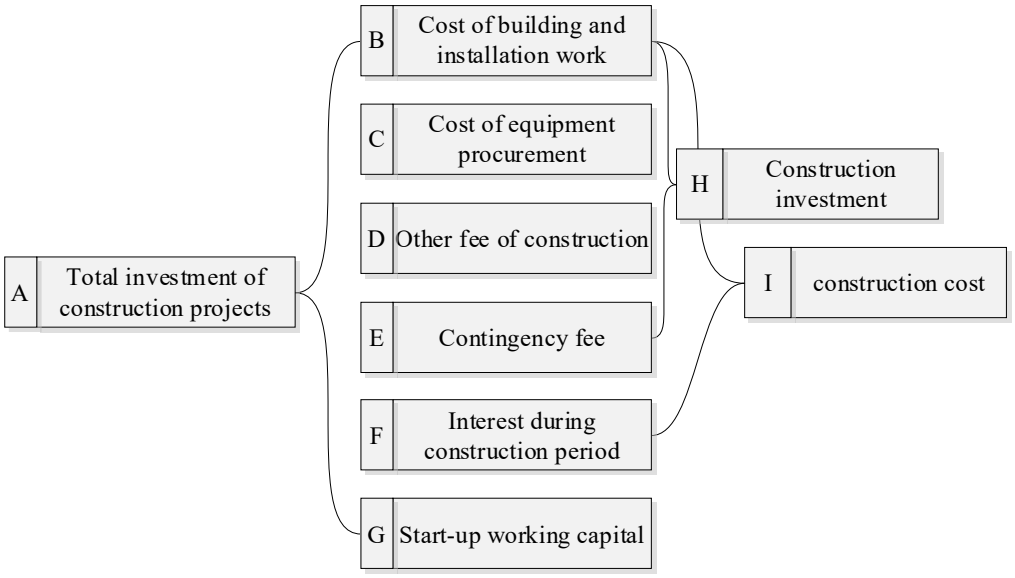


Figure B.2 Relationship between total investment and construction cost

Source: MOUHURD (2013, 2015); Professional Qualification Center of Ministry of Transport (2020); Z. M. Wu (2023)

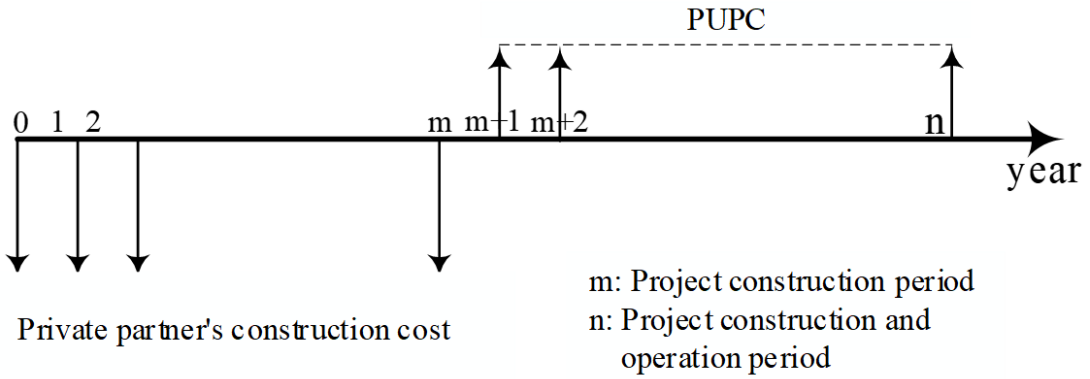


Figure B.3 Cash flow diagram for construction cost and PUPC

Source: J. T. Zhou et al. (2019, p. 21); Z. M. Wu (2023)

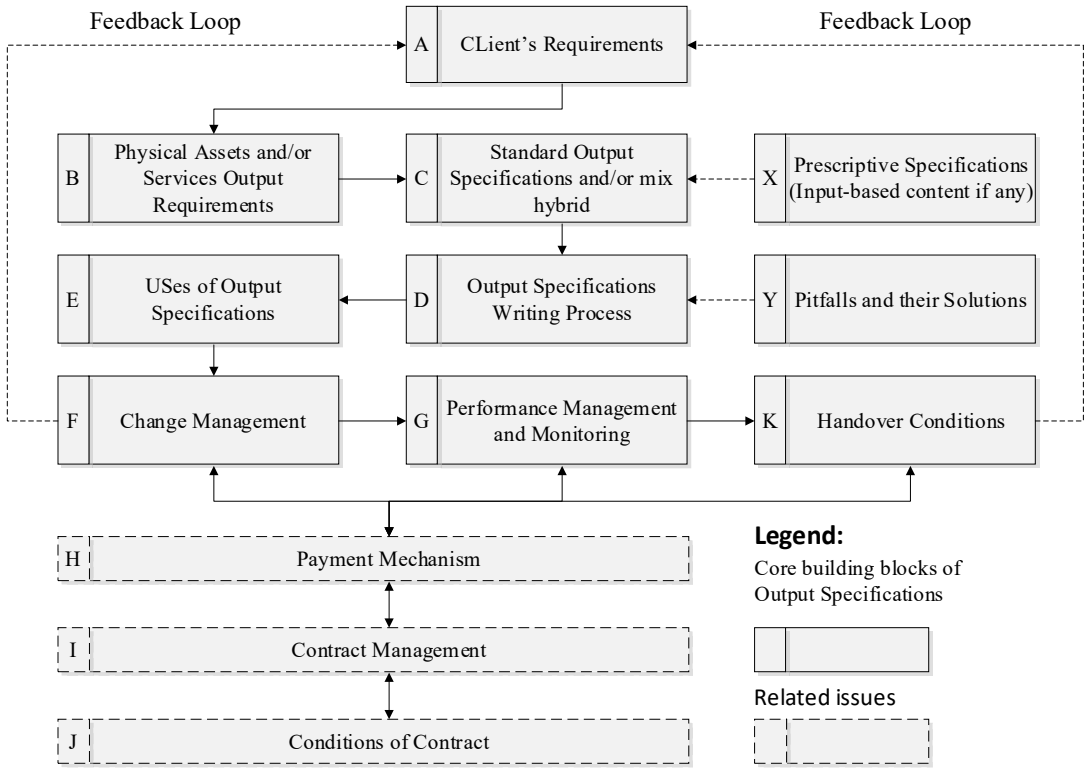


Figure B.4 Framework for output specifications

Source: Javed (2013, p. 282)

Table B.1 Methods and procedures for calculating C and the internal construction cost of the enterprise

No.	Calculation procedure of construction cost	Construction Cost Calculated by Norm and Standard for the Entire Project (C)		Internal construction cost of the enterprise (C')	
		Method of calculation	Basis of calculation	Method of calculation	Basis of calculation
1	Work quantities	Calculate quantities of work based	Output specifications, common construction methods,	Calculate quantities of work based	Output specifications, construction methods of the enterprise,

No.	Calculation procedure of construction cost	Construction Cost Calculated by Norm and Standard for the Entire Project (C)		Internal construction cost of the enterprise (C')	
		Method of calculation	Basis of calculation	Method of calculation	Basis of calculation
		on the data (Q)	Measurement Standard for Bills of Quantities for Highway Project	on the data (Q_1)	Measurement Standard for Bills of Quantities for Highway Project
2	Consumption of labor, materials, and machinery per unit quantity of work	Using professional pricing software to calculate the consumption of labor, materials, machinery, and equipment per unit quantity of work (S)	Investment estimation index (JTG/T3821-2018), Budget estimation norm and standard (JTG/T3831-2018), Calculation method of investment estimation (JTG/T3820-2018), Calculation method of budget estimate (JTG/T3830-2018), machinery shift norm and standard (JTG/T3833-2018)	Using professional pricing software to calculate the consumption of labor, materials, machinery, and equipment per unit quantity of work (S_1)	The enterprise's internal control data on the consumption of labor, materials, machinery, and equipment.
3	Unit price of labor, materials, machinery, and equipment	Calculating according to the average market price (P)	Price from *guidance of cost information* issued by government departments or industry management. Average price on market inquiry.	Internal control unit price of enterprise purchases (P_1)	Quotations from suppliers who have been cooperating with the private partner for a long period of time
4	Ratio of overhead cost, profit, statutory fee, and tax	Calculating the rate according to the average level of society (F)	The rate of overhead cost and profit shall be calculated according to the average social rate issued by government departments or industry management. The rate of statutory fee and tax shall be calculated according to the laws and regulations of the state.	Calculating the rate according to the situation of the enterprise itself (F_1)	The rate of overhead cost and profit shall be calculated according to the internal system of the enterprise. The rate of statutory fee and tax shall be calculated according to the laws and regulations of the state.
5	All-in unit price	$R_i=S_i\times P_i\times(1+F_i)$		$R_{1i}=S_{1i}\times P_{1i}\times(1+F_{1i})$	
6	Cost of building and installation work	$M=\sum_{i=1}^{N}(Q_i \times R_i)$		$M_1=\sum_{i=1}^{N}(Q_{1i} \times R_{1i})$	
7	Cost of equipment procurement	E= ∑(Quantity × unit price)	The quantity shall be calculated according to the design drawings or design schemes. The unit price shall be	E_1= ∑(Quantity × unit price)	The quantity shall be calculated according to the design drawings or design schemes.

No.	Calculation procedure of construction cost	Construction Cost Calculated by Norm and Standard for the Entire Project (C)		Internal construction cost of the enterprise (C')	
		Method of calculation	Basis of calculation	Method of calculation	Basis of calculation
			calculated according to the average market price.		The unit price shall be calculated according to the competitive offers from suppliers cooperating with the private partner
8	Other fee of construction	$O=\sum O_i$	Calculating survey fee, design fee and other fees according to the market average price.	$O_1=\sum O_{1i}$	Calculating survey fee, design fee and other fees according to the competitive offers from suppliers cooperating with the private partner
9	Contingency fee	$Y=(M+E+O)\times g$	g: Determined by the public authority according to the policy document. (Professional Qualification Center of Ministry of Transport, 2020), P342	$Y_1=(M_1+E_1+O_1)\times g$	Directly calculating according to the amounts provided in the bidding documents
10	Interest during construction period	I	Calculating according to the bank loan interest rate for the same period	I_1	Calculating according to the private partner's own finance scheme
11	construction cost	$C=M+E+O+Y+I$	Construction cost calculated by norm and standard for the entire project (C)	$C'=M_1+E_1+O_1+Y_1+I_1$	Internal construction cost of the enterprise (C')

Source: Professional Qualification Center of Ministry of Transport (2020, pp. 344, 357), MOUHURD (2013)

Table B.2 Classifications of non-cooperative games and corresponding equilibriums

Information condition	**Static**	**Dynamic**
Complete information	Static game of complete information Nash Equilibrium	Dynamic game of complete information Subgame perfect Nash Equilibrium
Incomplete information	Static game of incomplete information Bayesian Nash Equilibrium	Dynamic game of incomplete information Perfect Bayesian Nash Equilibrium

Source: Zhang (2012)

Annex C: Data Analysis Tables for Structured Interviews

Table C.1 Descriptive statistics of structured interviews

Questions for Interview	**Interviewee A1**	**Interviewee B1**	**Interviewee A2**	**…**	**Number of people** (support the initial assumption)	**Percentage**
2.6 Both the public authority and the private partner are rational person. Do you agree with this view?	Neutral. Most will still act according to their respective responsibilities, but a few public authorities may consider irrational factors.	Agree	Agree	…	18	82%
2.6.1 Does the public authority care about the proper functioning of the PPP project and the public authority and user payment?	Yes, it definitely does.	Yes, it definitely does.	Yes, it does.	…	22	100%
2.6.2 Does the private partner care about the proper functioning of the PPP project and the SPV's profitability?	Yes.	Yes.	Yes.	…	22	100%
2.7 Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), is there any space for savings in the PUPC?	There is room for savings	There is room for savings	There is room for savings	…	22	100%
2.7.1 Does the public authority take any measures in the transaction stage to reduce the contract price of the PPP project?	Yes, it does.	Yes, it does.	Yes, it does.	…	22	100%
2.7.2 Does the public authority take any measures in the construction stage to reduce future payment for construction cost?	Yes, it does.	Yes, it does.	Yes, there are measures to reduce construction cost.	…	22	100%
2.8 In the transaction stage, all valid bidders that have passed pre-qualification are homogeneous bidders (each bidder has the same probability of winning the bid.). Do you agree with this view?	Neutral. Technology, business, and price all affect the probability of winning the bid. When the technical and business scores of each bidder	Neutral. The PPP project is too large and too long, so mutual recognition and trust (in terms	Agree	…	15	68%

Questions for Interview	Interviewee A1	Interviewee B1	Interviewee A2	…	Number of people (support the initial assumption)	Percentage
	are close, the price becomes important.	of technology and strength) between the two parties are very important.				
2.8.1 When bidding for the PPP project, does the tender offer of the bidder who has passed the prequalification have a very significant impact on the probability of winning the bid?	Yes, it has a very significant impact.	Yes, it has a very significant impact.	Yes, it should have a significant impact.	…	21	95%
2.9 The transaction of the PPP project should follow the market rules of "full competition and fair competition". Do you agree with this view?	Strongly agree	Agree	Strongly agree	…	22	100%
2.9.1 Do you think there are any deficiencies in market competition in the PPP pattern?	Yes. Only a small number of enterprises can participate in projects that are large in scale, complex in technology, and high in financing capacity. The local business environment may also limit the willingness of enterprises to bid. These factors lead to insufficient market competition.	Yes, there are deficiencies	Yes, there are deficiencies.	…	22	100%
2.9.2 Do you think "full competition, fair competition" is important for the PPP project transaction?	Yes, fair competition is still very necessary.	Yes, fair competition is relatively important.	Yes, very important.	…	22	100%
2.10 The successful bidder for a PPP project transaction is determined according to the principle of "reasonably low price". Do you agree with this view?	Agree	Agree	Agree	…	19	86%
2.10.1 When evaluating bids for the PPP project, does the lower the price, the higher the score of the quotation (except if below cost)?	Yes, the advantage of a low bid price is quite significant.	Yes, this is generally the case.	Not necessarily. In the comprehensive scoring method, a lower bid price does not necessarily mean a higher score. In the reasonable low price method, the lower the bid price, the higher	…	14	64%

Questions for Interview	Interviewee A1	Interviewee B1	Interviewee A2	…	Number of people (support the initial assumption)	Percentage
			the score.			
2.11 When the private partner makes a tender offer, is the reservation profit rate for works specified and unspecified in the output specifications greater than or equal to 0?	Yes	Yes	Yes	…	19	86%
2.11.1 Have you come across any PPP projects in which the bidding profit rate for the private partner's construction investment is negative?	No, there should not be any.	No. Definitely greater than 0.	No.	…	18	82%
2.12 Should the results of design optimization (changes to output specifications) be shared between the public authority and the private partner?	Yes.	Yes.	Neutral. Design optimization changes output specifications, and normally the private partner does not necessarily enjoy the corresponding results.	…	20	91%
2.12.1 Does design optimization require joint decision-making by the public authority and the private partner? If so, would it be more motivating for both parties if they could share the corresponding results?	1. Yes. 2. Yes.	1. Yes. 2. Yes.	1. Yes. 2. Yes. Sharing should be based on the proportion agreed in the contract.	…	22	100%
2.13 Should the results of design deepening (without changes to the output specifications) be reserved exclusively for the private partner?	Yes.	Yes.	Yes.	…	20	91%
2.13.1 Does design deepening require public sector participation in decision-making?	No.	No.	Yes. The public authority participates in the approval of refined drawings, but design deepening involves more private partner participation.	…	17	77%
2.13.2 If not, would it be more appropriate for the private partner to exclusively own the corresponding results?	Definitely.	Yes.	Yes, it should be.	…	21	95%
2.14 If the private partner does not hide, can the public authority detect all opportunism on the target of the inspection?	Yes.	Yes.	Neutral. The vast majority can be detected, but not all.	…	15	68%
2.14.1 Are there any bottlenecks in the current inspection technology or methods that lead to opportunism not being	Yes, there are.	Yes, but very few.	Yes, but very few.	…	5	23%

Questions for Interview	**Interviewee A1**	**Interviewee B1**	**Interviewee A2**	**…**	**Number of people** (support the initial assumption)	**Percentage**
fully detected?						
2.15 Do you think that the cost of regulation for the PPP project meets the condition: "Cost of regulation ≤ the amount of fines and confiscations for the maximum opportunism"?	Yes.	Yes.	Yes.	…	20	91%
2.15.1 Have you encountered PPP projects in which, in the construction stage, the regulation cost by the public authority exceeded "the losses to the public authority due to opportunism resulting from the absence of regulation + penalties for opportunism"?	No, if the regulation cost is too high, there will be no regulation. Only when the regulation cost is lower than the amount of fines and confiscations will there be regulation.	No, I don't think it would be greater.	No.	…	16	73%

Table C.2 Theme analysis for structured interviews

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
2.6 Both the public authority and the private partner are rational person. Do you agree with this view?	18	82%	1. The supporting and opposing opinions on the main question The support rate stands at 82%, with 4 interviewees holding dissenting opinions, choosing the option "neutral". The reasons for dissenting opinions can be summarized as follows:
2.6.1 Does the public authority care about the proper functioning of the PPP project and the public authority and user payment?	22	100%	① Three interviewees believe that the public authority may consider non-rational factors such as politics. ② One interviewee believes that the private partner is sometimes irrational in submitting a tender offer, "first, it wants to win the project, and second, it wants to have a second round of business negotiations".
2.6.2 Does the private partner care about the proper functioning of the PPP project and the SPV's profitability?	22	100%	2. Supporting and opposing opinions on auxiliary questions 100% support rate, no dissenting opinions. 3. Theoretical analysis Regarding reason ①: The concept of "rational person" (Zhang, 2012) is an economic concept that abstracts and simplifies the principles of individual economic behavior in real-life scenarios. According to the statistical results, there is an 82% support rate, indicating that this principle is universal and representative, and the principle of "rational person" holds a dominant role in the PPP pattern. Regarding reason ②: The strategy of "winning the project first and then seeking profit" precisely proves that the private partner acts as a rational person. There is a contradiction between the interviewees' conclusion and the reasons they provided, so this reason lacks rigor. 4. Interpretation of the main question by auxiliary questions Very strong support for the initial assumption. 100% of the interviewees hold a positive opinion on two auxiliary questions, confirming that the public authority and the private partner are rational persons. Therefore, after excluding factors outside the scope of the PPP project, all the interviewees support the principle of "rational person". 5. Result The initial assumption will not be modified.

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
2.7 Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), is there any space for savings in the PUPC?	22	100%	1. All interviewees support the initial assumption. 2. Interpretation of the main question by auxiliary questions Very strong support for the initial assumption. 100% of interviewees believe that the public authority may take measures to save the payment for construction in the transaction and construction stages. 3. Result The initial assumption will not be modified.
2.7.1 Does the public authority take any measures in the transaction stage to reduce the contract price of the PPP project?	22	100%	
2.7.2 Does the public authority take any measures in the construction stage to reduce future payment for construction cost?	22	100%	
2.8 In the transaction stage, all valid bidders that have passed pre-qualification are homogeneous bidders (each bidder has the same probability of winning the bid). Do you agree with this view?	15	68%	1. The supporting and opposing opinions on the main question The support rate stands at 68%, with 7 interviewees holding dissenting opinions, choosing the option "neutral". The reasons for dissenting opinions can be summarized as follows: ① In addition to tender offer, factors such as technology, business, overall strength, creditworthiness, contract performance capability, and equipment renewal also have a significant impact on the probability of winning the bid. ② Compared with the reasonable low-price method, the tender offer in the comprehensive scoring method is no longer the most important factor. 2. Supporting and opposing opinions on auxiliary question The support rate stands at 95%, with one interviewee holding dissenting opinion and choosing the option "neutral". The reasons for dissenting opinions can be summarized as follows:
2.8.1 When bidding for the PPP project, does the tender offer of the bidder who has passed the prequalification have a very significant impact	21	95%	

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
on the probability of winning the bid?			③ If the comprehensive scoring method is used, the tender offer only has a general impact on the probability of winning the bid; However, if the reasonable low-price method is used, the tender offer has a significant impact on the probability of winning the bid. 3. Theoretical analysis Regarding reason ①: Due to the differences in tender offer, technology, business, overall strength, creditworthiness, contract performance capability, and equipment renewal among bidders, it is difficult to determine them as homogeneous bidders. Although 68% of the interviewees agree with this assumption, the reasons for opponents are also solid and reasonable. Therefore, for research purposes, the private partner studied in this thesis can be set as "the representative of the winning bidder among all bidders", that is, the private partner in this thesis has the common characteristic parameters with all bidders and wins the bid. To further confirm the feasibility of this viewpoint, the researchers followed up with all the interviewees by telephone, and they all expressed their agreement. Regarding reason ②③: Different evaluation methods can also lead to changes in the factors that affect winning the bid, so it is difficult to confirm the assumption of "homogeneous bidders" in practice. 4. Interpretation of the main question by auxiliary question 95% of the interviewees believe that the tender offer has a significant impact on the probability of winning the bid, which precisely indicates that it is difficult to achieve the goal of assumption "all bidders as homogeneous bidders" in reality. 5. Result The initial assumption is modified to: In the transaction stage, the private partner acts as the representative of the winning bidder among all bidders.
2.9 The transaction of the PPP project should follow the market rules of "full competition and fair competition". Do you agree with this view?	22	100%	1. All interviewees support the initial assumption 2. Interpretation of the main question by auxiliary questions Very strong support for the initial assumption. 100% of the interviewees believe that although there are some shortcomings in the competition of the PPP market, "full and fair competition" is important for PPP project transaction. 3. Result

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
2.9.1 Do you think there are any deficiencies in market competition in the PPP pattern?	22	100%	The initial assumption will not be modified.
2.9.2 Do you think "full competition, fair competition" is important for PPP project transaction?	22	100%	
2.10 The successful bidder for a PPP project transaction is determined according to the principle of "reasonably low price". Do you agree with this view?	19	86%	1. Supporting and opposing opinions on the main question The support rate stands at 86%, with 3 interviewees holding dissenting opinions and choosing "neutral". The reasons for dissenting opinions can be summarized as follows: ① Two interviewees believe that evaluation criteria should encompass technical, business, funding, financing, and credibility, rather than focusing solely on tender offer. ② One interviewee believes that when the boundary conditions for procurement are not clear enough, the reasonable low-price method may not necessarily be adopted. 2. Supporting and opposing opinions on auxiliary question The support rate stands at 64%, with 8 interviewees holding dissenting opinions. The reasons for dissenting opinions can be summarized as follows: ③ Six interviewees believe that under the comprehensive scoring method, a lower tender offer does not necessarily guarantee a higher total score. Conversely, when applying the reasonable low-price method, a lower tender offer directly correlates with a higher score. ④ Two interviewees believe that the key is to look at the pursuit of the public authority. If investment control is emphasized, the tender offer has a significant impact on the score; If ability and reputation are emphasized, the tender offer has a small impact on the score. 3. Theoretical analysis Regarding reasons ①③④: According to the latest policies of the PPP pattern, the evaluation criteria for bidding should consider "operational plan, charging unit price,
2.10.1 When evaluating bids for the PPP project, does the lower the price, the higher the score of the quotation (except if below cost)?	14	64%	

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
			concession period, management experience, professional operational ability, comprehensive strength of the enterprise, and credit rating status" (General Office of the State Council of the People's Republic of China, 2023). Therefore, the principle of "reasonable low price" is inappropriate to determine the winning bidder. In addition to the tender offer, attention should also be paid to the technology and business aspects of the bidder. However, according to the *Management Measures for Tendering and Bidding of Government Procurement of Goods and Services* (MOF, 2017), regardless of the reasonable low-price method or the comprehensive scoring method, low price should be given priority. Regarding reason ②: The clarity of boundary conditions is not necessarily related to the principle of "reasonable low price", and the reason is insufficient. 4. Interpretation of the main question by auxiliary question Weak support for the initial assumption. 64% of interviewees believe that the lower the tender offer, the higher the score. Those who hold dissenting opinions mostly emphasize the importance of technology, business, capability and credibility. 5. Result The initial assumption needs to be modified to: The PPP project transactions follow the principle of "low price priority", i.e., the lower the tender offer, the higher the price score in the total score (except for tender offer lower than the cost).
2.11 When the private partner makes a tender offer, is the reservation profit rate for works specified and unspecified in the output specifications greater than or equal to 0?	19	86%	1. Supporting and opposing opinions on the main question The support rate stands at 86%, with 3 interviewees holding dissenting opinions and choosing "neutral". The reasons for dissenting opinions can be summarized as follows: ① Two interviewees believe that obtaining project first, and then making profit through technological innovation and management approach. ② One interviewee believes that some private partners aim to obtain long-term cooperation (capturing the market), not necessarily for profit-making.
2.11.1 Have you come across any PPP projects in which the tender profit rate for the private partner's construction investment is negative?	18	82%	2. Supporting and opposing opinions on auxiliary question The support rate stands at 82%, with 4 interviewees holding dissenting opinions. The reasons for dissenting opinions can be summarized as follows: ③ Two interviewees believe that obtaining project first, and then making profit

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
			through technological innovation and management approach. ④ Two interviewees believe that some private partners aim to obtain long-term cooperation (capturing the market), not necessarily for profit-making. 3. Theoretical analysis Regarding reasons ①③: The fact that "profits are pursued through technological innovation and management approach" indicates that the private partner's ultimate objective remains profit-making. Consequently, this reason inherently supports the private partner's quest for a positive profit rate. Regarding reasons ②④: "This project is not profitable with the aim of capturing the market". It indicates that the private partner seeks long-term cooperation, yet its ultimate objective remains to achieve a positive profit rate. 4. Interpretation of the main question by auxiliary question Strong support for the initial assumption. 82% of interviewees believe that the reservation profit rate for private partner's investment should be greater than 0. 5. Result The initial assumption will not be modified.
2.12 Should the results of design optimization (changes to output specifications) be shared between the public authority and the private partner?	20	91%	1. Supporting and opposing opinions on the main question The support rate stands at 91%, with 2 interviewees holding dissenting opinions and choosing the option "neutral". The reasons for dissenting opinions can be summarized as follows: ① One interviewee believes that design optimization requires changes to output specifications, therefore, the private partner cannot enjoy the results of design optimization. ② Another interviewee believes that whoever proposes and carries out design optimization should enjoy the corresponding results. 2. Supporting and opposing opinions on auxiliary question 100% support rate, no dissenting opinions. 3. Theoretical analysis Regarding reason ①: Although design optimization changes the output specifications, if the public authority recognizes these changes, according to the theory of PPP and current policies, the results of saving construction cost should be shared
2.12.1 Does design optimization require the participation of both the public authority and the private partner in decision-making? If so, would it be more motivating for both parties if they could share the corresponding results?	22	100%	

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
			by both parties (General Office of the State Council of the People's Republic of China, 2023). Regarding reason ②: According to the definition of "design optimization" in the interview outline, the design optimization in this thesis is led and carried out by the private partner. If the public authority independently carries out technological innovation, it can be regarded as a "changes proposed by the public authority" rather than a "design optimization". So, the interviewee's reasons deviated from the original meaning of the interview theme. 4. Interpretation of the main question by auxiliary question Very strong support for the initial assumption. 100% of interviewees believe that design optimization requires joint participation and sharing of results between the public authority and the private partner. 5. Result The initial assumption will not be modified.
2.13 Should the results of design deepening (without changes to the output specifications) be reserved exclusively for the private partner?	20	91%	1. Supporting and opposing opinions on the main question The support rate stands at 91%, with 2 interviewees holding dissenting opinions and choosing the option "neutral". The reasons for dissenting opinions can be summarized as follows: ① One interviewee believes that the interests of the public authority should be protected and the public authority should be involved in sharing the corresponding results. ② One interviewee believes that if the return rate of design deepening is within a certain limit, it should be exclusively enjoyed by the private partner; If it exceeds the limit, it does not necessarily exclusively enjoy by the private partner.
2.13.1 Does design deepening require public authority's participation in decision-making?	17	77%	
2.13.2 If not, would it be more appropriate for the private partner to exclusively own the corresponding results?	21	95%	2. Supporting and opposing opinions on auxiliary questions The second auxiliary question is crucial, with a support rate of 95% and one interviewee holding dissenting opinions. The reasons for dissenting opinions can be summarized as follows: ③ One interviewee believes that within a certain limit, the private partner should bear the profit or investment risk; beyond this limit, both parties should negotiate, especially so that public services must not generate excessive profits.

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
			3. Theoretical analysis Regarding reason ①: According to PPP theory and current policies, the results of technological innovation mainly belong to the private partner, which means that sharing and exclusive ownership are in line with policy direction (General Office of the State Council of the People's Republic of China, 2023). So, should the private partner share or have exclusive ownership? For the results of design deepening, the proportion of sharing by the public authority will ultimately be reflected in the tender offer. The greater the proportion of sharing by the public authority, the higher the private partner's tender offer will be. Conversely, the smaller the proportion of sharing by the public authority, the lower the tender offer will be. Therefore, sharing the results by the public authority does not necessarily ensure better safeguarding of public interests. In fact, because of the public authority's dominant position and the challenges in quantifying the results of design deepening, the public authority's involvement in sharing ultimately lowers the expectation of the private partner's benefits. This, in turn, dampens the private partner's enthusiasm for design deepening, and may ultimately harm the public authority's interests. Regarding reasons ②③: Due to the public-welfare nature of the PPP project, return exceeding a certain limit should be shared, and excessive profit must be avoided. Therefore, the initial assumptions should be modified. 4.Interpretation of the main question by auxiliary questions Regarding the first auxiliary question, some interviewees believe that the public authority should participate in decision-making or supervision of design deepening. In fact, there is no close connection between whether the public authority participates in decision-making and whether the corresponding results are shared. Therefore, the interview results for the first auxiliary question are not considered. The second auxiliary question strongly supports the initial assumption. 95% of interviewees believe that the results of design deepening should be exclusively held by the private partner. 5. Result The initial assumption needs to be modified to: The results of design deepening (without changing the output specifications) should be exclusively enjoyed by the

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
			private partner (except for excessive profit).
2.14 If the private partner does not hide, can the public authority detect all opportunism on the target of the inspection?	15	68%	1. Supporting and opposing opinions on the main question The support rate stands at 68%, with 7 interviewees holding dissenting opinions and choosing the option "neutral". The reasons for dissenting opinions can be summarized as follows: ① Seven interviewees believe that if the private partner does not engage in any behavior of hiding, the public authority can detect most opportunism, but it is difficult to detect all opportunism. 2. Supporting and opposing opinions on auxiliary question The support rate stands at 23%, with only 23% of interviewees believing that the current technologies and methods have no bottlenecks, while 17 interviewees believe that there are some bottlenecks. The reasons for dissenting opinions can be summarized as follows: ② Most interviewees believe that current regulatory technologies and methods have minor bottlenecks. 3. Theoretical analysis Regarding reasons ①②: Seven interviewees believe that opportunism cannot be fully detected, while 17 interviewees believe that current regulatory technologies and methods have certain and minor bottlenecks. The results of the interview indicate that if the private partner does not engage in any behavior of hiding, the public authority can detect most opportunism through regulation, but cannot guarantee 100% detection of opportunism. 4. Interpretation of the main question by auxiliary question The auxiliary question does not support the initial assumption. Only 23% of interviewees believe that current regulatory technologies and methods are completely flawless. 5. Result The initial assumption has been canceled.
2.14.1 Are there any bottlenecks in the current inspection technology or methods that lead to opportunism not being fully detected?	5	23%	
2.15 Do you think that the cost of regulation for the PPP project meets the condition:	20	91%	1. Supporting and opposing opinions on the main question The support rate stands at 91%, with 2 interviewees holding dissenting opinions and choosing the option "neutral".

Questions for Interview	The number of people who support the initial assumption	Percentage	Theme analysis
"Cost of regulation ≤ the amount of fines and confiscations for the maximum opportunism"?			The reasons for dissenting opinions can be summarized as follows: ① In most cases, it is "less than". But in extreme cases, a "greater than" situation may occur. For example, the private partner is highly self-regulated, refraining from opportunism even in the absence of regulation.
2.15.1 Have you ever come across a scenario in the construction stage of a PPP project where "the public authority's expenditure arising from regulation (i.e. the behavior cost of regulation) is greater than the sum of losses and penalties due to opportunism stemming from a lack of regulation"?	16	73%	2. Supporting and opposing opinions on auxiliary question The support rate stands at 73%, with 6 interviewees holding dissenting opinions. The reasons for dissenting opinions can be summarized as follows: ② Most of them will not have "greater than", but in special circumstances, "greater than" may occur. 3. Theoretical analysis Regarding reasons ①②: A small number of interviewees believe that in special circumstances, it is possible that "regulation cost exceeds the sum of fines and confiscated amount for maximum opportunism". This special situation is characterized by "the public authority refraining from regulation, and the private partner refraining from opportunism". However, the likelihood of such a situation occurring in reality is extremely low, and it also contradicts the assumption of the "rational person". Therefore, the interviewees suggested that "special circumstances" theoretically exist, but can be ignored in reality. 4. Interpretation of the main question by auxiliary question Auxiliary question generally supports the initial assumption. 73% of interviewees believe that there will not be a situation of "greater than". 5. Result The initial assumption will not be modified.

Table C.3 Formal assumptions of mathematical modeling methods of game theory

NO.	Inputs for mathematical modeling method	Source/Basis
Assumption 1	The public authority and the private partner are both rational persons.	Structured interviews; H. J. Liu (2010); Meng (2019); Ni (2019)
Assumption 2	Assuming that financing, usage and operational performance of the PPP project are normal (i.e. actual value = expected value at the time of the transaction), there is room for savings for PUPC.	Structured interviews; CCEA (2018); Grimsey and Lewis (2016)
Assumption 3	In the transaction stage, the private partner acts as the representative of the winning bidder among all bidders.	Structured interviews; J. T. Zhou et al. (2019); Weber et al. (2018)
Assumption 4	Transaction of the PPP project follows the market rules of "full competition and fair competition".	Structured interviews; MOF (2014); General Office of the State Council of the People's Republic of China (2023)
Assumption 5	PPP project transactions follow the principle of "low price priority", i.e., the lower the tender offer, the higher the price score in the total score (except for tender offer lower than the cost).	Structured interviews; MOF (2016)
Assumption 6	When tender offer is made in the private partner, the reservation profit rate of the works specified and unspecified in the output specifications is ≥0.	Structured interviews; S. Q. Wang and Wang (2017); ADB (2008)
Assumption 7	The results of design optimization (changes the output specifications) are shared between the public authority and the private partner.	Structured interviews; CCEA (2018); General Office of the State Council of the People's Republic of China (2023)
Assumption 8	The results of design deepening (without changing the output specifications) should be exclusively enjoyed by the private partner (except for excessive profit).	Structured interviews; CCEA (2018); General Office of the State Council of the People's Republic of China (2023)
Assumption 9	The cost of regulation of the PPP project can meet: the cost of regulation ≤ the amount of fines and confession for maximum opportunism.	Structured interviews; NDRC (2007); Hemanta (2012)
Assumption 10	The dynamic game of complete information can be used to study the interest game between the public authority and the private partner.	Huang et al. (2009); L. Li et al. (2013); H. J. Liu (2010); Meng (2019); Ni (2019); Zhao (2016)
Assumption 11	In the transaction stage, based on the output specifications from the public authority, the CS (construction cost calculated by Norm and Standard) for the PPP project can be calculated.	Professional Qualification Center of Ministry of Transport (2020); MOF (2016); MOHURD (2013)
Assumption 12	Behavioral cost of design optimization in the private partner = $\frac{1}{2}\Phi_1 d_1 x^2$, where d_1 is the enterprise's internal construction cost of the works specified in the output specifications before design optimization, Φ_1 is the behavioral cost coefficient of design optimization, and x is the rate of construction cost savings due to design optimization.	Zhang (2012); H. J. Liu (2010); M. S. Li and Meng (2018); Y. L. Wang et al. (2016); China International Engineering Consulting Corporation (2021); J. Q. Wang (2018)
Assumption 13	Behavioral cost of design deepening in the private partner = $\frac{1}{2}\Phi_2 d_2 y^2$, where d_2 is the enterprise's internal construction cost of the works unspecified in the output specifications before design	Zhang (2012); H. J. Liu (2010); M. S. Li and Meng (2018); Y. L. Wang et al. (2016); China International Engineering Consulting Corporation (2021);

NO.	Inputs for mathematical modeling method	Source/Basis
	deepening, Φ_2 is the behavioral cost coefficient of design deepening, and y is the rate of construction cost savings due to design deepening.	J. Q. Wang (2018)
Assumption 14	Behavior cost of hiding = $\Phi_3 L$, where Φ_3 is the behavioral cost coefficient of hiding in the private partner. L is the amount of hidden opportunism due to the private partner's behavior of hiding.	Y. L. Yin et al. (2014); Y. L. Wang et al. (2016); Chen et al. (2014); J. Q. Wang (2018)
Assumption 15	The behavioral cost of regulation = $-wE_1p$, where w is the behavioral cost coefficient of regulation by the public authority, $-E_1$ is the expenditure of the public authority, and p is the intensity of regulation by the public authority.	NDRC (2007); S. Q. Wang and Liu (2014); M. S. Li and Meng (2018)

Annex D: Data Analysis Tables for Unstructured Interviews

Table D.1 Open codings of unstructured interviews

Open coding (initial concept)	Reference point	Original sentence (Example)
a1 Project scale$_{c1}$	1	The larger and more complex the project, and the more difficult the entire project, then the more detailed the output specifications need to be.
a1 Project scale$_{c3}$	4	The first factor influencing the intensity of incentives is the scale of investment. For projects with relatively large investment, incentives should be linked to the proportion of technological innovation.
a1 Project scale$_{c4}$	6	The construction cost savings rate from design optimization is also somewhat affected by the scale of the project.
a2 Complexity of project	7	First, the optimal level of output specifications for the public authority is influenced by the complexity of the project, ...
a3 Understanding level of project	4	First, I think that the level of detail of the output specifications is mainly influenced by the depth of the preliminary work and the public authority's understanding of the project.
a4 Preparation time	1	The fourth influencing factor is time. If the project bidding time is tight, then the output specifications will be less detailed.
a5 Depth of preliminary work	3	The first is the depth of preliminary work. Because most domestic PPP projects start implementing the PPP pattern from the feasibility study or preliminary design stage.
a6 Understanding of technology and the site	2	The third is the public authority's understanding and mastery of current technology. When writing output specifications, the project may be in the feasibility study stage, ...
a7 Risk allocation$_{c1}$	2	Then, the second influencing factor is risk allocation, which means that if the private partner is asked to bear more risk, the output specifications should be more detailed.
a7 Risk allocation$_{c2}$	10	Risk allocation should also be considered; the more risk the private partner bears, the higher the tender offer will be.
a7 Risk allocation$_{c3}$	4	Private partner's risk is slightly higher, so I think incentives should be increased accordingly.
a8 Deviation coefficient of quantities$_{c1}$	14	Then, the larger the deviation coefficient of quantities, the more detailed the output specifications should be. That is my summary.
a8 Deviation coefficient of quantities$_{c2}$	11	There are also other factors that affect tender offer, such as the risk of deviation in the quantities of unidentified works ...
a9 Difference in behavioral cost coefficients between design optimization and design deepening	24	When the behavioral cost coefficient of technological innovation for specified works is greater than that for unspecified works, the level of detail of the output specifications will be reduced.
a10 Expected value of construction cost	1	The level of detail of the output specifications should minimize the expected construction cost for the private partner, so that it is advantageous for the public authority, and this is the direction to take.

Open coding (initial concept)	Reference point	Original sentence (Example)
a11 Difference in the construction cost savings rates between the specified and unspecified engineering content	5	When the construction cost savings rate for specified engineering content exceeds that of unspecified engineering content, the level of detail of the output specifications will be higher.
a12 Difference in maximum construction cost savings rates between design optimization and design deepening	7	When the maximum construction cost savings rate for specified engineering content exceeds that of unspecified engineering content, the level of detail of the output specifications is higher.
a13 Difference in tender profit rates between specified and unspecified engineering content	18	When the reservation profit rate for specified engineering content exceeds that for unspecified engineering content, the level of detail of the output specifications will be lower.
a14 Market competitiveness$_{c1}$	3	The third influencing factor is the degree of market competition. The greater the need of the public authority for full market competition, the more detailed the output specifications become, ...
a14 Market competitiveness$_{c2}$	10	Then the market competitiveness: if the bidders are numerous and the competition is very strong, the tender offer may be lower.
a15 Policies and regulations	4	The fifth influencing factor is policies and regulations. if policies impose more stringent requirements on output specifications, then the level of detail of output specifications may be higher.
a16 Market maturity	4	The greater the project complexity and industry maturity, the greater the optimal level of detail of output specifications becomes...
a17 Influence of level of detail of output specifications on PUPC	27	From the perspective of the public authority, the primary factor influencing PUPC is the level of detail of the output specifications. The project's investment estimation or budget estimate is calculated according to the output specifications, …
a18 Influence path of the level of detail of output specifications	15	The first path is that the original factors influence the level of detail of the output specifications and the tender offer. Subsequently, the level of detail of the output specifications and the tender offer in turn influence the PUPC.
a19 Cost forecast	1	Firstly, cost forecasting. The more accurate the cost forecast, the more reasonable the tender offer will be.
a20 Scope of cooperation for project	2	The habitat improvement project involves a more complex scope of cooperation than the sewage treatment project, and its tender offer from the private partner will be higher.
a21 Project characteristics	4	The first factor influencing the optimal tender offer is the inherent characteristics of the project itself, …
a22 Performance credit of the public authority	2	The fourth factor is performance credit of the public authority. everyone may say the principle of risk is equal to opportunity, …
a23 CS / Investment scale	22	The trend is that the higher the CS, the higher the optimal tender offer will be.

Open coding (initial concept)	Reference point	Original sentence (Example)
a24 Behavioral cost coefficient of design optimization$_{c2}$	7	The higher the discount rate of productivity level and the greater the behavioral cost of design optimization, then the higher the tender offer will be.
a24 Behavioral cost coefficient of design optimization$_{c4}$	15	The higher the behavioral cost coefficient of design optimization, the lower the optimal construction cost savings rate of design optimization.
a25 Behavioral cost coefficient of design deepening$_{c2}$	7	The higher the behavioral cost coefficient of the design deepening, the higher the optimal tender offer will be.
a25 Behavioral cost coefficient of design deepening$_{c4}$	11	Similarly, the higher the behavioral cost coefficient of design deepening, the lower the optimal construction cost savings rate of design deepening.
a26 Construction cost savings rate of specified engineering content / Construction cost savings rate of design optimization$_{c2}$	5	The cost savings rate from design optimization and design deepening by the private partner significantly impacts the tender offer of the overall project...
a26 Construction cost savings rate of specified engineering content / Construction cost savings rate of design optimization$_{c3}$	7	The greater the construction cost savings rate, the stronger the intensity of incentives for the public authority should be.
a27 Construction cost savings rate of unspecified engineering content/ Construction cost savings rate of design deepening	4	If the construction cost savings rate for design deepening increases, the optimal tender offer will decrease.
a28 Tender profit rate of the specified engineering content in the output specifications	9	The higher the tender profit rate for the content specified in the output specifications, the higher the optimal tender offer will be.
a29 Tender profit rate of the unspecified	8	The higher the tender profit rate of the unspecified content in the output specifications, the higher the optimal tender offer will be.

Open coding (initial concept)	Reference point	Original sentence (Example)
engineering content in the output specifications		
a30 Project return rate/ Internal rate of return / Expected return	5	The factors influencing the optimal tender offer are, firstly, the characteristics of the project itself, and secondly, the return rate of the project.
a31 Technological and management capability of the private partner	8	The primary factor influencing tender offer is the technological advancement or the management excellence within the private partner, which form the foundation for the optimal tender offer.
a32 Discount rate for productivity level in the private partner	17	The productivity level may be the most fundamental factor, as higher productivity level in the private partner leads to lower construction cost and, consequently, lower tender offer.
a33 Influence of tender offer on PUPC	27	Secondly, the lower the tender offer, the lower the PUPC, …
a34 Influence path of tender offer	16	The first pathway: certain factors influence the level of detail of the output specifications and the tender offer, which in turn influence the PUPC.
a35 Potential return	2	One is the potential return. if there is a significant reduction in the cost or an increase in the efficiency, then the intensity of the incentives from the public authority will be increased.
a36 Tender profit rate	19	The factors influencing optimal intensity of incentives are…, also the tender profit rate for specified engineering content in the output specifications.
a37 Risk preference	1	The fourth influencing factor is risk preference. When the public authority is risk-averse…, the public authority may reduce the intensity of incentives.
a38 Technological progress / Technological maturity$_{c3}$	4	The fifth influencing factor is technological progress. As current BIM technology, digital technology, and AI technology have reduced the cost of technological innovation, the public authority will correspondingly lower the intensity of incentives.
a38 Technological progress / Technological maturity$_{c4}$	1	The greater the maturity of innovation technologies, the higher the construction cost savings rate; they are positively correlated.
a39 Timeliness of fiscal fund payment	1	A prepayment system for fiscal funds has been established. The higher the prepayment rate, …, the shorter the time required to recoup investments, …, and the lower intensity of incentives may become.
a40 Behavioral cost coefficient of technological innovation$_{c3}$	26	The higher the management level or the greater the experience in the private partner, the lower the behavioral cost coefficient of technological innovation, and the less intensity of incentives required.
a40 Behavioral cost coefficient of	15	The second factor is the behavioral cost of technological innovation itself. Some behavioral cost is high, some may not be particularly

Open coding (initial concept)	Reference point	Original sentence (Example)
technological innovation$_{c4}$		high, and some technological innovations may be quite simple.
a41 Political factors or project's political sensitivity	4	The factors influencing the optimal intensity of incentives in the public authority are numerous. The first one is political factors.
a42 Difficulty in implementing policy	2	Then, the third influencing factor is the difficulty in implementing policy, …
a43 Identification of design optimization	6	Secondly, how to identify design optimization is crucial.
a44 Influence of intensity of incentives on PUPC	28	Second, the intensity of incentives has an impact on PUPC. Generally speaking, the optimal intensity of incentives aims to minimize the PUPC.
a45 Influence path of intensity of incentives	18	The second pathway is that the original factors influence the intermediate variables (i.e., intensity of incentives and technological innovation), which in turn ultimately transmit to the PUPC.
a46 Private partner's ability for technological innovation	7	The construction cost savings rate, I think, is mainly influenced by the professional and technical level of the private partner…
a47 Familiarity of technical strength with innovation / Project experience	1	When the private partner has previously undertaken similar projects, or the technical personnel are very familiar with such projects, or there is a reserve of technical strength, then the construction cost savings rate will be high.
a48 Standardization of corporate internal management	2	The more standardized the internal management of the enterprise, the higher the construction cost savings rate for the private partner, …
a49 Market competitiveness	3	The third influencing factor is market competitiveness. In competitive markets, the private partner can explore construction cost savings through design optimization.
a50 Return mechanism of project	2	I believe the optimal construction cost savings rate is somewhat related to the return mechanism.
a51 Intensity of incentives	4	The greater the intensity of incentives, the more inclined the private partner becomes to adopt strategies that enhance the construction cost savings rate (x and y values).
a52 Strategic expectation for long-term cooperation	1	The fourth influencing factor is the private partner's strategic expectations for long-term cooperation...
a53 Efficiency boundary of design optimization	5	In other words, there exists a critical cost for the construction cost savings rate from design optimization. If it reaches this critical cost, the input-output ratio may become unsuitable.
a54 Limitation of	2	Due to various external conditions, the optimal construction cost

Open coding (initial concept)	Reference point	Original sentence (Example)
external conditions		savings rate will inevitably be capped at a maximum level.
a55 Influence of technological innovation on PUPC	15	I believe that the construction cost savings rate from technological innovation (including design deepening and design optimization) is negatively correlated with PUPC...
a56 Influence path of technological innovation	14	The second path is that many factors influence the intensity of incentives in the public authority and the technological innovation strategies of the private partner, which in turn influence the PUPC.
a57 Regulation cost	5	If the investment of regulation cost becomes excessive, then the intensity of regulation will decrease.
a58 Regulatory scope and responsibilities under contract	3	I believe that the more detailed the scope and content of regulation stipulated in the PPP contract, the stronger the intensity of regulation will be.
a59 Inspection intensity by superior authorities	3	The passive factor influencing the intensity of regulation is the inspection intensity of the superior administrative department. The public authority will determine the intensity of regulation for the PPP project based on this.
a60 Standardization of management / Compliance risk	4	The intensity of regulation is related to the standardization of management in the private partner. Standardization of management is self-supervision within the private partner.
a61 Risk structure of contract	1	The first is risk allocation and transaction structure. For such significant risks, if the top-level design is sufficiently robust…
a62 Project characteristics / Project scale	1	The factors influencing the intensity of regulation also include the characteristics and scale of the project.
a63 Social attention	2	The factors positively correlated with optimal intensity of regulation are as follows: Firstly, the sensitivity of public interests. The higher the sensitivity, the stronger the intensity of regulation may need to be.
a64 Proportion of hiding	10	That is to say, the greater the amount of opportunism in the private partner and the greater the proportion of hiding, then the stronger the intensity of regulation.
a65 Maximum proportion of hiding opportunism	3	I believe the first factor is the maximum proportion of hiding in the private partner. The higher the maximum proportion of hidden opportunism in the private partner, the stronger the optimal intensity of regulation in the public authority.
a66 Behavioral cost coefficient of hiding$_{c5}$	19	The first factor is the behavior cost of hiding. The lower the behavior cost of hiding, the greater the intensity of regulation will inevitably be.
a66 Behavioral cost coefficient of hiding$_{c6}$	3	The second influencing factor is the behavior cost of hiding. The higher the behavior cost of hiding, the lower the opportunistic willingness of the private partner will definitely be.
a67 Severity of punishment / Intensity of punishment / Punishment	21	Then, there is the severity of punishment; that is to say, the greater the severity of punishment, the lower the intensity of regulation may be.

Open coding (initial concept)	**Reference point**	**Original sentence (Example)**
coefficient$_{c5}$		
a67 Severity of punishment / Intensity of punishment / Punishment coefficient$_{c6}$	24	Thirdly, the severity of punishment is also to be considered for the private partner.
a68 Influence of intensity of regulation on PUPC	25	The intensity of regulation from the public authority has a significant impact on PUPC…
a69 Influence path of intensity of regulation	14	The third path is that some factors influence the intensity of regulation and the amount of opportunism, which in turn influence PUPC.
a70 Profitable return / Expected return / Potential return of opportunism	7	Firstly, its influencing factors are profitable. For the private partner, the obtainable benefits are important…
a71 Intensity of regulation	16	When the intensity of regulation decreases, opportunism in the private partner will certainly increase; that is to say, the strategy of opportunism in the private partner is closely related to the intensity of regulation.
a72 Trends in regulation	4	The influencing factors of opportunism strategies are, first of all, the degree of grasp of regulation policy trends, and...
a73 Deficiency in public authority's regulatory capacity	1	If the regulation capacity is weak, it may create opportunities for opportunism in the private partner.
a74 Corporate credibility	1	The greater the positive incentives are given to the private partner, the fewer negative behaviors there will be from the private partner.
a75 Moral hazard propensity	1	The private partner contemplates how to obtain the same profit through legitimate means.
a76 Influence of opportunism on PUPC	31	The degree of opportunism (or the amount of opportunism) may be positively correlated with PUPC.
a77 Influence path of opportunism	28	The third pathway is that some factors influence the intensity of regulation and the amount of opportunism, which in turn influence PUPC.

Table D.2 Open codings and the number of their reference points

Open Coding	RP	Open Coding	RP	Open Coding	RP	Open Coding	RP
a1 Project scale (c1/c3/c4)	1+4+6	a21 Project characteristics	4	a41 Political factors or project's political sensitivity	4	a61 Risk structure of contract	1
a2 Complexity of project	7	a22 Performance credit of the public authority	2	a42 Difficulty in implementing policy	2	a62 Project characteristics / Project scale	1

Open Coding	RP	Open Coding	RP	Open Coding	RP	Open Coding	RP
a3 Understanding level of project	4	a23 CS / Investment scale	22	a43 Identification of design optimization	6	a63 Social attention	2
a4 Preparation time	1	a24 Behavioral cost coefficient of design optimization (c2/c4)	7+15	a44 Influence of intensity of incentives on PUPC	28	a64 Proportion of hiding	10
a5 Depth of preliminary work	3	a25 Behavioral cost coefficient of design deepening (c2/c4)	7+11	a45 Influence path of intensity of incentives	18	a65 Maximum proportion of hiding opportunism	3
a6 Understanding of technology and the site	2	a26 Construction cost savings rate of specified engineering content / Construction cost savings rate of design optimization (c2/c3)	5+7	a46 Private partner's ability for technological innovation	7	a66 Behavioral cost coefficient of hiding (c5/ c6)	19+3
a7 Risk allocation (c1/c2/c3)	2+10+4	a27 Construction cost savings rate of unspecified engineering content/ Construction cost savings rate of design deepening	4	a47 Familiarity of technical strength with innovation / Project experience	1	a67 Severity of punishment / Intensity of punishment / Punishment coefficient (c5/c6)	21+24
a8 Deviation coefficient of quantities (c1/c2)	14+11	a28 Tender profit rate of the specified engineering content in the output specifications	9	a48 Standardization of corporate internal management	2	a68 Influence of intensity of regulation on PUPC	25
a9 Difference in behavioral cost coefficients between design optimization and design deepening	24	a29 Tender profit rate of the unspecified engineering content in the output specifications	8	a49 Market competitiveness	3	a69 Influence path of intensity of regulation	14
a10 Expected value of construction cost	1	a30 Project return rate/ Internal rate of return / Expected return	5	a50 Return mechanism of project	2	a70 Profitable return / Expected return / Potential return of opportunism	7
a11 Difference in the construction cost	5	a31 Technological and management capability of the	8	a51 Intensity of incentives	4	a71 Intensity of regulation	16

Open Coding	RP	Open Coding	RP	Open Coding	RP	Open Coding	RP
savings rates between the specified and unspecified engineering content		private partner					
a12 Difference in maximum construction cost savings rates between design optimization and design deepening	7	a32 Discount rate for productivity level in the private partner	17	a52 Strategic expectation for long-term cooperation	1	a72 Trends in regulation	4
a13 Difference in tender profit rates between specified and unspecified engineering content	18	a33 Influence of tender offer on PUPC	27	a53 Efficiency boundary of design optimization	5	a73 Deficiency in public authority's regulatory capacity	1
a14 Market competitiveness (c1/c2)	3+10	a34 Influence path of tender offer	16	a54 Limitation of external conditions	2	a74 Corporate credibility	1
a15 Policies and regulations	4	a35 Potential return	2	a55 Influence of technological innovation on PUPC	15	a75 Moral hazard propensity	1
a16 Market maturity	4	a36 Tender profit rate	19	a56 Influence path of technological innovation	14	a76 Influence of opportunism on PUPC	31
a17 Influence of level of detail of output specifications on PUPC	27	a37 Risk preference	1	a57 Regulation cost	5	a77 Influence path of opportunism	28
a18 Influence path of the level of detail of output specifications	15	a38 Technological progress / Technological maturity (c3/c4)	4+1	a58 Regulatory scope and responsibilities under contract	3		
a19 Cost forecast	1	a39 Timeliness of fiscal fund payment	1	a59 Inspection intensity by superior authorities	3		
a20 Scope of cooperation for project	2	a40 Behavioral cost coefficient of technological innovation (c3/c4)	26+15	a60 Standardization of management / Compliance risk	4		

Table D.3 Correlation statistics among subcategory, axial coding, and selective coding

Axial coding and subcategories	**Interviewee A1**	**Interviewee B1**	**Interviewee A2**	**…**	**Number of people 1**	**Mainstream view**	**Number of people 2**	**n1**	**n2**
Note: The total number of interviewees was 22. "Number of people 1" refers to the number of people after excluding those who did not express an opinion; "Number of people 2" refers to the number of people who held the mainstream view. n1 refers to the number of people holding mainstream views divided by the total number of interviewees; n2 refers to the number of people who hold mainstream views divided by the number of interviewees after excluding those who have not expressed their opinions ((i.e., those marked as "blank"). The contents in ( ) in this table are the quantitative indicators corresponding to the subcategories; the contents in [ ] are explanations.									
c1 Optimal level of detail of output specifications									
b01 Project characteristics and preparation (eigenvalue) [The larger the scale, the more complex the project, the deeper the understanding, the longer the preparation time, the more thorough the preliminary work, and the more familiar with the site, then the larger the b01]	+	N	+	…	9	+	5	0.227	0.556
b02 Risk allocation principles (Risk borne by the private partner) [The greater the risk borne by the private partner and the greater the deviation coefficient of quantities, then the greater b02]	+		+	…	13	+	12	0.545	0.923
b03 Difference in the behavioral cost coefficient (the former/the latter)		-	-	…	16	-	15	0.682	0.938
b04 Difference in construction cost savings rate (the former/the latter)	N	+	+	…	13	+	12	0.545	0.923
b05 Difference in profit rate (the former/the latter)		-		…	15	-	15	0.682	1.000
b06 Market and industry factors (Intensity or maturity) [The more intense the competition, the clearer the regulations, and the more mature the market, then the greater the b06]	+			…	6	+	5	0.227	0.833
b07 Storyline of the level of detail of output specifications	N	N	N	…	20	N	18	0.818	0.900
c2 Optimal tender offer									

Axial coding and subcategories	Interviewee A1	Interviewee B1	Interviewee A2	…	Number of people 1	Mainstream view	Number of people 2	n1	n2
b08 Project CS [The higher the cost, the more complex the project, the poorer the credit, and the larger the scale, then the higher the b08]	+	+	N	···	21	+	20	0.909	0.952
b09 Behavioral cost coefficient of technological innovation$_{c2}$ [The larger the behavioral cost coefficient, the higher b09]				···	9	+	9	0.409	1.000
b10 Construction cost savings rate		-		···	8	-	7	0.318	0.875
b11 Risk quotation coefficient (Risk borne by the private partner) [The greater the risk and the deviation coefficient of quantities, then the greater the b11]		+	+	···	16	+	15	0.682	0.938
b12 Reservation profit rate [The milder the competition and the higher the profit rate, then the higher the b12]	+		+	···	19	+	18	0.818	0.947
b13 Productivity level [The stronger the technical or management capabilities, the lower the discount rate, then the higher the b13]	N	-	-	···	20	-	17	0.773	0.850
b14 Storyline of tender offer	N	+	+	···	21	+	20	0.909	0.952
c3 Optimal intensity of incentives									
b15 Profit rate driven (Reservation profit rate) [The higher the profit rate, the higher the b15]	+	N	+	···	18	+	17	0.773	0.944
b16 Risk premium [The higher the risk, the more risk averse, the less familiar with the technology, and the more delayed the payoff, then the greater the b16]	+			···	6	+	5	0.227	0.833
b09 Behavioral cost coefficient of technological innovation$_{c3}$ [The higher the behavioral cost and the lower the construction cost savings rate, then the greater the	+	N	-	···	21	+	17	0.773	0.810

Axial coding and subcategories	Interviewee A1	Interviewee B1	Interviewee A2	…	Number of people 1	Mainstream view	Number of people 2	n1	n2
b09]									
b17 Project characteristic constraints (Public interest) [The higher the political sensitivity, the larger the scale, then the larger the b17]				…	4	+	2	0.091	0.500
b18 Implementation conditions of policy (Condition value) [The lower the difficulty in implementing policy, the easier the determination, then the larger the b18]		N		…	4	+	2	0.091	0.500
b19 Storyline of intensity of incentives	N	Min	Min	…	22	Min	20	0.909	0.909
c4 Optimal technological innovation strategy									
b20 Corporate capability (Capability Value) [The higher the capability, the more experience, the more familiar with the project, the more standardized the management, and the stronger the competitiveness, then the larger the b20]	+			…	5	+	4	0.182	0.800
b09 Behavioral cost coefficient of technological innovation$_{c4}$ [The higher the behavioral cost, the greater b09]	-	-	N	…	19	-	17	0.773	0.895
b21 Incentives and benefit (Benefits to the private partner) [The stronger the incentives, the larger the scale, the higher the returns, the better the strategic expectations, and the higher the marginal efficiency, then the greater b21 will be]		N	N	…	10	+	7	0.318	0.700
b22 External conditions (External space value) [The more mature the technology and the larger the external space, then the larger the b22]	+			…	13	+	11	0.500	0.846
b23 Technological innovation storyline	N	-	-	…	22	-	19	0.864	0.864
c5 Optimal intensity of regulation									
b24 Regulatory mechanism and sensitivity (Demand for regulation)	+		+	…	11	+	11	0.500	1.000

Axial coding and subcategories	**Interviewee A1**	**Interviewee B1**	**Interviewee A2**	**…**	**Number of people 1**	**Mainstream view**	**Number of people 2**	**n1**	**n2**
[The lower the cost of regulation, the broader its scope, the greater the responsibility, the stricter the supervision by higher authorities, the greater the risk, the larger the scale, and the higher the level of attention, then the greater the b24]									
b25 Proportion of hiding [The greater the proportion of hiding, the larger space of hiding, then the higher the b25]	+	+		…	12	+	11	0.500	0.917
b26 Behavior cost coefficient of hiding	-	-	-	…	16	-	16	0.727	1.000
b27 Punishment coefficient$_{c5}$	-	-	-	…	19	-	19	0.864	1.000
b28 Storyline of intensity of regulation	N	Min	Min	…	22	Min	20	0.909	0.909
c6 Optimal opportunism strategy									
b29 Expected net benefit [The higher the revenue and the lower the cost of hiding, then the higher the b29]	+	N	+	…	9	+	8	0.364	0.889
b30 Intensity of regulation [The higher the regulation intensity, the more random the regulation trends, and the stronger the regulatory capacity, then the higher the b30]	-	N	-	…	22	-	21	0.955	0.955
b27 Punishment coefficient$_{c6}$ [The stronger the punishment, the greater the b27]	-	N	-	…	22	-	21	0.955	0.955
b31 Preference for corporate credibility [The better the reputation and the higher the moral standards, then the higher the b31]			-	…	2	-	2	0.091	1.000
b32 Opportunism storyline	N	0	0	…	22	0	16	0.727	0.727

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Annex E: Find the Solutions of the Subgame Perfect Nash Equilibrium

This thesis adopts the backward induction to solve the optimal solution of complete information dynamic game, with reference to the method of solving Stackelberg Model (Zhang, 2012). The order of solving with backward induction is as follows: Stage III-2 (opportunism) → Stage III-1 (intensity of regulation) → Stage II-2 (technological innovation) → Stage II-1 (intensity of incentives) → Stage I-3 (winning the bid) → Stage I-2 (tender offer) → Stage I-1 (level of detail of output specifications).

E.1 Stage III-2 of the game: finding the optimal solution of private partner's opportunism (t^*, e^*)

E.1.1 The mathematical expression for decision-making on *t*

In stage III-2, the strategies [h, (α, β), k, (x, y), p] of the predecessors of opportunism are known, and the optimal solution of the opportunism (t, e) of the private partner needs to be solved. According to (5.11), under the condition of private partner's profit maximization, the mathematical expression for finding the optimal solution of (t, e) is as follows:

$\max_{t,e} F_3'$ =(1-x+kx)α+β-θ(1-x)hC-θδ(1-y)(1-h)C- $\frac{1}{2}$ Φ_1θhCx^2- $\frac{1}{2}$ Φ_2θδ(1-h)Cy^2+(em+e-pm-p+1-eΦ_3)t

Satisfying the above expression can also satisfy the participation constraint and incentive compatibility constraint for the private partner (agent). The specific reasons for this are as follows:

1. Participation constraint (IR). The participation constraint for the agent is that the expected utility of participating in the action is greater than the reservation utility of not participating in the action. When $F_3'|_{t=0} \geq F_3'|_{t>0}$, the private partner does not practice opportunism, i.e., the strategy for t is t=0. When $F_3'|_{t=0} < F_3'|_{t>0}$, the private partner practices opportunism, i.e., the strategy for t is t>0. Thus, the private partner's participation constraint is the value of t when $\max_{t,e} F_3'$.

2. Incentive compatibility constraint (IC). The incentive compatibility constraint is that the agent chooses the action strategy that maximizes its own expected utility among several action strategies, and, this action strategy is the one that the principal (the public authority) wants.

The predecessor of opportunism (t, e) is regulation intensity (p). According to the characteristics of dynamic game of complete information, p can satisfy $\max_{p} E_3$. The agent chooses (t, e) according to the given p and $\max_{t,e} F_3'$. Thus, if (t, e) satisfies $\max_{t,e} F_3'$ and $\max_{p} E_3$, it can satisfy the incentive compatibility constraint.

The same is true for the latter propositions, which will not be repeated.

E.1.2 Solving for t^*

According to (5.9), the following can be obtained:

$F_3'=F_2'+(em+e-pm-p+1-e\Phi_3)t$

From the above equation, when $em+e-pm-p+1-e\Phi_3<0$ (i.e.: $e<\frac{p(1+m)-1}{1+m-\Phi_3}$), the smaller t is, the larger F_3' is. Since $t\geq 0$, $t^*=0$.

When $em+e-pm-p+1-e\Phi_3=0$ (i.e.: $e=\frac{p(1+m)-1}{1+m-\Phi_3}$), the change in t has no effect on F_3'. Since $t\geq 0$, $t^*=0$.

When $em+e-pm-p+1-e\Phi_3>0$ (i.e.: $e>\frac{p(1+m)-1}{1+m-\Phi_3}$), the larger t is, the larger F_3' is. Since $t\leq t_0$, $t^*=t_0$.

E.1.3 Solving for e^*

According to the definition of Φ_3, it can be known that $0\leq\Phi_3\leq 1$, so, $m+1-\Phi_3\geq 0$ is constant. According to (5.9), the following can be obtained:

$\max_{e} F_3' = F_2' + (1-pm-p)t+(m+1-\Phi_3)te$

Combined with the analysis in Section E.1.2, the function graph of e-F_3' can be drawn (See Figure E.1):

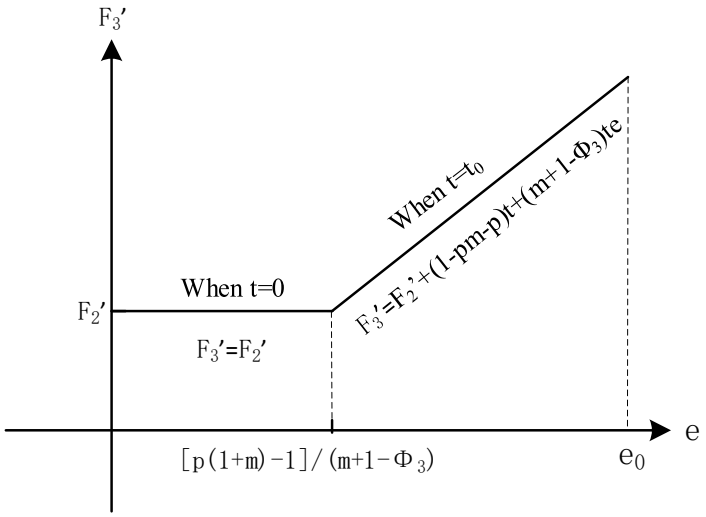


Figure E.1 Function graph of e-F_3'

The maximum value of e is e_0, and whether $e=e_0$ lies on the left or the right of $e=\frac{p(1+m)-1}{1+m-\Phi_3}$ influences the maximum value of F_3'.

Figure E-1 shows that:

When $e=e_0$ lies on the left of $e=\frac{p(1+m)-1}{1+m-\Phi_3}$, i.e.: $e_0\leq\frac{p(1+m)-1}{1+m-\Phi_3}$, then $e^*=0$.

When $e=e_0$ lies on the right of $e=\frac{p(1+m)-1}{1+m-\Phi_3}$, i.e.: $e_0>\frac{p(1+m)-1}{1+m-\Phi_3}$, then $e^*=e_0$.

So:

When $e_0\leq\frac{p(1+m)-1}{1+m-\Phi_3}$, i.e.: $p\geq e_0+\frac{1-e_0\Phi_3}{m+1}$, then $e^*=0$, according to Section E.1.2, it further follows that $t^*=0$.

When $e_0>\frac{p(1+m)-1}{1+m-\Phi_3}$, i.e.: $p<e_0+\frac{1-e_0\Phi_3}{m+1}$, then $e^*=e_0$, according to Section E.1.2, it further follows that $t^*=t_0$.

E.1.4 Summary of (t^*, e^*) - Proposition 1

According to the characteristics of the dynamic game of complete information, the parameters γ_1, γ_2, w, m, Φ_1, Φ_2, Φ_3, θ, δ, C, x_0, y_0, t_0, and e_0 are known. In this thesis, these parameters are referred to as "characteristic parameters".

Based on the above analysis, Proposition 1 can be obtained.

Proposition 1: The strategies [h, (α, β), k, (x, y), p] of the predecessors of opportunism are known. The characteristic parameters are known. Then the optimal solution of the private partner's opportunism (t, e) is:

$$\begin{cases} t^* = 0;\ e^* = 0, & if\ p \geq e_0 + \dfrac{1 - e_0\Phi_3}{m+1} \quad \text{(E.1)} \\ t^* = t_0;\ e^* = e_0, & if\ p < e_0 + \dfrac{1 - e_0\Phi_3}{m+1} \quad \text{(E.2)} \end{cases}$$

E.2 Stage III-1 of the game: finding the optimal solution of public authority's regulation intensity (p^*)

E.2.1 The mathematical expression for decision-making on *p*

In stage III-1, the strategies [h, (α, β), k, x] of the predecessors of regulation intensity are known, and the forecasted strategy [(t^*, e^*)] of its successor is given in Proposition 1. The optimal solution of the regulation intensity (p) of the public authority needs to be solved. According to (5.12), under the condition of the public authority's payoff maximization, the mathematical expression for finding the optimal solution of p is as follows:

$\max_p E_3$=-(1-x+kx)α-β-wp(α+β)+(pm+p-em-e-1)t

E.2.2 Payoff function for the public authority and users (E_3)

E_3=-(1-x+kx)α-β-wp(α+β)+(pm+p-em-e-1)t

=E_2+wpE_1+(pm+p-em-e-1)t

When p≥e_0+$\frac{1-e_0\Phi_3}{m+1}$, the private partner does not practice opportunism (t^*=0; e^*=0), and the payoff function of the public authority and users is:

$$E_3=E_2+wE_1p \quad \text{(E.3)}$$

When p<e_0+$\frac{1-e_0\Phi_3}{m+1}$, the private partner practices opportunism (t^*=t_0; e^*=e_0), and the payoff function of the public authority and users is:

$$E_3=E_2+(wE_1+mt_0+t_0)p-(e_0m+e_0+1)t_0 \quad \text{(E.4)}$$

Both E_2 and E_1 are negative and known. w is the coefficient of regulation cost, which is positive.

E.2.3 First case (solve for p^*)

The first case: When wE_1+mt_0+t_0≥0, solve for p^*, i.e., solve for $\max_p E_3$.

In the most cases, -wE_1≤mt_0+t_0 is valid, therefore, the case of "wE_1+mt_0+t_0≥0" is the focus

of this thesis.

According to $wE_1+mt_0+t_0\geq 0$, (E.3) and (E.4), the function graph of p-E_3 is as follows (See Figure E.2):

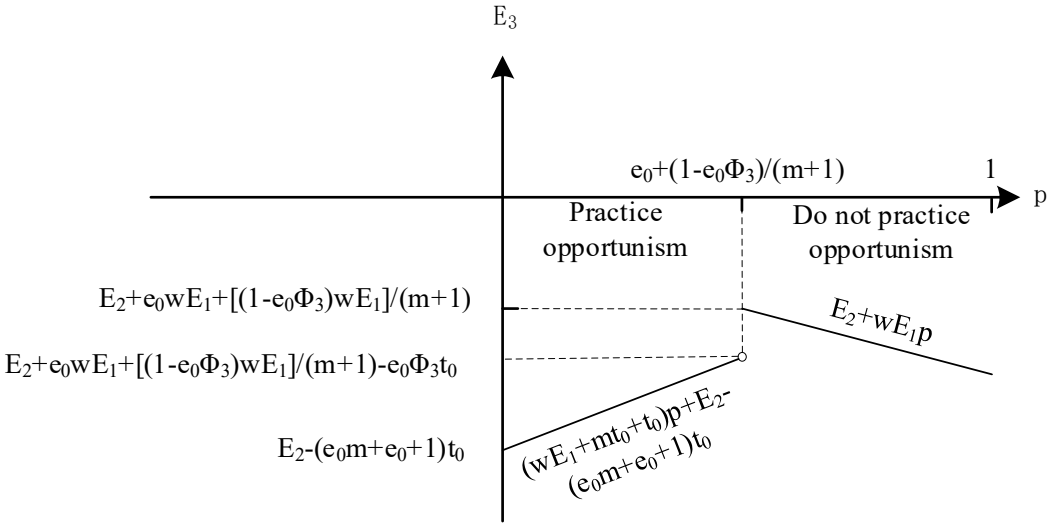


Figure E.2 Function graph of p-E3

The maximum value of p is 1, and whether p=1 lies on the left or the right of $p=e_0+\frac{1-e_0\Phi_3}{m+1}$ influences the maximum value of E_3.

On the p-axis, when p=1 lies to the left of $p=e_0+\frac{1-e_0\Phi_3}{m+1}$, i.e.: $e_0+\frac{1-e_0\Phi_3}{m+1}>1$, it follows that: $m<\frac{e_0(1-\Phi_3)}{1-e_0}$. Similarly, when p=1 lies to the right of $p=e_0+\frac{1-e_0\Phi_3}{m+1}$, it follows that: $m\geq\frac{e_0(1-\Phi_3)}{1-e_0}$.

1. When $m<\frac{e_0(1-\Phi_3)}{1-e_0}$

Observing Figure E.2, the optimal solution of the public authority's regulation intensity (p) is as follows. Substituting the value of p^* into (E.1) and (E.2) yields t^* and e^*:

When $m<\frac{e_0(1-\Phi_3)}{1-e_0}$, then $p^*=1$. It further follows that:

$$t^*=t_0;\quad e^*=e_0 \tag{E.5}$$

2. When $m\geq\frac{e_0(1-\Phi_3)}{1-e_0}$

Observing Figure E.2, the optimal solution of the public authority's regulation intensity (p) is as follows. Substituting the value of p^* into (E.1) and (E.2) yields t^* and e^*:

When $m\geq\frac{e_0(1-\Phi_3)}{1-e_0}$, then $p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$. It further follows that:

$$t^*=0;\ e^*=0 \tag{E.6}$$

E.2.4 Second case (solve for p^*)

The second case: When $wE_1+mt_0+t_0<0$, solve for p^*, i.e., solve for $\max_p E_3$.

According to $wE_1+mt_0+t_0<0$, redraw the function graph of p-E_3 as follows.

The following compares the magnitude of E_3 at points A and B. When $E_{3(A)} \le E_{3(B)}$, i.e.: $E_2-(e_0m+e_0+1)t_0 \le E_2+e_0wE_1+[(1-e_0\Phi_3)wE_1]/(m+1)$, which further follows:

$$-wE_1 \le \frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$$

Similarly, when $E_{3(A)}>E_{3(B)}$, then: $-wE_1 > \frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$

1. When $mt_0+t_0<-wE_1 \le \frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$

In this case, $E_{3(A)} \le E_{3(B)}$, the function graph is shown in Figure E.3.

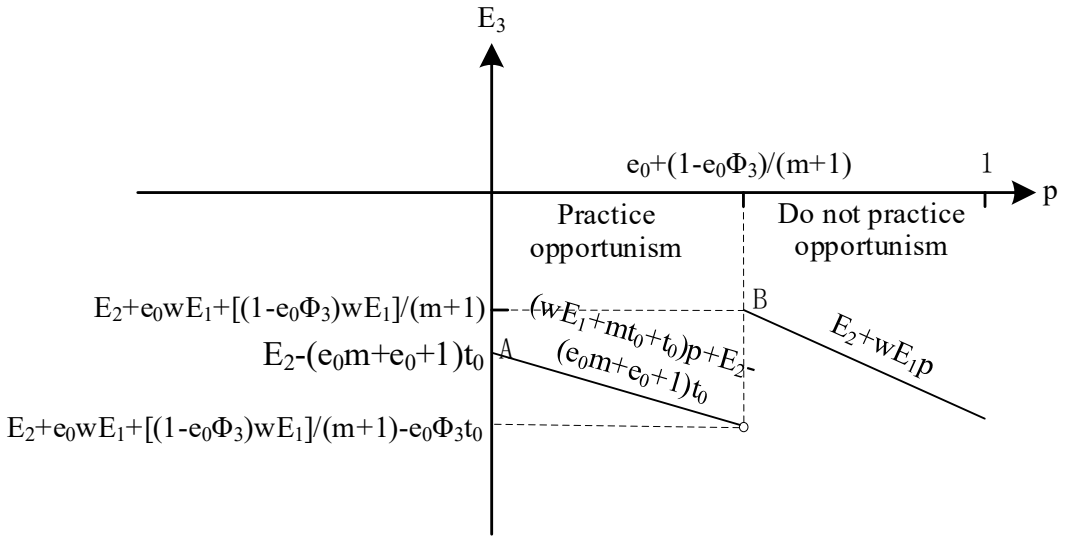


Figure E.3 Function graph of p-E3

1) On the p-axis, when p=1 lies to the left of $p=e_0+\frac{1-e_0\Phi_3}{m+1}$, i.e.: $e_0+\frac{1-e_0\Phi_3}{m+1}>1$, it further follows that: $m<\frac{e_0(1-\Phi_3)}{1-e_0}$.

Observing Figure E.3, the optimal solution of the public authority's regulation intensity (p) is as follows. Substituting the value of p^* into (E.1) and (E.2) yields t^* and e^*:

When $mt_0+t_0<-wE_1 \le \frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$ and $m<\frac{e_0(1-\Phi_3)}{1-e_0}$, then:

$$p^*=0;\ t^*=t_0;\ e^*=e_0 \qquad (E.7)$$

2) On the p-axis, when p=1 lies to the right of $p=e_0+\frac{1-e_0\Phi_3}{m+1}$, it follows that: $m \ge \frac{e_0(1-\Phi_3)}{1-e_0}$.

Observing Figure E.3, the optimal solution of the public authority's regulation intensity (p)

is as follows. Substituting the value of p^* into (E.1) and (E.2) yields t^* and e^*:

$$\text{When } mt_0+t_0<-wE_1\leq\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)} \text{ and } m\geq\frac{e_0(1-\Phi_3)}{1-e_0}, \text{ then}$$
$$p^*=e_0+\frac{1-e_0\Phi_3}{m+1};\ t^*=0;\ e^*=0 \tag{E.8}$$

2. When $-wE_1>\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$

Note: $\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}\geq(m+1)t_0$ is constant.

In this case, $E_{3(A)}>E_{3(B)}$, the function graph is shown in Figure E.4.

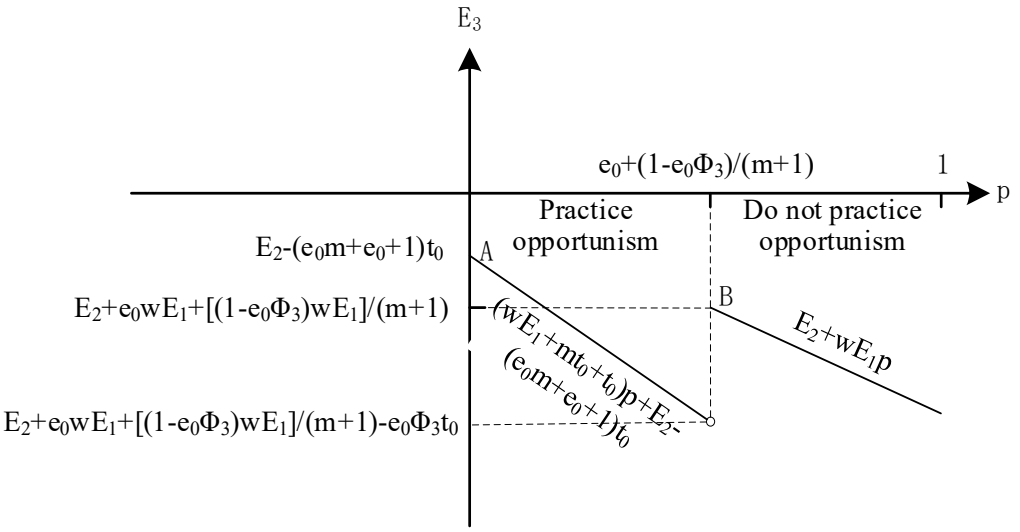


Figure E.4 Function graph of p-E3

Observing Figure E.4, the optimal solution of the public authority's regulation intensity (p) is as follows. Substituting the value of p^* into (E.1) and (E.2) yields t^* and e^*:

$$\text{When } -wE_1>\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}, \text{ then } p^*=0;\ t^*=t_0;\ e^*=e_0 \tag{E.9}$$

Note: Whether p=1 lies to the left or right of $p=e_0+\frac{1-e_0\Phi_3}{m+1}$, the above conclusion holds.

E.2.5 Values of p^*

Summarizing (E.5), (E.6), (E.7), (E.8), and (E.9) yields p^*, t^*, and e^*, as shown in Table E.1.

Table E.1 Results for p^*, t^* and e*

Pre-conditions	Equilibrium solution	Serial number
1. $-wE_1\leq mt_0+t_0$ When $-wE_1\leq mt_0+t_0$ and $m<\frac{e_0(1-\Phi_3)}{1-e_0}$	$p^*=1;\ t^*=t_0;\ e^*=e_0$	(E.5)
When $-wE_1\leq mt_0+t_0$ and $m\geq\frac{e_0(1-\Phi_3)}{1-e_0}$	$p^*=e_0+\frac{1-e_0\Phi_3}{m+1};\ t^*=0;\ e^*=0$	(E.6)
2. $-wE_1>mt_0+t_0$		

Pre-conditions	Equilibrium solution	Serial number
When $mt_0+t_0<-wE_1\leq\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$ and $m<\frac{e_0(1-\Phi_3)}{1-e_0}$	$p^*=0$; $t^*=t_0$; $e^*=e_0$	(E.7) rarely seen
When $mt_0+t_0<-wE_1\leq\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$ and $m\geq\frac{e_0(1-\Phi_3)}{1-e_0}$	$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $t^*=0$; $e^*=0$	(E.8) rarely seen
When $-wE_1>\frac{(e_0m+e_0+1)(m+1)t_0}{(e_0m+e_0+1-e_0\Phi_3)}$	$p^*=0$; $t^*=t_0$; $e^*=e_0$	(E.9) rarely seen

E.2.6 Effect of m on p^*

According to Assumption 9, the cost of regulation is ≤ the confiscation of opportunism + fines, so the case of "$-wE_1>mt_0+t_0$" is not discussed further. (E.7), (E.8), and (E.9) are not options for optimal solution.

The following only discusses the case of "$-wE_1\leq mt_0+t_0$".

1. When $m<\frac{e_0(1-\Phi_3)}{1-e_0}$, According to (E.5), $e_0+\frac{1-e_0\Phi_3}{m+1}>p^*=1$. Substituting (E.5) into (E.4) yields:

$E_3=E_2+(wE_1+mt_0+t_0)p-(e_0m+e_0+1)t_0=E_2+wE_1+(1-e_0)t_0m-e_0t_0$

2. When $m\geq\frac{e_0(1-\Phi_3)}{1-e_0}$, then $p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$. Substituting (E.6) into (E.3) yields:

$E_3=E_2+wE_1p=E_2+wE_1(e_0+\frac{1-e_0\Phi_3}{m+1})$

In summary, the graph of the m-E_3 function is shown in Figure E.5.

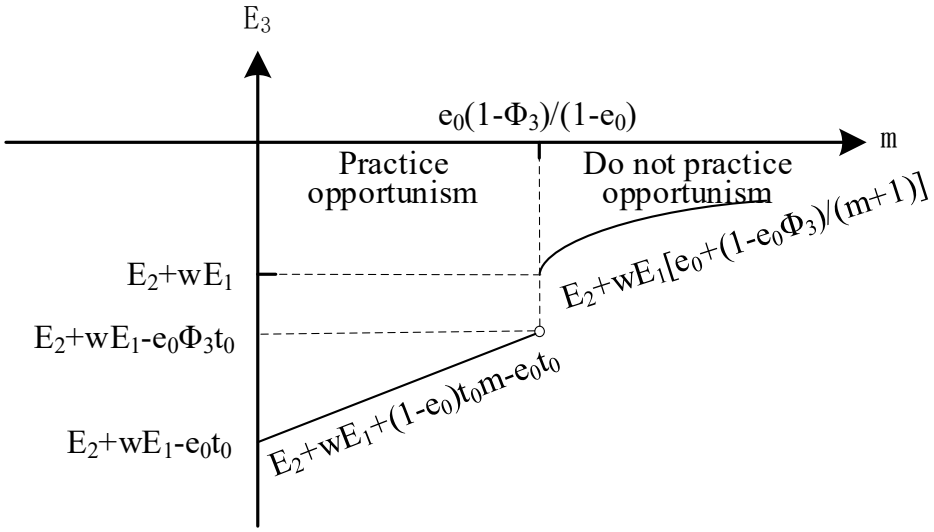


Figure E.5 Function graph of m-E3

Observing Figure E.5, the public authority can inhibit the private partner's opportunism

and enhance its own revenue by setting a suitable value of m. When $-wE_1 \leq mt_0+t_0$, the public authority should choose $m^* \geq \frac{e_0(1-\Phi_3)}{1-e_0}$, i.e.: choose (E.6).

E.2.7 Summary of p^* - Proposition 2

Based on the above analysis, Proposition 2 can be obtained.

Proposition 2: The strategies [h, (α, β), k, x] of the predecessors of regulation intensity are known. The forecasted strategy (t^*, e^*) of its successor is given in Proposition 1. The characteristic parameters are known. Then the optimal solution of public authority's regulation intensity (p) is:

$$\text{When } -wE_1 \leq mt_0+t_0, \text{ then } m^* \geq \frac{e_0(1-\Phi_3)}{1-e_0},\ p^* = e_0+\frac{1-e_0\Phi_3}{m+1} \tag{E.10}$$

E.2.8 New changes to the payoff function (E_3, F_3')

Substituting (E.10) into (5.11) and (5.12) yields: After stage III of the game, the payoff functions are:

$$F_3' = (1-x+kx)\alpha+\beta-\theta(1-x)hC-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_1\theta hCx^2-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2 \tag{E.11}$$

$$E_3 = -(1-x+kx)\alpha-\beta-w(\alpha+\beta)(e_0+\frac{1-e_0\Phi_3}{m+1}) \tag{E.12}$$

E.3 Stage II-2 of the game: finding the optimal solution of private partner's technological innovation (x^*, y^*)

E.3.1 The mathematical expression for decision-making on (x, y)

In stage II-2, the strategies [h, (α, β), k] of the predecessors of technological innovation are known, and the forecasted strategies [(t^*, e^*), p^*] of its successors are given in Proposition 1 and Proposition 2. The optimal solution of technological innovation (x, y) of the private partner needs to be solved. According to (E.11), under the condition of the private partner's profit maximization, the mathematical expression for finding the optimal solution of (x, y) is as follows:

(1) Incentive compatibility constraint (IC):

$$\max_{x,y} F_3' = (1-x+kx)\alpha+\beta-\theta(1-x)hC-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_1\theta hCx^2-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2$$

(2) Participation constraint (IR):

Profit after technological innovation ≥ Profit before technological innovation

E.3.2 Solving for x^*

According to the participation constraint, it can be seen that:

$(1-x+kx)\alpha-\theta(1-x)hC-\frac{1}{2}\Phi_1\theta hCx^2\geq\alpha-\theta hC$

$\Longrightarrow x(2\theta hC+2k\alpha-2\alpha-\Phi_1\theta hCx)\geq 0$

Since $x\geq 0$, so:

$$0\leq x\leq 2\frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC} \tag{E.13}$$

Further:

$$k\geq 1-\frac{\theta hC}{\alpha} \tag{E.14}$$

According to the incentive compatibility constraint, it can be seen that:

$\max_x F_3'=(1-x+kx)\alpha+\beta-\theta(1-x)hC-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_1\theta hCx^2-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2$

$\Longrightarrow\frac{\partial F_3'}{\partial x}=-(1-k)\alpha+\theta hC-\Phi_1\theta hCx=0$

$\Longrightarrow x=\frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC}$

This equation satisfies (E.13).

The graph of above function $x\text{-}F_3'$ is a parabola with a downward opening.

Since $0\leq x\leq x_0$, and $\max_x F_3'$, so:

$$x^*=\begin{cases}\frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC}, & if\ \frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC}<x_0 \quad (E.15)\\ x_0, & if\ \frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC}\geq x_0 \quad (E.16)\end{cases}$$

E.3.3 Solving for y^*

According to the participation constraint, it can be seen that:

$\beta-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2\geq\beta-\theta\delta(1-h)C$

$\Longrightarrow\theta\delta y(1-h)C(1-\frac{1}{2}\Phi_2 y)\geq 0$

Since $y\geq 0$, so:

$$0 \le y \le \frac{2}{\Phi_2} \tag{E.17}$$

According to the incentive compatibility constraint, it can be seen that:

$\max_y F_3' = (1-x+kx)\alpha+\beta-\theta(1-x)hC-\theta\delta(1-y)(1-h)C-\frac{1}{2}\Phi_1\theta hCx^2-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2$

$\Longrightarrow \frac{\partial F_3'}{\partial y} = \theta\delta(1-h)C - \Phi_2\theta\delta(1-h)Cy = 0$

$\Longrightarrow y = \frac{1}{\Phi_2}$

This equation satisfies (E.17).

The graph of above function y-F_3' is a parabola with a downward opening.

Since $0 \le y \le y_0$, and $\max_y F_3'$, so:

$$y^* = \begin{cases} \frac{1}{\Phi_2}, & if\ y_0 > \frac{1}{\Phi_2} \end{cases} \tag{E.18}$$

$$y^* = \begin{cases} y_0, & if\ y_0 \le \frac{1}{\Phi_2} \end{cases} \tag{E.19}$$

E.3.4 Summary of (x^*, y^*) - Proposition 3

Based on the above analysis, Proposition 3 can be obtained.

Proposition 3: The strategies [h, (α, β), k] of the predecessors of technological innovation are known. The forecasted strategies [(t^*, e^*), p^*] of its successors are given in Proposition 1 and Proposition 2. The characteristic parameters are known. Then the optimal solution of private partner's technological innovation (x, y) is:

$$x^* = \begin{cases} \frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC}, & if\ \frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC} < x_0 \end{cases} \tag{E.15}$$

$$x^* = \begin{cases} x_0, & if\ \frac{\theta hC-(1-k)\alpha}{\Phi_1\theta hC} \ge x_0 \end{cases} \tag{E.16}$$

$$y^* = \begin{cases} \frac{1}{\Phi_2}, & if\ y_0 > \frac{1}{\Phi_2} \end{cases} \tag{E.18}$$

$$y^* = \begin{cases} y_0, & if\ y_0 \le \frac{1}{\Phi_2} \end{cases} \tag{E.19}$$

E.4 Stage II-1 of the game: finding the optimal solution of public authority's incentive intensity (k^*)

E.4.1 The mathematical expression for decision-making on (k)

In stage II-1, the strategies [h, (α, β)] of the predecessors of incentive intensity are known, and

the forecasted strategies [(t^*, e^*), p^*, (x^*, y^*)] of its successors are given in Proposition 1 to 3. The optimal solution of the incentive intensity (k) of the public authority needs to be solved. According to (E.12), under the condition of the public authority's payoff maximization, the mathematical expression for finding the optimal solution of k is as follows:

$\max_k E_3$=-(1-x+kx)α-β-w(α+β)(e_0+$\frac{1-e_0\Phi_3}{m+1}$)

According to (E.15) and (E.16), $E_3(k)$ is obtained in two cases.

E.4.2 First case (solve for $E_3(k)$)

The first case: When $\frac{\theta hC-(1-K)\,\alpha}{\Phi_1\theta hC}$<$x_0$, solve for $E_3(k)$.

$\frac{\theta hC-(1-k)\,\alpha}{\Phi_1\theta hC}$<$x_0$

$\Longrightarrow$ k<1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$

According to the definition of k $\Longrightarrow$ k∈[0, 1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$)

In this case, x^*=$\frac{\theta hC-(1-k)\,\alpha}{\Phi_1\theta hC}$, and substituting it into (E.12) yields:

$E_3(k)$ =-(α+β)[1+w(e_0+$\frac{1-e_0\Phi_3}{m+1}$)]+(1-k)$\frac{\theta hC-(1-K)\,\alpha}{\Phi_1\theta hC}$α

When k∈[0, 1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$), k-$E_3$ is a parabola with a downward opening, and k=1-$\frac{\theta hC}{2\alpha}$ is the central axis of the parabola.

E.4.3 Second case (solve for $E_3(k)$)

The second case: When $\frac{\theta hC-(1-k)\,\alpha}{\Phi_1\theta hC}$≥$x_0$, solve for $E_3(k)$.

$\frac{\theta hC-(1-k)\,\alpha}{\Phi_1\theta hC}$≥$x_0$

$\Longrightarrow$ k≥1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$

According to the definition of k $\Longrightarrow$ k∈[1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$, 1]

In this case, x^*=x_0, and substituting it into (E.12) yields:

$E_3(k)$ =-(α+β)[1+w(e_0+$\frac{1-e_0\Phi_3}{m+1}$)]+(1-k)x_0α

When k∈[1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$, 1], k-$E_3$ is a decreasing line segment.

E.4.4 Drawing the function graph of k-E_3

According to Sections E.4.2 and E.4.3, draw the graph of k-E_3. Assuming A=-(α+β)[1+w(e_0+$\frac{1-e_0\Phi_3}{m+1}$)], the function graph is shown in Figure E.6.

The left of k=1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$ is a parabola, while the right is a line segment, and the parabola and the line segment intersect at k=1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$.

Observing Figure E.6, on the k axis, whether the central axis of the parabola (k=1-$\frac{\theta hC}{2\alpha}$) lies on the left or the right of the intersection (k=1-$\frac{\theta hC}{\alpha}$+$\frac{\Phi_1\theta hCx_0}{\alpha}$) influences the maximum value of E_3.

The central axis of the parabola lies on the left of the intersection ⇔ $x_0>\frac{1}{2\Phi_1}$

The central axis of the parabola lies on the right of the intersection ⇔ $x_0\leq\frac{1}{2\Phi_1}$

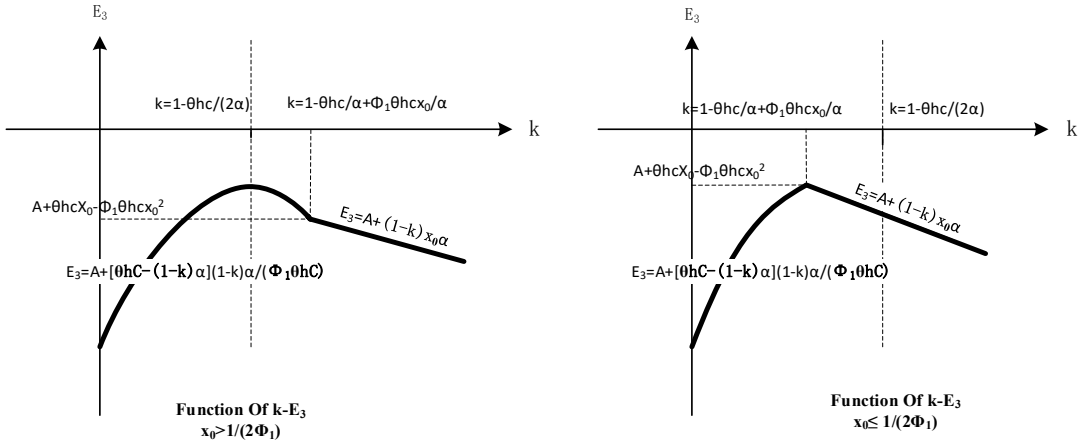


Figure E.6 Function graph of k-E_3

By observing Figure E.6, the value of k^* can be obtained (see Proposition 4).

E.4.5 Summary of k^* - Proposition 4

Based on the above analysis, Proposition 4 can be obtained.

Proposition 4: The strategies [h, (α, β)] of the predecessors of incentive intensity are known. The forecasted strategies [(t^*, e^*), p^*, (x^*, y^*)] of its successors are given in Proposition 1 to 3. The characteristic parameters are known. Then the optimal solution of the public authority's incentive intensity (k) is:

(E.20)

$$k^{*}=\begin{cases}1-\frac{\theta hC}{2\alpha}, & if\ x_0>\frac{1}{2\Phi_1}\\ 1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}, & if\ x_0\le\frac{1}{2\Phi_1}\end{cases} \quad (E.21)$$

Clearly, the value of k^{*} given above satisfies the requirements of equation (E.14).

E.4.6 New changes to x^{*}

1. According to (E.20), when $x_0>\frac{1}{2\Phi_1}$, then $k^{*}=1-\frac{\theta hC}{2\alpha}$.

⇒ $\frac{\theta hC-(1-k^{*})\alpha}{\Phi_1\theta hC}=\frac{1}{2\Phi_1}<x_0$

⇒ According to (E.15), it can be seen that: $x^{*}=\frac{\theta hC-(1-k^{*})\alpha}{\Phi_1\theta hC}=\frac{1}{2\Phi_1}$

2. According to (E.21), when $x_0\le\frac{1}{2\Phi_1}$, then $k^{*}=1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}$

⇒ $\frac{\theta hC-(1-k^{*})\alpha}{\Phi_1\theta hC}=x_0$

⇒ According to (E.16), it can be seen that: $x^{*}=x_0$

To sum up the above reasoning:

$$x^{*}=\begin{cases}\frac{1}{2\Phi_1}, & if\ x_0>\frac{1}{2\Phi_1} \quad (E.22)\\ x_0, & if\ x_0\le\frac{1}{2\Phi_1} \quad (E.23)\end{cases}$$

E.4.7 New changes to the payoff function (E_3, F_3')

After stage II of the game, the payoff function changes as follows.

Substituting (E.22) and (E.20) into (E.12) yields:

$$\text{When } x_0>\frac{1}{2\Phi_1}, \text{ then } E_3=-(\alpha+\beta)\left[1+w\left(e_0+\frac{1-e_0\Phi_3}{m+1}\right)\right]+\frac{\theta hC}{4\Phi_1} \quad (E.24)$$

Substituting (E.23) and (E.21) into (E.12) yields:

$$\text{When } x_0\le\frac{1}{2\Phi_1}, \text{ then } E_3=-(\alpha+\beta)\left[1+w\left(e_0+\frac{1-e_0\Phi_3}{m+1}\right)\right]+\theta hCx_0-\Phi_1\theta hCx_0^{2} \quad (E.25)$$

Based on (E.18), (E.19), (E.20), (E.21), (E.22), and (E.23), recalculating F_3', the results are summarized in Table E.2.

Table E.2: Payoff functions (F_3') after the stage II of the game

Prerequisite	Results of calculation	NO.
$x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$	$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{\theta hC}{8\Phi_1}+\frac{\theta\delta(1-h)C}{2\Phi_2}$ $k^{*}=1-\frac{\theta hC}{2\alpha}$; $x^{*}=\frac{1}{2\Phi_1}$; $y^{*}=\frac{1}{\Phi_2}$	(E.26)
$x_0>\frac{1}{2\Phi_1}$ and	$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{\theta hC}{8\Phi_1}+\theta\delta y_0(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy_0^{2}$	(E.27)

Prerequisite	Results of calculation	NO.
$y_0 \leq \frac{1}{\Phi_2}$	$k^*=1-\frac{\theta hC}{2\alpha}$; $x^*=\frac{1}{2\Phi_1}$; $y^*=y_0$	
$x_0 \leq \frac{1}{2\Phi_1}$ and $y_0 > \frac{1}{\Phi_2}$	$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{1}{2}\Phi_1\theta hCx_0^2+\frac{\theta\delta(1-h)C}{2\Phi_2}$ $k^*=1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}$; $x^*=x_0$; $y^*=\frac{1}{\Phi_2}$	(E.28)
$x_0 \leq \frac{1}{2\Phi_1}$ and $y_0 \leq \frac{1}{\Phi_2}$	$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{1}{2}\Phi_1\theta hCx_0^2+\theta\delta y_0(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy_0^2$ $k^*=1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}$; $x^*=x_0$; $y^*=y_0$	(E.29)

E.5 Stage I-3 of the game: participation constraint for the tender offer from the private partner

In stages I-3, the participation constraint for the tender offer from the private partner is:

The expectation of profit $=\zeta F_3'-(1-\zeta)C_t \geq 0$, i.e., when $\zeta \geq \frac{C_t}{C_t+F_3'}$, the private partner participates in the tender offer, otherwise it does not.

E.6 Stage I-2 of the game: Finding the optimal solution of private partner's tender offer (α^*, β^*)

E.6.1 The mathematical expression for decision-making on (α, β)

In stage I-2, the strategy [h] of the predecessor of tender offer is known, and the forecasted strategies [(t^*, e^*), p^*, (x^*, y^*), k^*] of its successors are given in Propositions 1 to 4. The optimal solution of the tender offer (α, β) of the private partner needs to be solved. According to (E.26), (E.27), (E.28) and (E.29), under the condition of the private partner's profit maximization, the mathematical expression for finding the optimal solution of (α, β) is as follows:

$(\alpha^*, \beta^*) = \{\min(\alpha), \min(\beta) | \text{Forecasted profit} \geq \text{Reservation profit}\}$

1. Participation constraint of the private partner's tender offer: Forecasted profit ≥ reservation profit

2. Incentive compatibility constraint of the private partner's tender offer: the PPP project transaction follows the principle of "low price priority", which means that lower tender offer will get higher tender score. Therefore, subject to the condition of satisfying the participation constraint, the tender offer (α, β) is as low as possible to increase the probability of winning the bid.

E.6.2 Solving for α^* and β^* according to (E.26)

$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{\theta hC}{8\Phi_1}+\frac{\theta\delta(1-h)C}{2\Phi_2}$

$=[\alpha-\theta hC+\frac{\theta hC}{8\Phi_1}]+[\beta-\theta\delta(1-h)C+\frac{\theta\delta(1-h)C}{2\Phi_2}]$

$x^*=\frac{1}{2\Phi_1}$, $y^*=\frac{1}{\Phi_2}$

For the works specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\alpha-\theta hC+\frac{\theta hC}{8\Phi_1}\geq[\theta(1-x)hC+\frac{1}{2}\Phi_1\theta hCx^2]\gamma_1$

For the works not specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\beta-\theta\delta(1-h)C+\frac{\theta\delta(1-h)C}{2\Phi_2}\geq[\theta\delta(1-y)(1-h)C+\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2]\gamma_2$

Since α and β are taken as small as possible, so:

When $x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, then:

$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta hC$

$\beta^*=(1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h)C$

E.6.3 Solving for α^* and β^* according to (E.27)

$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{\theta hC}{8\Phi_1}+\theta\delta y_0(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy_0^2$

$x^*=\frac{1}{2\Phi_1}$, $y^*=y_0$

For the works specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\alpha-\theta hC+\frac{\theta hC}{8\Phi_1}\geq[\theta(1-x)hC+\frac{1}{2}\Phi_1\theta hCx^2]\gamma_1$

For the works not specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\beta-\theta\delta(1-h)C+\theta\delta y_0(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy_0^2\geq[\theta\delta(1-y)(1-h)C+\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2]\gamma_2$

Since α and β are taken as small as possible, so:

When $x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, then:

$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta hC$

$\beta^*=(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h)C$

E.6.4 Solving for α^* and β^* according to (E.28)

$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{1}{2}\Phi_1\theta hCx_0^2+\frac{\theta\delta(1-h)C}{2\Phi_2}$

$x^*=x_0$，$y^*=\frac{1}{\Phi_2}$

For the works specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\alpha-\theta hC+\frac{1}{2}\Phi_1\theta hCx_0^2\geq[\theta(1-x)hC+\frac{1}{2}\Phi_1\theta hCx^2]\gamma_1$

For the works not specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\beta-\theta\delta(1-h)C+\frac{\theta\delta(1-h)C}{2\Phi_2}\geq[\theta\delta(1-y)(1-h)C+\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2]\gamma_2$

Since α and β are taken as small as possible, so:

When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, then:

$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2+\frac{1}{2}\Phi_1\gamma_1x_0^2)\theta hC$

$\beta^*=(1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h)C$

E.6.5 Solving for α^* and β^* according to (E.29)

$F_3'=[\alpha+\beta-\theta hC-\theta\delta(1-h)C]+\frac{1}{2}\Phi_1\theta hCx_0^2+\theta\delta y_0(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy_0^2$

$x^*=x_0$，$y^*=y_0$

For the works specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\alpha-\theta hC+\frac{1}{2}\Phi_1\theta hCx_0^2\geq[\theta(1-x)hC+\frac{1}{2}\Phi_1\theta hCx^2]\gamma_1$

For the works not specified in the output specifications, forecasted profit ≥ reservation profit, the mathematical expression is as follows:

$\beta-\theta\delta(1-h)C+\theta\delta y_0(1-h)C-\frac{1}{2}\Phi_2\theta\delta(1-h)Cy_0^2\geq[\theta\delta(1-y)(1-h)C+\frac{1}{2}\Phi_2\theta\delta(1-h)Cy^2]\gamma_2$

Since α and β are taken as small as possible, yields:

When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, then:

$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2+\frac{1}{2}\Phi_1\gamma_1x_0^2)\theta hC$

$\beta^*=(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h)C$

E.6.6 Summary of (α^*, β^*) - Proposition 5

Based on the above analysis, Proposition 5 can be obtained.

Proposition 5: The strategy [h] of the predecessor of tender offer is known. The forecasted strategies [(t^*, e^*), p^*, (x^*, y^*), k^*] of its successors are given in Propositions 1 to 4. The characteristic parameters are known. Then the optimal solution of the private partner's tender offer (α, β) is:

$$\alpha^*=\begin{cases}\left(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2+\frac{1}{2}\Phi_1\gamma_1x_0^2\right)\theta hC, & if\ x_0\le\frac{1}{2\Phi_1}\\ (1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta hC, & if\ x_0>\frac{1}{2\Phi_1}\end{cases} \quad (E.30)$$

$$\beta^*=\begin{cases}(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2y_0^2)\theta\delta(1-h)C, & if\ y_0\le\frac{1}{\Phi_2}\\ (1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h)C, & if\ y_0>\frac{1}{\Phi_2}\end{cases} \quad (E.31)$$

E.6.7 New changes to k^*

Substituting the above α^* into (E.20) and (E.21) yields:

$$k^*=\begin{cases}1-\frac{\theta hC}{2\alpha}=1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}, & if\ x_0>\frac{1}{2\Phi_1} \quad (E.34)\\ 1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}=\frac{\Phi_1x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2(1-\gamma_1)}, & if\ x_0\le\frac{1}{2\Phi_1} \quad (E.35)\end{cases}$$

E.7 Stage I-1 of the game: finding the optimal solution of the level of detail of output specifications from the public authority (h^*)

E.7.1 The mathematical expression for decision-making on h

In stage I-1, the forecasted strategies [(t^*, e^*), p^*, (x^*, y^*), k^*, (α^*, β^*)] of the successors of the level of detail of output specifications are given in Propositions 1 to 5. The optimal solution of the level of detail of output specifications (h) of the public authority needs to be solved. According to (E.24) and (E.25), under the condition of the public authority's payoff maximization, the mathematical expression for finding the optimal solution of h is as follows:

$\max_h E_3$= (E.24) and (E.25)

E.7.2 First case (solve for h^*)

The first case: When $x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, solve for h^*.

For ease of expression, assume that $b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$.

When $x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, then $k^*=1-\frac{\theta hC}{2\alpha}$, $x^*=\frac{1}{2\Phi_1}$, $y^*=\frac{1}{\Phi_2}$.

Substituting (E.31) and (E.33) into (E.24), yields:

$$E_3=[\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta Ch+(\frac{1}{2\Phi_2}-1)(1+\gamma_2)\theta b\delta C \quad (E.36)$$

So:

When $\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma 1)b+(1-\frac{1}{2\Phi_2})(1+\gamma 2)\delta b\leq 0$, $h^*=h_0$

When $\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma 1)b+(1-\frac{1}{2\Phi_2})(1+\gamma 2)\delta b>0$, $h^*=h_1$

E.7.3 Second case (solve for h^*)

The second case: When $x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, solve for h^*.

When $x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, then $k^*=1-\frac{\theta hC}{2\alpha}$, $x^*=\frac{1}{2\Phi_1}$, $y^*=y_0$.

Substituting (E.31) and (E.32) into (E.24) yields:

$$E_3=[\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta Ch-(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C \quad (E.37)$$

So:

When $\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\leq 0$, then $h^*=h_0$

When $\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b>0$, then $h^*=h_1$

E.7.4 Third case (solve for h^*)

The third case: When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, solve for h^*.

When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, then $k^*=1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}$, $x^*=x_0$, $y^*=\frac{1}{\Phi_2}$.

Substituting (E.30) and (E.33) into (E.25) yields:

$$E_3=[x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta Ch+(\frac{1}{2\Phi_2}-1)(1+\gamma_2)\theta b\delta C \quad (E.38)$$

So:

When $x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\leq 0$, then $h^*=h_0$

When $x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b>0$, then $h^*=h_1$

E.7.5 Fourth case (solve for h^*)

The fourth case: When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, solve for h^*.

When $x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, then $k^*=1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hCx_0}{\alpha}$, $x^*=x_0$, $y^*=y_0$.

Substituting (E.30) and (E.32) into (E.25) yields:

$$E_3=[x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta Ch-(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C \quad (E.39)$$

So:

When $x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\leq 0$, then $h^*=h_0$

When $x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b>0$, then $h^*=h_1$

E.7.6 Summary of h^* - Proposition 6

Based on the above analysis, Proposition 6 can be obtained.

Proposition 6: The forecasted strategies [(t^*, e^*), p^*, (x^*, y^*), k^*, (α^*, β^*)] of the successors of the level of detail of output specifications are given in Propositions 1 to 5. The characteristic parameters are known. $b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$, then the optimal solution of the level of detail of output specifications (h) from the public authority is:

Δ is the discriminant of the value of h^*, when $\Delta\leq 0$, then $h^*=h_0$; when $\Delta>0$, then $h^*=h_1$.

$$\Delta=\begin{cases}\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b, & if\ x_0>\frac{1}{2\Phi_1}\ and\ y_0>\frac{1}{\Phi_2}\\ \frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b, & if\ x_0>\frac{1}{2\Phi_1}\ and\ y_0\leq\frac{1}{\Phi_2}\\ x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b, & if\ x_0\leq\frac{1}{2\Phi_1}\ and\ y_0>\frac{1}{\Phi_2}\\ x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b & if\ x_0\leq\frac{1}{2\Phi_1}\ and\ y_0\leq\frac{1}{\Phi_2}\end{cases}$$

Substituting h^* into E_3, F_3', α^*, and β^* yields the final equilibrium outcome.

E.8 Summary for the solution of subgame perfect Nash equilibrium

Substituting (E.31) and (E.33) into (E.26), substituting (E.31) and (E.32) into (E.27), substituting (E.30) and (E.33) into (E.28), substituting (E.30) and (E.32) into (E.29), and replacing h with h^*, the outcomes of the subgame perfect Nash equilibrium of this thesis are finally obtained, as shown in Table E.3. The following outcomes are based on the prerequisite that the private partner is willing to participate in the tender offer (i.e.: $\zeta \geq \frac{C_t}{C_t+F_3'}$).

Table E.3: Outcomes of the subgame perfect Nash equilibrium

NO.	Prerequisite	Outcomes of the subgame perfect Nash equilibrium	Source
1	$x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$	$E_3= [\frac{b+3\gamma_1 b+2}{8\Phi_1}$ -$(1+\gamma_1)b+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta C h^*+(\frac{1}{2\Phi_2}$ -$1)(1+\gamma_2)\theta b\delta C$ $F_3'=(1-\frac{3}{8\Phi_1})\theta h^* C\gamma_1+(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C\gamma_2$	Replacing h in (E.36) with h^*; substituting (E.31) and (E.33) into (E.26)
2		$h^*=h_0$ or h_1	Proposition 6
3		$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta h^* C$; $\beta^*=(1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C$	Replacing h in (E.31) and (E.33) with h^*
4		$k^*=1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}$	(E.34)
5		$x^*=\frac{1}{2\Phi_1}$; $y^*=\frac{1}{\Phi_2}$	(E.22), (E.18)
6		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$	(E.10)
7		$t^*=0$; $e^*=0$	(E.6)
8	$x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$	$E_3=[\frac{b+3\gamma_1 b+2}{8\Phi_1}$ -$(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta C h^*$- $(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C$ $F_3'=(1-\frac{3}{8\Phi_1})\theta h^* C\gamma_1+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C\gamma_2$	Replacing h in (E.37) with h^*; substituting (E.31) and (E.32) into (E.27)
9		$h^*=h_0$ or h_1	Proposition 6
10		$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta h^* C$; $\beta^*=(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C$	Replacing h in (E.31) and (E.32) with h^*
11		$k^*=1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}$	(E.34)
12		$x^*=\frac{1}{2\Phi_1}$; $y^*=y_0$	(E.22), (E.19)
13		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$	(E.10)
14		$t^*=0$; $e^*=0$	(E.6)
15	$x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$	$E_3=[x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta C h^*+(\frac{1}{2\Phi_2}-1)(1+\gamma_2)\theta b\delta C$ $F_3'=(1-x_0+\frac{1}{2}\Phi_1 x_0^2)\theta h^* C\gamma_1+(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C\gamma_2$	Replacing h in (E.38) with h^*; substituting (E.30) and (E.33) into (E.28)
16		$h^*=h_0$ or h_1	Proposition 6
17		$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2+\frac{1}{2}\Phi_1\gamma_1 x_0^2)\theta h^* C$; $\beta^*=(1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C$	Replacing h in (E.30) and (E.33) with h^*

NO.	Prereq uisite	Outcomes of the subgame perfect Nash equilibrium	Source
18		$k^*=\frac{\Phi_1 x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$	(E.35)
19		$x^*=x_0$; $y^*=\frac{1}{\Phi_2}$	(E.23), (E.18)
20		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$	(E.10)
21		$t^*=0$; $e^*=0$	(E.6)
22	$x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$	$E_3=[x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta C h^*-(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C$ $F_3'=(1-x_0+\frac{1}{2}\Phi_1 x_0^2)\theta h^* C\gamma_1+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C\gamma_2$	Replacing h in (E.39) with h^*; substituting (E.30) and (E.32) into (E.29)
23		$h^*=h_0$ or h_1	Proposition 6
24		$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2+\frac{1}{2}\Phi_1\gamma_1 x_0^2)\theta h^* C$; $\beta^*=(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C$	Replacing h in (E.30) and (E.32) with h^*
25		$k^*=\frac{\Phi_1 x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$	(E.35)
26		$x^*=x_0$; $y^*=y_0$	(E.23), (E.19)
27		$p^*=e_0+\frac{1-e_0\Phi_3}{m+1}$; $m^*\geq\frac{e_0(1-\Phi_3)}{1-e_0}$	(E.10)
28		$t^*=0$; $e^*=0$	(E.6)

Annex F: Factors and Trends Influencing the Equilibrium Solution

Propositions 1 to 6 in Annex E obtain the equilibrium solution model for each decision and the optimal utility function of the public authority. This section further analyzes the equilibrium solution models and the optimal utility function, and reveal the factors and trends influencing the optimal solution of each decision and the optimal utility of the public authority.

F.1 Derivation for Result 1 (h^*)

Result 1: h^* is related to the following factors:

(1) $\frac{\Phi_1}{\Phi_2}$ and $\frac{\gamma_1}{\gamma_2}$ are both negatively correlated with h^*, but in a staircase decrease. On the function graph of $h^*(\frac{\Phi_1}{\Phi_2})$, h^* takes high value to the left of the critical threshold of $\frac{\Phi_1}{\Phi_2}$, and low value to the right. The same applies to $\frac{\gamma_1}{\gamma_2}$.

(2) δ and $\frac{x_0}{y_0}$ (condition: $x_0 \leq \frac{1}{2\Phi_1}$ and $y_0 \leq \frac{1}{\Phi_2}$) are both positively correlated with h^*, but in a staircase increase. On the function graph of $h^*(\delta)$, h^* takes low value to the left of the critical threshold of δ, and high value to the right. The same applies to $\frac{x_0}{y_0}$.

(3) If multiple factors simultaneously influence h^*, use the positivity or negativity of Δ to determine the value of h^*. When $\Delta \leq 0$, h^* takes the low value (h_0); when $\Delta > 0$, h^* takes the high value (h_1).

Prove as follows:

According to Proposition 6 in Annex E, the four discriminants for the value of h^* are as follows:

$\Delta =$

$$\begin{cases} \frac{b+3\gamma_1 b+2}{8\Phi_1} - (1+\gamma_1)b + (1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b, & if\ x_0 > \frac{1}{2\Phi_1}\ and\ y_0 > \frac{1}{\Phi_2} \\ \frac{b+3\gamma_1 b+2}{8\Phi_1} - (1+\gamma_1)b + (1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b, & if\ x_0 > \frac{1}{2\Phi_1}\ and\ y_0 \leq \frac{1}{\Phi_2} \\ x_0(b\gamma_1+1) - (1+\gamma_1)b + \frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2) + (1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b, & if\ x_0 \leq \frac{1}{2\Phi_1}\ and\ y_0 > \frac{1}{\Phi_2} \\ x_0(b\gamma_1+1) - (1+\gamma_1)b + \frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2) + (1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b & if\ x_0 \leq \frac{1}{2\Phi_1}\ and\ y_0 \leq \frac{1}{\Phi_2} \end{cases}$$

Observing the above four discriminants, the following analysis is made.

F.1.1 Discriminant Δ_1

$\Delta_1=\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b$ (when $x_0>\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$)

1. Analyze the correlation between Φ_1 and Δ_1

By observing, when $\Phi_1\uparrow$, then $\Delta_1\downarrow$.

2. Analyze the correlation between γ_1 and Δ_1

Obtained by deformation:

$\Delta_1=\frac{b+2}{8\Phi_1}-b+(\frac{3}{8\Phi_1}-1)b\gamma_1+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b$

Because: $x_0>\frac{1}{2\Phi_1}$ and $x_0<1$, so: $\frac{3}{8\Phi_1}-1<0$, further obtained: when $\gamma_1\uparrow$, then $\Delta_1\downarrow$.

3. Analyze the correlation between Φ_2, δ, γ_2 and Δ_1

Because: $x_0>\frac{1}{2\Phi_1}$ and $x_0<1$, so: $1-\frac{1}{2\Phi_2}>0$, further obtained: when any of ($\Phi_2\downarrow$, $\delta\downarrow$, $\gamma_2\downarrow$) occurs, then $\Delta_1\downarrow$.

To sum up, when any of ($\Phi_1\uparrow$, $\Phi_2\downarrow$, $\delta\downarrow$, $\gamma_1\uparrow$, $\gamma_2\downarrow$) occurs, then $\Delta_1\downarrow$. Conversely, $\Delta_1\uparrow$.

F.1.2 Discriminant Δ_2

$\Delta_2=\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1+\gamma_1)b+(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b$ (when $x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$)

1. Analyze the correlation between Φ_1, γ_1 and Δ_2

Like Δ_1, when any of ($\Phi_1\uparrow$, $\gamma_1\uparrow$) occurs, then $\Delta_2\downarrow$.

2. Analyze the correlation between Φ_2, δ, γ_2 and Δ_2

Obviously, $\frac{1}{2}y_0^2\geq 0$, $1-y_0+\frac{1}{2}\Phi_2 y_0^2>0$, further obtained: when any of ($\Phi_2\downarrow$, $\delta\downarrow$, $\gamma_2\downarrow$) occurs, then $\Delta_2\downarrow$.

3. Analyze the correlation between y_0 and Δ_2

Because: the parabola $f(y_0)=1-y_0+\frac{1}{2}\Phi_2 y_0^2$, with an upward opening, and its central axis is $y_0=\frac{1}{\Phi_2}$, So: when $y_0\leq\frac{1}{\Phi_2}$, and $y_0\uparrow$, then $f(y_0)\downarrow$, further: $\Delta_2\downarrow$.

To sum up, when any of ($\Phi_1\uparrow$, $\Phi_2\downarrow$, $\delta\downarrow$, $y_0\uparrow$, $\gamma_1\uparrow$, $\gamma_2\downarrow$) occurs, then $\Delta_2\downarrow$. Conversely, $\Delta_2\uparrow$.

F.1.3 Discriminant Δ_3

$\Delta_3=x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b$ (when $x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$)

1. Analyze the correlation between x_0 and Δ_3

According to Proposition 2 in Annex E and the definition of Φ_3, it follows that:

$m^{*}\geq\frac{e_0(1-\Phi_3)}{1-e_0}$ and $0\leq e_0\Phi_3\leq 1$

$\Longrightarrow 0\leq e_0+\frac{1-e_0\Phi_3}{m+1}\leq 1$

According to the definition of w, $0<w<1$. According to Proposition 6 in Annex E, $b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$. Further, it can be shown that $1 \leq b < 2$.

Because: $\gamma_1 \geq 0$, so: $b\gamma_1+2-b > 0$, and furthermore, $b - b\gamma_1 - 2 < 0$.

Obtained by deformation of Δ_3:

$\Delta_3=\frac{1}{2}\Phi_1(b-b\gamma_1-2)x_0^2+(b\gamma_1+1)x_0-(1+\gamma_1)b+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b$

The function $\Delta_3(x_0)$ is a parabola with a downward opening, and its central axis is: $x_0=\frac{1}{\Phi_1(1-\frac{b-1}{b\gamma_1+1})}$.

Because: $b-b\gamma_1-2<0$, $\gamma_1\geq 0$, and $1\leq b<2$, so: $0<1-\frac{b-1}{b\gamma_1+1}\leq 1$, further: $\frac{1}{2\Phi_1}<\frac{1}{\Phi_1(1-\frac{b-1}{b\gamma_1+1})}$.

Because: the value interval of x_0 in $\Delta_3(x_0)$ is $x_0\leq\frac{1}{2\Phi_1}$, which is to the left of the central axis of the parabola ($x_0=\frac{1}{\Phi_1(1-\frac{b-1}{b\gamma_1+1})}$), so: when $x_0\downarrow$, then $\Delta_3\downarrow$.

2. Analyze the correlation between Φ_1 and Δ_3

Because: $b-b\gamma_1-2<0$, so: when $\Phi_1\uparrow$, then $\Delta_3\downarrow$.

3. Analyze the correlation between γ_1 and Δ_3

Obtained by deformation of Δ_3:

$\Delta_3=(x_0-1-\frac{1}{2}\Phi_1x_0^2)b\gamma_1+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b+x_0-b+\frac{1}{2}\Phi_1x_0^2(b-2)$

Because: $x_0<1$, so: $x_0-1-\frac{1}{2}\Phi_1x_0^2<0$, further, when $\gamma_1\uparrow$, then $\Delta_3\downarrow$.

4. Analyze the correlation between Φ_2, δ, γ_2 and Δ_3

Like Δ_1, when any of ($\Phi_2\downarrow$, $\delta\downarrow$, $\gamma_2\downarrow$) occurs, then $\Delta_3\downarrow$.

To sum up, when any of ($\Phi_1\uparrow$, $\Phi_2\downarrow$, $\delta\downarrow$, $x_0\downarrow$, $\gamma_1\uparrow$, $\gamma_2\downarrow$) occurs, then $\Delta_3\downarrow$. Conversely, $\Delta_3\uparrow$.

F.1.4 Discriminant Δ_4

$\Delta_4=x_0(b\gamma_1+1)-(1+\gamma_1)b+\frac{1}{2}\Phi_1x_0^2(b-b\gamma_1-2)+(1-y_0+\frac{1}{2}\Phi_2y_0^2)(1+\gamma_2)\delta b$ (when $x_0\leq\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$)

1. Analyze the correlation between x_0, Φ_1 and Δ_4

Like Δ_3, when any of ($x_0\downarrow$, $\Phi_1\uparrow$) occurs, then $\Delta_4\downarrow$.

2. Analyze the correlation between Φ_2, δ, y_0, γ_2 and Δ_4

Like Δ_2, when any of ($\Phi_2\downarrow$, $\delta\downarrow$, $y_0\uparrow$, $\gamma_2\downarrow$) occurs, then $\Delta_4\downarrow$.

3. Analyze the correlation between γ_1 and Δ_4

Like Δ_3, when $\gamma_1\uparrow$, then $\Delta_4\downarrow$.

To sun up, when any of ($\Phi_1\uparrow$, $\Phi_2\downarrow$, $\delta\downarrow$, $x_0\downarrow$, $y_0\uparrow$, $\gamma_1\uparrow$, $\gamma_2\downarrow$) occurs, then $\Delta_4\downarrow$. Conversely, $\Delta_4\uparrow$.

F.1.5 Correlation between the factors and Δ

To summarize the common characteristics of the above four discriminants, when one of the following conditions occurs, then $\Delta\downarrow$. Conversely, $\Delta\uparrow$: (1) Any of ($\Phi_1\uparrow$, $\Phi_2\downarrow$, $\delta\downarrow$, $\gamma_1\uparrow$, $\gamma_2\downarrow$) occurs. (2) $x_0\leq\frac{1}{2\Phi_1}$ and $x_0\downarrow$. (3) $y_0\leq\frac{1}{\Phi_2}$ and $y_0\uparrow$.

F.1.6 Correlation between the factors and h^*

The factors influencing Δ mentioned above can be divided into four categories: behavioral cost of technological innovation (Φ_1 and Φ_2), reservation profit rate (γ_1 and γ_2), deviation coefficient of quantities (δ), and space for technological innovation (x_0 and y_0). The following is the analysis of their influence on h^*.

First, behavioral cost of technological innovation (Φ_1 and Φ_2). Since Φ_1 and Φ_2 have opposite effects on Δ, their joint influence on Δ can be expressed by the difference value ($\frac{\Phi_1}{\Phi_2}$). According to Proposition 6 and Section F.1.5, $\frac{\Phi_1}{\Phi_2}$ is negatively correlated with Δ. If other factors remain unchanged, it can be assumed the critical threshold $=\left\{\frac{\Phi_1}{\Phi_2}\middle|\Delta=0\right\}$. When $\frac{\Phi_1}{\Phi_2}\geq$critical threshold, then $\Delta\leq 0$, $h^*=h_0$; when $\frac{\Phi_1}{\Phi_2}<$critical threshold, then $\Delta>0$, $h^*=h_1$. Therefore, $\frac{\Phi_1}{\Phi_2}$ is negatively correlated with h^*, but it is a staircase decrease. On the graph of $h^*(\frac{\Phi_1}{\Phi_2})$, h^* takes high value to the left of the critical threshold of $\frac{\Phi_1}{\Phi_2}$, and low value to the right.

Then, using the same reasoning, the correlation between the reservation profit rate ($\frac{\gamma_1}{\gamma_2}$), the deviation coefficient of quantities (δ), the space for technological innovation ($\frac{x_0}{y_0}$), and h^* can be obtained.

F.1.7 Summary

Result 1: h^* is related to the following factors:

(1) $\frac{\Phi_1}{\Phi_2}$ and $\frac{\gamma_1}{\gamma_2}$ are both negatively correlated with h^*, but in a staircase decrease. On the

function graph of $h^*(\frac{\Phi_1}{\Phi_2})$, h^* takes high value to the left of the critical threshold of $\frac{\Phi_1}{\Phi_2}$, and low value to the right. The same applies to $\frac{\gamma_1}{\gamma_2}$.

(2) δ and $\frac{x_0}{y_0}$ (condition: $x_0 \leq \frac{1}{2\Phi_1}$ and $y_0 \leq \frac{1}{\Phi_2}$) are both positively correlated with h^*, but in a staircase increase. On the function graph of $h^*(\delta)$, h^* takes low value to the left of the critical threshold of δ, and high value to the right. The same applies to $\frac{x_0}{y_0}$.

(3) If multiple factors simultaneously influence h^*, use the positivity or negativity of Δ to determine the value of h^*. When $\Delta \leq 0$, h^* takes the low value (h_0); when $\Delta > 0$, h^* takes the high value (h_1).

F.2 Derivation for Result 2 (α^*, β^*)

Result 2: The tender offer ($\alpha^*+\beta^*$) of the private partner is influenced by the following factors:

(1) C, δ, θ, γ_1, γ_2, ϕ_1 ($x_0 > \frac{1}{2\Phi_1}$) and ϕ_2 are positively correlated with the tender offer.

(2) x_0 ($x_0 \leq \frac{1}{2\Phi_1}$) and y_0 ($y_0 \leq \frac{1}{\Phi_2}$) are negatively correlated with the tender offer.

(3) The tender offer is influenced by $h_0(h_1)$, but the trend of influence needs to be determined through discriminant calculation.

Prove as follows:

According to Proposition 5 of Annex E, the value of α^* is as follows:

$$\alpha^*=\begin{cases}(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2+\frac{1}{2}\Phi_1\gamma_1x_0^2)\theta hC, & if\ x_0 \leq \frac{1}{2\Phi_1}\\ (1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta hC, & if\ x_0 > \frac{1}{2\Phi_1}\end{cases}$$

The value of β^* is as follows:

$$\beta^*=\begin{cases}(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2y_0^2)\theta\delta(1-h)C, & if\ y_0 \leq \frac{1}{\Phi_2}\\ (1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h)C, & if\ y_0 > \frac{1}{\Phi_2}\end{cases}$$

F.2.1 First case (α^*)

The first case is: when $x_0 \leq \frac{1}{2\Phi_1}$, the factors and trends influencing α^* are analyzed.

$\alpha^*=(1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1x_0^2+\frac{1}{2}\Phi_1\gamma_1x_0^2)\theta h^*C$

1. Analyze the correlation between Φ_1 and α^*

Through observation, it is obtained that:

When $\gamma_1>1$, Φ_1 is positively correlated with α^*. When $\gamma_1=1$, Φ_1 has no correlation with α^*. When $0\leq\gamma_1<1$, Φ_1 is negatively correlated with α^*.

2. Analyze the correlation between x_0 and α^*

Obtained by deformation:

$\alpha^*=[\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1 x_0+1+\gamma_1]\theta h^* C$

According to the definition of γ_1, $\gamma_1\geq 0$.

When $0\leq\gamma_1<1$, $\alpha^*(x_0)$ is a parabola with downward opening, and its central axis is $x_0=\frac{\gamma_1}{(\gamma_1-1)\Phi_1}$. In the interval $x_0\leq\frac{1}{2\Phi_1}$, x_0 is negatively correlated with α^*.

When $\gamma_1=1$, then $\alpha^*(x_0)=-x_0+2$, x_0 is negatively correlated with α^*.

When $\gamma_1>1$, $\alpha^*(x_0)$ is a parabola with upward opening, and its central axis is $x_0=\frac{\gamma_1}{(\gamma_1-1)\Phi_1}$. In the interval $x_0\leq\frac{1}{2\Phi_1}$, x_0 is negatively correlated with α^*.

To sum up, when $x_0\leq\frac{1}{2\Phi_1}$, x_0 is negatively correlated with α^*.

3. Analyze the correlation between θ, h^*, C, γ_1 and α^*

Through observation, it is obtained that: θ, h^*, C, γ_1 are all positively correlated with α^*.

F.2.2 Second case (α^*)

The second case is: when $x_0>\frac{1}{2\Phi_1}$, the factors and trends influencing α^* are analyzed.

$\alpha^*=(1+\gamma_1-\frac{1+3\gamma_1}{8\Phi_1})\theta h^* C$

1. Analyze the correlation between Φ_1 and α^*

Through observation, it is obtained that: Φ_1 is positively correlated with α^*.

2. Analyze the correlation between γ_1 and α^*

Obtained by deformation of α^*:

$\alpha^*=[1+\frac{(8\Phi_1-3)\gamma_1-1}{8\Phi_1}]\theta h^* C$

Because: $x_0>\frac{1}{2\Phi_1}$, and $0\leq x_0<1$, so: $8\Phi_1-3>0$, further: γ_1 is positively correlated with α^*.

3. Analyze the correlation between θ, h^*, C and α^*

Through observation, it is obtained that: θ, h^* and C are all positively correlated with α^*.

F.2.3 Summary of the analysis of α^*

α^* is correlated with the following factors: ① θ, h^*, C, γ_1 are all positively correlated with α^*.

② When $x_0 \leq \frac{1}{2\Phi_1}$, x_0 is negatively correlated with α^*. ③ When $x_0 > \frac{1}{2\Phi_1}$, Φ_1 is positively related to α^*.

F.2.4 First case (β^*)

The first case is: when $y_0 \leq \frac{1}{\Phi_2}$, the factors and trends influencing β^* are analyzed.

$\beta^* = (1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta\delta(1-h^*)C$

1. Analyze the correlation between Φ_2, γ_2, θ, δ, C, h^* and β^*

Through observation, it is obtained that: Φ_2, γ_2, θ, δ, C are all positively correlated with β^*, h^* is negatively correlated with β^*.

2. Analyze the correlation between y_0 and β^*

The central axis of $f(y_0) = 1-y_0+\frac{1}{2}\Phi_2 y_0^2$ is $y_0 = \frac{1}{\Phi_1}$, and $1-y_0+\frac{1}{2}\Phi_2 y_0^2 > 0$ always holds. When $y_0 \leq \frac{1}{\Phi_2}$, y_0 is negatively correlated with $f(y_0)$, further: y_0 is negatively correlated with β^*.

F.2.5 Second case (β^*)

The second case is: when $y_0 > \frac{1}{\Phi_2}$, the factors and trends influencing β^* are analyzed.

$\beta^* = (1+\gamma_2)(1-\frac{1}{2\Phi_2})\theta\delta(1-h^*)C$

Through observation, it is obtained that: Φ_2, γ_2, θ, δ, C are all positively correlated with β^*, h^* is negatively correlated with β^*.

F.2.6 Summary of the analysis of β^*

β^* is correlated with the following factors: ① Φ_2, γ_2, θ, δ, C are all positively correlated with β^*. ② h^* is negatively correlated with β^*. ③ When $y_0 \leq \frac{1}{\Phi_2}$, y_0 is negatively correlated with β^*.

F.2.7 Summary of the analysis of ($\alpha^*+\beta^*$)

Summarizing the factors influencing α^* and β^* mentioned above, the following results are obtained.

Result 2: The tender offer ($\alpha^*+\beta^*$) of the private partner is influenced by the following factors:

(1) C, δ, θ, γ_1, γ_2, ϕ_1 ($x_0 > \frac{1}{2\Phi_1}$) and ϕ_2 are positively correlated with the tender offer.

(2) x_0 ($x_0 \leq \frac{1}{2\Phi_1}$) and y_0 ($y_0 \leq \frac{1}{\Phi_2}$) are negatively correlated with the tender offer.

(3) The tender offer is influenced by $h_0(h_1)$, but the trend of influence needs to be determined through discriminant calculation.

F.3 Derivation for Result 3 (k^*)

Result 3: J_1, Φ_1, and γ_1 are all positively correlated with k^*, and J_1 is an intermediate variable influencing k^*.

Prove as follows:

The value of k^* is as follows:

$$k^*=\begin{cases}\frac{\Phi_1 x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}, & if\ x_0 \leq \frac{1}{2\Phi_1} \\ 1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}, & if\ x_0 > \frac{1}{2\Phi_1}\end{cases}$$

F.3.1 First case (k^*)

The first case is: when $x_0 \leq \frac{\mathbf{1}}{\mathbf{2\Phi_1}}$, the factors and trends influencing k^* are analyzed.

$$k^* = \frac{\Phi_1 x_0+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$$

Obtained by deformation:

$$k^*=1-\frac{1-\Phi_1 x_0}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}=1-\frac{1-\Phi_1 x_0}{1-\frac{1}{2}\Phi_1 x_0^2+\gamma_1(1-x_0+\frac{1}{2}\Phi_1 x_0^2)}$$

1. Analyze the correlation between γ_1 and k^*

When $x_0 \leq \frac{1}{2\Phi_1}$, $\Phi_1 x_0 \leq \frac{1}{2}$.

Further: $1-\Phi_1 x_0>0$, $1-\frac{1}{2}\Phi_1 x_0^2>0$.

Obviously: $1-x_0+\frac{1}{2}\Phi_1 x_0^2>0$.

Through observation, it is obtained that: γ_1 is positively correlated to k^*.

2. Analyze the correlation between $\mathbf{\Phi_1}$ and k^*

$$k^*=1-\frac{1-\Phi_1 x_0}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$$

$$\frac{\partial k^*}{\partial \Phi_1}=\frac{x_0(1-\frac{1}{2}x_0)(1+\gamma_1)}{[1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)]^2}>0$$

Therefore, Φ_1 is positively correlated to k^*.

3. Analyze the correlation between $\mathbf{x_0}$ and k^*

$k^*=1-\frac{1-\Phi_1 x_0}{1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)}$.

$\frac{\partial k^*}{\partial x_0}=\frac{\Phi_1+\Phi_1\gamma_1+\Phi_1 x_0\gamma_1+\frac{1}{2}\Phi_1^2 x_0^2(1-\gamma_1)-\Phi_1 x_0-\gamma_1}{[1+\gamma_1-x_0\gamma_1-\frac{1}{2}\Phi_1 x_0^2(1-\gamma_1)]^2}$.

The positive or negative of $\frac{\partial k^*}{\partial x_0}$ cannot be determined, so the correlation between x_0 and k^* is uncertain.

4. Analyze the correlation between J_1 and k^*

Because: $\Phi_1 x_0 \leq \frac{1}{2}$, so: $1-\Phi_1 x_0>0$.

According to the definition of J_1, it is obtained that: $J_1=\frac{\alpha}{hC}$.

$k^*=1-\frac{\theta hC}{\alpha}+\frac{\Phi_1\theta hC x_0}{\alpha}==1-\frac{\theta}{J_1}+\frac{\Phi_1\theta x_0}{J_1}=1-\frac{\theta}{J_1}(1-\Phi_1 x_0)$.

Through observation, it is obtained that: J_1 is positively correlated with k^*.

F.3.2 Second case (k^*)

The second case is: when $x_0>\frac{1}{2\Phi_1}$, the factors and trends influencing k^* are analyzed.

$k^*=1-\frac{\theta hC}{2\alpha}=1-\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}$

1. Analyze the correlation between J_1 and k^*

Because: $\alpha^*=J_1 hC$, so: $k^*=1-\frac{\theta}{2J_1}$.

J_1 is positively correlated with k^*.

2. Analyze the correlation between γ_1 and k^*

$k^*=1-\frac{4}{8-\frac{1}{\Phi_1}+\frac{(8\Phi_1-3)\gamma_1}{\Phi_1}}$, analyze the correlation between γ_1 and k^*.

when $x_0>\frac{1}{2\Phi_1}$, then $\Phi_1>\frac{1}{2x_0}>\frac{1}{2}$, further: $\frac{8\Phi_1-3}{\Phi_1}>0$.

when $x_0>\frac{1}{2\Phi_1}$, then $\frac{1}{\Phi_1}<2x_0<2$, further: $8-\frac{1}{\Phi_1}>0$.

In summary, observing the equation for k^*, γ_1 is positively correlated with k^*.

3. Analyze the correlation between Φ_1 and k^*

Because: $\frac{8\Phi_1-3}{\Phi_1}>0$, $8-\frac{1}{\Phi_1}>0$, and $\gamma_1\geq 0$, so: $\frac{4}{8+8\gamma_1-\frac{1+3\gamma_1}{\Phi_1}}=\frac{4}{8-\frac{1}{\Phi_1}+\frac{(8\Phi_1-3)\gamma_1}{\Phi_1}}>0$.

Further: Φ_1 is positively correlated with k^*.

F.3.3 Summary

To summarize the above two cases, k^* is correlated with the following factors:

Result 3: J_1, Φ_1, and γ_1 are all positively correlated with k*, and J_1 is an intermediate variable influencing k^*.

F.4 Derivation for Result 7 (Correlation between independent variables and PUPC)

Result 7： PUPC of the public authority is correlated with the following factors:

(1) C, δ, w, e_0, θ, Φ_1, Φ_2, γ_1, γ_2 are all positively correlated with PUPC.

(2) m and Φ_3 are negatively correlated with PUPC.

(3) When $\Delta \leq 0$, h_0 is positively correlated with PUPC; when $\Delta > 0$, h_1 is negatively correlated with PUPC.

(4) When $x_0 \leq \frac{1}{2\Phi_1}$, x_0 is negatively correlated with PUPC.

(5) When $y_0 \leq \frac{1}{\Phi_2}$, y_0 is negatively correlated with PUPC.

Prove as follows:

Since PUPC = $-E_3$, according to Table E.3 in Annex E, E_3 has four possible cases.

F.4.1 First case (PUPC)

The first case is: when $x_0 > \frac{1}{2\Phi_1}$ and $y_0 > \frac{1}{\Phi_2}$, the factors and trends influencing PUPC are analyzed.

Substituting PUPC = $-E_3$ into the function of E_3 in Table E.3 yields:

PUPC = $[(1+\gamma_1)b - \frac{b+3\gamma_1 b+2}{8\Phi_1} - (1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta C h^* + (1-\frac{1}{2\Phi_2})(1+\gamma_2)\theta b \delta C$

1. Analyze the correlation between θ, C, δ and PUPC

1) Value range of Φ_1

Because: $x_0 > \frac{1}{2\Phi_1}$, so: $\Phi_1 > \frac{1}{2}$.

2) Value range of b

According to Proposition 2 of Annex E and the definition of Φ_3, it is obtained that:

$m^* \geq \frac{e_0(1-\Phi_3)}{1-e_0}$, and $0 \leq e_0\Phi_3 \leq 1$.

$\Longrightarrow 0 \leq e_0 + \frac{1-e_0\Phi_3}{m+1} \leq 1$.

According to the definition of w, $0<w<1$.

According to Proposition 6 of Annex E, it is known that: $b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$.

$\Longrightarrow 1\leq b<2$.

3) The positive and negative of the equation

Obtained by deformation:

$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}]\theta C h^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C$

Because: $\Phi_1>\frac{1}{2}$, and $1\leq b<2$, so:

$(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}=\frac{8\Phi_1(1+\gamma_1)b-b-3\gamma_1 b-2}{8\Phi_1}>\frac{4(1+\gamma_1)b-b-3\gamma_1 b-2}{8\Phi_1}>0$.

Because: $\frac{1}{\Phi_2}<y_0<1$, so: $1-\frac{1}{2\Phi_2}>0$, further: $(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)>0$.

4) Correlation

Because: $(1+\gamma_1)\ b-\frac{b+3\gamma_1 b+2}{8\Phi_1}>0$, $(1-h^*)\ (1-\frac{1}{2\Phi_2})(1+\gamma_2)>0$, so: θ, C and δ are all positively correlated with PUPC.

2. Analyze the correlation between b and PUPC

Obtained by deformation:

$PUPC=\frac{8\Phi_1(1+\gamma_1)-1-3\gamma_1}{8\Phi_1}\theta C h^* b+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta\theta Cb-\frac{1}{4\Phi_1}\theta C h^*$

Because: $\Phi_1>\frac{1}{2}$, and $1\leq b<2$, so: $\frac{8\Phi_1(1+\gamma_1)-1-3\gamma_1}{8\Phi_1}>\frac{4(1+\gamma_1)-1-3\gamma_1}{8\Phi_1}>0$.

Because: $\frac{8\Phi_1(1+\gamma_1)-1-3\gamma_1}{8\Phi_1}>0$, and $(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)>0$, so: b is positively correlated with PUPC.

3. Analyze the correlation between h^* and PUPC

When $\Delta\leq 0$, $[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\geq 0$, h^* is positively correlated with PUPC; when $\Delta>0$, h^* is negatively correlated with PUPC.

4. Analyze the correlation between Φ_1, Φ_2 and PUPC

$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}]\theta C h^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C$

Obviously, Φ_1 and Φ_2 are all positively correlated with PUPC.

5. Analyze the correlation between γ_1, γ_2 and PUPC

Obtained by deformation:

PUPC$=[\frac{8\Phi_1-3}{8\Phi_1}b\gamma_1+\frac{8\Phi_1 b-b-2}{8}]\theta C h^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C$

Because: $\Phi_1>\frac{1}{2}$, so: $8\Phi_1-3>0$.

Observing the equation of PUPC, it is obtained that: γ_1 and γ_2 are all positively correlated

with PUPC.

F.4.2 Second case (PUPC)

The second case is: when $x_0>\frac{1}{2\Phi_1}$ and $y_0\leq\frac{1}{\Phi_2}$, the factors and trends influencing PUPC are analyzed.

Substituting PUPC = $-E_3$ into the function of E_3 in Table E.3 yields:

$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}-(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b]\theta C h^*+(1+\gamma_2)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)\theta b\delta C$

1. Analyze the correlation between θ, C, δ and PUPC

Obtained by deformation:

$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$

As described in Section F.4.1: $(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}>0$.

Obviously, $(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)>0$.

Observing the equation of PUPC, it is obtained that: θ, C and δ are all positively correlated with PUPC.

2. Analyze the correlation between b and PUPC

Obtained by deformation:

$PUPC=\frac{8\Phi_1(1+\gamma_1)-1-3\gamma_1}{8\Phi_1}\theta C h^* b+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta\theta C b-\frac{1}{4\Phi_1}\theta C h^*$

Because: $\frac{8\Phi_1(1+\gamma_1)-1-3\gamma_1}{8\Phi_1}>0$, and $(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)>0$, so: b is positively correlated with PUPC.

3. Analyze the correlation between h^* and PUPC

When $\Delta\leq 0$, h^* is positively correlated with PUPC; when $\Delta>0$, h^* is negatively correlated with PUPC.

4. Analyze the correlation between Φ_1, Φ_2 and PUPC

$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$

Obviously, Φ_1 and Φ_2 are all positively correlated with PUPC.

5. Analyze the correlation between y_0 and PUPC

$PUPC=[(1+\gamma_1)b-\frac{b+3\gamma_1 b+2}{8\Phi_1}]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$

The parabola $f(y_0)=1-y_0+\frac{1}{2}\Phi_2 y_0^2$, with an upward opening, has a central axis $y_0=\frac{1}{\Phi_2}$.

When $y_0\leq\frac{1}{\Phi_2}$, y_0 is negatively correlated with $f(y_0)$.

It can be further obtained that: y_0 is negatively correlated with PUPC.

6. Analyze the correlation between γ_1, γ_2 and PUPC

Obtained by deformation:

$$PUPC=[\frac{8\Phi_1-3}{8\Phi_1}b\gamma_1+\frac{8\Phi_1 b-b-2}{8}]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$$

Because: $\Phi_1>\frac{1}{2}$, so: $8\Phi_1-3>0$.

Obviously, γ_1 and γ_2 are all positively correlated with PUPC.

F.4.3 Third case (PUPC)

The third case is: when $x_0\leq\frac{1}{2\Phi_1}$ and $y_0>\frac{1}{\Phi_2}$, the factors and trends influencing PUPC are analyzed.

Substituting PUPC = $-E_3$ into the function of E_3 in Table E.3 yields:

$$PUPC=[(1+\gamma_1)b-x_0(b\gamma_1+1)-\frac{1}{2}\Phi_1 x_0^2(b-b\gamma_1-2)-(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b]\theta C h^*+(1-\frac{1}{2\Phi_2})(1+\gamma_2)\theta b\delta C$$

1. Analyze the correlation between C, δ, θ and PUPC

Obtained by deformation:

$$PUPC=[\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b]\theta C h^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C$$

1) The positive and negative of the equation

Because $x_0<1$, so:

$$\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b$$

$$>\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)+(1+\gamma_1)b$$

$$=\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2+b-1>0.$$

2) The positive and negative of the equation

Because: $y_0>\frac{1}{\Phi_2}$, so: $\frac{1}{\Phi_2}<y_0<1$, further: $(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)>0$.

3) Correlation

Because: $\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b>0$, and $(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)>0$, so: θ, C and δ are all positively correlated with PUPC.

2. Analyze the correlation between x_0 and PUPC

Obtained by deformation:

$$PUPC=[\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b]\theta C h^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C$$

As described in Section F.4.1, $1\leq b<2$.

Because: $\gamma_1 \geq 0$, so: $b\gamma_1+2-b>0$.

Assuming $f(x_0)=\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b$, the function $f(x_0)$ is a parabola with an upward opening, and the central axis is $x_0=\frac{1}{\Phi_1(1-\frac{b-1}{b\gamma_1+1})}$.

Because: $\gamma_1 \geq 0$, $1 \leq b<2$, so: $0 \leq \frac{b-1}{b\gamma_1+1}<1$, and further: $0<1-\frac{b-1}{b\gamma_1+1} \leq 1$.

Furthermore, interval $x_0 \leq \frac{1}{2\Phi_1}$ lies to the left of $x_0=\frac{1}{(1-\frac{b-1}{b\gamma_1+1})\Phi_1}$.

Because: the interval $x_0 \leq \frac{1}{2\Phi_1}$ lies to the left of the central axis of the parabola ($x_0=\frac{1}{(1-\frac{b-1}{b\gamma_1+1})\Phi_1}$), so: x_0 is negatively correlated with $f(x_0)$. Furthermore, x_0 is negatively correlated with PUPC.

3. Analyze the correlation between b and PUPC

Obtained by deformation:

$PUPC=[\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1x_0+1+\gamma_1]b\theta Ch^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C-(x_0-\Phi_1x_0^2)\theta Ch^*$

When $\gamma_1>1$, then $\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1x_0+1+\gamma_1>\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1+1+\gamma_1>0$.

When $\gamma_1=1$, then $\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1x_0+1+\gamma_1=2-x_0>0$.

When $\gamma_1<1$, because $\Phi_1x_0 \leq \frac{1}{2}$, and $x_0<1$, so: $\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1x_0+1+\gamma_1=-\frac{1}{2}\Phi_1(1-\gamma_1)x_0^2-\gamma_1x_0+1+\gamma_1>-\frac{1}{4}(1-\gamma_1)-\gamma_1+1+\gamma_1=\frac{3}{4}+\frac{1}{4}\gamma_1>0$.

To sum up, $\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1x_0+1+\gamma_1>0$.

Because: $\frac{1}{2}\Phi_1(\gamma_1-1)x_0^2-\gamma_1x_0+1+\gamma_1>0$, and $(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)>0$, so: b is positively correlated with PUPC.

4. Analyze the correlation between h^* and PUPC

When $\Delta \leq 0$, h^* is positively correlated with PUPC; when $\Delta>0$, h^* is negatively correlated with PUPC.

5. Analyze the correlation between Φ_1, Φ_2 and PUPC

$PUPC=[\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b]\theta Ch^*+(1-h^*)(1-\frac{1}{2\Phi_2})(1+\gamma_2)\delta b\theta C$

Because: $\frac{1}{2}(b\gamma_1+2-b)x_0^2>0$, $(1-h^*)(1+\gamma_2)>0$, and $1-\frac{1}{2\Phi_2}>0$, so: Φ_1 and Φ_2 are all positively correlated with PUPC.

6. Analyze the correlation between γ_1、γ_2 and PUPC

Obtained by deformation:

PUPC=[($\frac{1}{2}\Phi_1 x_0^2$-x_0+1)bγ_1+$\frac{1}{2}\Phi_1$(2-b)x_0^2+b-x_0]θCh^*+(1-h^*)(1-$\frac{1}{2\Phi_2}$)(1+γ_2)δbθC

Obviously, $\frac{1}{2}\Phi_1 x_0^2$-x_0+1>0. As mentioned above, 1-$\frac{1}{2\Phi_2}$>0.

So: γ_1 and γ_2 are all positively correlated with PUPC.

F.4.4 Fourth case (PUPC)

The fourth case is: when $x_0 \leq \frac{1}{2\Phi_1}$ and $y_0 \leq \frac{1}{\Phi_2}$, the factors and trends influencing PUPC are analyzed.

Substituting PUPC = -E_3 into the function of E_3 in Table E.3 yields:

PUPC=[(1+γ_1)b -x_0(bγ_1+1) - $\frac{1}{2}\Phi_1 x_0^2$(b-bγ_1-2)-(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)(1+γ_2)δb]θC h^* +(1+γ_2)(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)θbδC

1. Analyze the correlation between C, δ, θ and PUPC

Obtained by deformation:

PUPC =[$\frac{1}{2}\Phi_1$(bγ_1+2-b)x_0^2-(bγ_1+1)x_0+(1+γ_1)b]θCh^*+(1-h^*)(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)(1+γ_2)δbθC

As described in Section F.4.3, $\frac{1}{2}\Phi_1$(bγ_1+2-b)x_0^2-(bγ_1+1)x_0+(1+γ_1)b>0.

Obviously, 1-y_0+$\frac{1}{2}\Phi_2 y_0^2$>0.

Because: $\frac{1}{2}\Phi_1$(bγ_1+2-b)x_0^2-(bγ_1+1)x_0+(1+γ_1)b>0, and (1-h^*)(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)(1+γ_2)>0, so: θ, C and δ are all positively correlated with PUPC.

2. Analyze the correlation between x_0 and PUPC

Obtained by deformation:

PUPC =[$\frac{1}{2}\Phi_1$(bγ_1+2-b)x_0^2-(bγ_1+1)x_0+(1+γ_1)b]θCh^*+(1-h^*)(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)(1+γ_2)δbθC

As described in Section F.4.3, x_0 is negatively correlated with PUPC.

3. Analyze the correlation between b and PUPC

Obtained by deformation:

PUPC =[$\frac{1}{2}\Phi_1$(γ_1-1)x_0^2-$\gamma_1 x_0$+1+γ_1]bθCh^*+(1-h^*)(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)(1+γ_2)δbθC+($\Phi_1 x_0^2$-x_0)θCh^*

As described in Section F.4.3, $\frac{1}{2}\Phi_1$(γ_1-1)x_0^2-$\gamma_1 x_0$+1+γ_1>0. Obviously, 1-y_0+$\frac{1}{2}\Phi_2 y_0^2$>0.

Because: $\frac{1}{2}\Phi_1$(γ_1-1)x_0^2-$\gamma_1 x_0$+1+γ_1 >0, and (1-h^*)(1-y_0+$\frac{1}{2}\Phi_2 y_0^2$)(1+γ_2)>0, so: b is positively correlated with PUPC.

4. Analyze the correlation between h and PUPC

When Δ≤0, h^* is positively correlated with PUPC; when Δ>0, h^* is negatively correlated

with PUPC.

5. Analyze the correlation between Φ_1, Φ_2 and PUPC

PUPC=[$\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$

Because: $\frac{1}{2}(b\gamma_1+2-b)x_0^2>0$, $(1-h^*)(1+\gamma_2)>0$, and $1-y_0+\frac{1}{2}\Phi_2 y_0^2>0$, so: Φ_1 and Φ_2 are all positively correlated with PUPC.

6. Analyze the correlation between γ_1, γ_2 and PUPC

Obtained by deformation:

PUPC=[$(\frac{1}{2}\Phi_1 x_0^2-x_0+1)b\gamma_1+\frac{1}{2}\Phi_1(2-b)x_0^2+b-x_0]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$

Because: $\frac{1}{2}\Phi_1 x_0^2-x_0+1>0$, $(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)>0$, so: γ_1 and γ_2 are all positively correlated with PUPC.

7. Analyze the correlation between y_0 and PUPC

PUPC=[$\frac{1}{2}\Phi_1(b\gamma_1+2-b)x_0^2-(b\gamma_1+1)x_0+(1+\gamma_1)b]\theta C h^*+(1-h^*)(1-y_0+\frac{1}{2}\Phi_2 y_0^2)(1+\gamma_2)\delta b\theta C$

As described in Section F.4.2, y_0 is negatively correlated with PUPC.

F.4.5 Summary

Since $b=1+w(e_0+\frac{1-e_0\Phi_3}{m+1})$, w and e_0 are positively correlated with b, while m and Φ_3 are negatively correlated with b.

Summarizing the common characteristics of the above four cases, it can be seen that PUPC of the public authority is correlated with the following factors:

(1) C, δ, w, e_0, θ, Φ_1, Φ_2, γ_1, γ_2 are all positively correlated with PUPC.

(2) m and Φ_3 are negatively correlated with PUPC.

(3) When $\Delta\leq 0$, h_0 is positively correlated with PUPC; when $\Delta>0$, h_1 is negatively correlated with PUPC.

(4) When $x_0\leq\frac{1}{2\Phi_1}$, x_0 is negatively correlated with PUPC.

(5) When $y_0\leq\frac{1}{\Phi_2}$, y_0 is negatively correlated with PUPC.

Annex G: Evaluation Materials and Focus Group Guidelines

G.1 Focus group expert informed consent form

The purpose of the focus group is to evaluate the results of two research methods used in a doctoral thesis (hereinafter referred to as "this thesis").

The research objectives of this thesis are to: from the perspective of public authority and users, in order to save PUPC, to seek the optimal level of detail of output specifications in the transaction stage, as well as the optimal strategies of incentives and regulation in the construction stage, and ultimately explore the influencing factors of PUPC and the path for saving PUPC.

In order to ensure the authenticity of the research, the content of the focus group will be audio recorded and minutes. The researchers solemnly promise to the participating experts that the identities of the participating experts will be kept strictly confidential and their personal information will not be disclosed when the researchers publish their research results. If you are willing to participate in the focus group, please sign below. The activity is expected to last 150 minutes. The researchers sincerely thank you for your support!

Please read the above content carefully and voluntarily participate in this study.

Thank you very much for taking the time to participate.

Expert signature:_____

Date:_____

Dear Focus Group experts:

Hello! Thank you very much for participating in the focus group activity for the thesis "Strategies for Saving Public Authority and User Payment for Construction of China's PPP Project: Output Specifications, Incentives and Regulation" (hereinafter: this thesis).

This activity will set up an expert focus group, which is expected to take approximately 150 minutes. Thank you once again for your support!

G.2 Part I: Basic information used for the evaluation

G.2.1 Research background

In the transaction stage of the PPP project, the public authority's action is the level of detail of output specifications, while the private partner's action is the tender offer. The decision on the optimal level of detail of output specifications for the public authority needs to tradeoff between "specifying detailed functional requirements and technical quality indicators' and 'leaving sufficient space for technological innovation". The decision on the optimal tender offer for the private partner needs to tradeoff between "an appropriately high tender offer that realizes the enterprise's reservation profit" and "an appropriately low tender offer that increases the probability of winning the bid".

In the construction stage, the public authority's action is the intensity of incentives, while the private partner's action is technological innovation. The decision on the optimal intensity of incentives for the public authority needs to tradeoff between "incentivizing technological innovation" and "reducing PUPC". The decision on the optimal technological innovation strategy for the private partner needs to tradeoff between "increasing the behavioral cost due to technological innovation" and "decreasing the construction cost due to technological innovation".

In the construction stage, the public authority's action is regulation, while the private partner's action is opportunism. The decision on the optimal intensity of regulation for the public authority needs to tradeoff between "curbing opportunism" and "reducing regulation cost". The decision on the optimal opportunism strategy for the private partner is based on the expected value of extra profit.

The facilitator will provide the electronic version of the completed research process (Chapters 1 to 5) of this thesis to the experts.

G.2.2 Research questions

1. In the project transaction stage, how does the public authority choose the optimal level of detail of output specifications to save PUPC?

2. In the project construction stage, how does the public authority choose the optimal intensity of incentives and regulation to save PUPC?

3. What are the factors influencing PUPC and the path to saving PUPC?

Note: PUPC is an abbreviation for "Public Authority and User Payment for Construction". The public authority in this thesis is the government side. The private partner is the social capital side.

G.2.3 Scope of the research

The research in this thesis is made specifically from the public authority's perspective, instead of the private partner.

The research in this thesis is centered around saving PUPC. The research does not deal with payment for operation and payment for all other matters. This thesis studies how to save PUPC in the transaction and construction stages, rather than the operation stage. Except for the responsibilities and risks borne by the public authority as agreed in the contract, the risks of construction investment shall be borne by the private partner.

When project financing, usage and operational performance are normal:

1. If no risks and responsibilities (rights) borne by the public authority occur during construction, the private partner obtains the PUPC at a fixed cost, which will not be adjusted due to changes in the actual construction cost.

2. If risks and responsibilities (rights) borne by the public authority occur during construction (e.g. design optimization), PUPC = a fixed cost + adjustment amount for Contract changes.

G.2.4 Purpose of focus group activities

The purpose of this focus group activities is to evaluate the similarities and differences between the results of the interview method and the modeling analysis method of game theory, improve the reliability and validity of this thesis, and form the research findings of this thesis.

G.2.5 Terms

1. PUPC

The public authority and user payment (PUP) refers to the **public** authority and **user payment** in the PPP project according to the performance evaluation results and the contract, abbreviated as "PUP". PUP consists of three parts: Public authority and user payment for construction (PUPC), public authority and user payment for operation (PUPO), and public authority and user payment for all other matters (PUPA).

PUPC refers to the **public** authority and the **user payment** for **construction** cost of the private partner and project regulation services according to the performance evaluation results and the PPP contract.

2.Construction Cost Calculated by Norm and Standard for the Entire Project (C)

Construction Cost Calculated by Norm and Standard, abbreviated as CS.

CS refers to the project construction cost calculated by Norm and Standard of the country, province or industry. It is the project construction cost with the social average productivity level.

Construction Cost Calculated by Norm and Standard for the Entire Project (C) refers the *CS* for the entire project.

3. Discount rate of productivity level (θ)

The construction cost calculated by Norm and Standard for the Entire Project (C) reflects the social average productivity level, the private partner as an individual of the society, its level of project management and engineering technology will be generally higher than the social average productivity level (in general, only large enterprises or investors with strong strength can participate in the construction of the PPP project), and this advancement of the project management and engineering technology will be ultimately reflected in the reduction of the construction cost (*the private partner's internal construction cost is lower than C*), therefore, the enterprise's internal construction cost will be appropriately discounted on the basis of C. This discount rate is called **discount rate of productivity level (θ)**. The higher the level of productivity, the lower discount rate of productivity level.

4. Level of detail of the output specifications (h)

The level of detail of output specifications is expressed as the proportion of *CS* of the works specified in the output specifications to *C*.

The works specified in the output specifications refers to the works in the output specifications whose quantities can be accurately calculated.

5. Deviation coefficient of quantities (δ)

In the transaction stage of the PPP project, for works unspecified in the output specifications, the private partner forecasts the conventional estimated quantities according to the available information. There will be a deviation between these conventional estimated quantities and the

corresponding quantities of future design drawings, which is usually expressed by **the deviation coefficient (δ).**

$$\delta=\frac{\text{CS corresponding to quantities for the first set of design drawings}}{\text{CS corresponding to regular estimated quantities}}$$

6. Reservation profit rates (γ_1 and γ_2)

Reservation profit rates (γ_1 and γ_2) refer to the profit rates that the private partner calculates separately for the works specified and unspecified in the output specifications when submitting the tender offer of the PPP project.

7. Tender offer (α, β)

The tender offer from the private partner consists of two parts: the tender offer for PUPC of works specified in the output specifications (α) and the tender offer for PUPC of works unspecified in the output specifications (β).

8. Intensity of incentives (k)

Intensity of incentives (k): The percentage of PUPC savings that are shared with the private partner in order to incentivize design optimization.

9. Technological innovation (x, y)

Technological innovation: The private partner carries out design optimization and design deepening on the basis of the output specifications provided by the public authority.

Design optimization: It refers to the private partner modifies and improves the design of engineering contents that have been specified in the output specifications during the construction stage, so as to enhance the value of the project, which is characterized by the private partner's modification of the output specifications agreed in the contract. The level of effort of design optimization is expressed as "construction cost saving rate due to design optimization (x)".

Design deepening: It refers to the private partner supplements and refines the design of engineering contents that have not been specified in the output specifications during the construction stage, so as to meet constructability and enhance the value of the project, which is characterized by the private partner's ability not to modify output specifications agreed in the contract. The level of effort of design deepening is expressed as "construction cost saving rate due to design deepening (y)".

Behavioral cost coefficient of design optimization (Φ_1): If the behavioral cost of design optimization from the private partner is $\frac{1}{2}\Phi_1 d_1 x^2$, then d_1 is the enterprise's internal construction cost of specified work in the output specifications before design optimization. Φ_1 is the behavioral cost coefficient of design optimization. x is the saving rate of construction cost for

design optimization.

Behavioral cost coefficient of design deepening (Φ_2): If the behavioral cost of design deepening from the private partner is $\frac{1}{2}\Phi_2 d_2 y^2$, then d_2 is the enterprise's internal construction cost of not specified work in the output specifications before design deepening. Φ_2 is the behavioral cost coefficient of design deepening. y is the saving rate of construction cost for design deepening.

10. Intensity of regulation (p)

Intensity of regulation (p): The proportion of checking and finding opportunism by the public authority, assuming that the private partner does not hide.

Behavioral cost coefficient of regulation (w): The proportion of the behavioral cost of regulation by the public authority to the regulated cost expenditure.

Penalty coefficient (m): If opportunism by the private partner is detected, the public authority will confiscate the unjust enrichment (*t*) from the opportunism, and impose a fine of *m* times the unjust enrichment, where *m* is the penalty coefficient.

11. Opportunism amount (t)

Opportunism amount (t): It refers to the overestimation and miscalculation of additional PUPC outside the contract, or the concealment of savings from design optimization that have already occurred, by the private partner in the construction stage.

Proportion of hidden opportunism (e): By hiding, the private partner reduces the proportion of opportunism that is discovered. This proportion of reduction is e.

Maximum amount of opportunism (t_0): influenced by exogenous conditions except for regulation, the private partner's opportunism can reach a maximum.

Maximum proportion of hidden opportunism (e_0): the maximum rate of hidden opportunism by the private partner that can be achieved under the influence of exogenous conditions and regulation.

Behavior cost coefficient of hiding (Φ_3): The proportion of the behavioral cost of hiding to the amount of undetected opportunism.

12. Six Optimal Strategies

Six Optimal Strategies: Optimal level of detail of output specifications, optimal tender offer, optimal intensity of incentives, optimal technological innovation strategy, optimal intensity of regulation, optimal opportunism strategy.

G.2.6 Activity schedule

The focus group of experts will proceed as follows:

(1) Experts receive the evaluation materials.

(2) Before the meeting, the facilitator communicates with every expert by telephone to understand their familiarity with the evaluation materials and answer any questions they may have.

(3) All experts submit their written opinions on the proposed discussion questions to the facilitator no later than four days prior to the formal meeting. The facilitator then gathers all experts' opinions and feedbacks them to each expert.

(4) Organize video conference for the expert focus group. Firstly, the facilitator delivers an opening remark. Secondly, regarding the first research theme, each expert shall express supplementary opinions in turn after reading all experts' opinions. Thirdly, the facilitator shall ask questions, and the experts shall freely respond and discuss. If necessary, further questions and answers may follow. Fourthly, proceed to the next theme. Each expert's total speaking time during this meeting shall be approximately 15-20minutes; experts shall manage their time according to their own key speech points. Fifthly, the facilitator shall deliver a speech of thanks. The entire process shall be recorded in the meeting minutes, and finally, the facilitator shall summarize the evaluation results.

(5) Paying fees to experts. Researchers organize the focus group materials.

G.3 Part II: Focus group guidelines (Evaluation content and facilitator questions)

Table G.1 lists the research questions of this thesis, the comparison of the results from the two research methods, and the facilitator's questions. In order to control the research risks, the experts should only make judgments, supplements and improvements to the existing research results, and should not add brand-new viewpoints, concepts or internal connections.

Table G.1 Comparison of the results of the two research methods and questions from the facilitator

NO.	Research themes	Comparison of the results of the two research methods and questions from the facilitator (+ indicates a positive correlation with the research theme, - indicates a negative correlation with the research theme. Interview method is abbreviated as "IM", mathematical modelling method of game theory is abbreviated as "MM")	
1	Optimal level of detail of	Similarities	1.1 Difference in the behavioral cost coefficient of technological innovation (-), difference in reservation profit

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	output specifications		(-), size of risk allocation (+), and difference in construction cost savings rate (+).
		Differences	1.2 Difference in space for technological innovation (IM: not mentioned; MM: +).
			1.3 The level of detail of output specifications is inherently unstable (IM: not mentioned; MM: yes).
		Questions	1.4 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the results of the similarities?
			1.5 Does the difference in space for technological innovation affect the optimal level of detail of output specifications? If so, what is the correlation?
			1.6 Do you agree that the level of detail of output specifications is inherently unstable?
2	Optimal tender offer	Similarities	2.1 Project construction cost calculated by Norm and Standard (+), productivity level (-), construction cost savings rate (-), behavioral cost coefficient of technological innovation (+), deviation risk coefficient of quantities (+), reservation profit rate (+).
		Differences	2.2 Space for Technological Innovation (IM: Not mentioned; MM: -).
		Questions	2.3 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the results of the similarities?
			2.4 Does the space for technological innovation in the PPP project affect the optimal tender offer? If so, what is the correlation?
3	Optimal intensity of incentives	Similarities	3.1 Behavioral cost coefficient of technological innovation (+), profit rate driven (+).
		Differences	3.2 Risk premium (IM: +; MM: not mentioned).
		Questions	3.3 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the results of the similarities?
			3.4 Does risk premium affect the optimal intensity of incentives? If so, what is the correlation?
4	Optimal technological innovation strategy	Similarities	4.1 When the space for technological innovation is sufficiently large, the behavioral cost coefficient of technological innovation (–); When the space for technological innovation is not sufficiently large, the space for technological innovation (+).
		Differences	4.2 Corporate capability (IM: +; MM: not mentioned).
		Questions	4.3 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the results of the similarities?
			4.4 Does corporate capability affect the optimal construction cost savings rate? If so, what is the correlation?
5	Optimal intensity of regulation	Similarities	5.1 Maximum ratio of hiding (+), the behavioral cost coefficient of hiding (-), and the punishment coefficient (-).
		Differences	5.2 Regulation mechanisms and sensitivity [demand for

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			regulation] (IM: +; MM: not mentioned). 5.3 Optimal intensity of regulation can only be effective when used in conjunction with punishment coefficients (IM: not mentioned; MM: yes).
		Questions	5.4 Do you agree with the results of the above similarities? Or do you have any questions, additions or improvements regarding the results of the similarities? 5.5 Does the demand for regulation affect the optimal intensity of regulation? If so, what is the correlation? 5.6 Do you agree that the optimal intensity of regulation can only be effective when used in conjunction with punishment coefficients? What improvement suggestions do you have in this regard?
6	Optimal opportunism strategy	Similarities	6.1 Regulation intensity (–), punishment coefficient (–), expected net benefit (+).
		Differences	6.2 Preference for corporate credibility (IM: -; MM: not mentioned).
		Questions	6.3 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the results of the similarities? 6.4 Does the preferences of enterprise credibility affect the optimal opportunism strategy? If so, what is the correlation?
7	Factors influencing PUPC and their correlations	Similarities	7.1 The factors influencing PUPC include: construction cost calculated by Norm and Standard, discount rate of productivity level (or productivity level), reservation profit rate, behavioral cost coefficient of technological innovation, deviation coefficient of quantities, maximum ratio of hiding, behavioral cost coefficient of hiding, punishment coefficient, external conditions (space for design optimization, space for design deepening), and regulation cost coefficient.
		Differences	7.2 For IM, the factors influencing PUPC also include: construction cost savings rate, risk premium, corporate capability, regulation mechanisms and sensitivity (demand for regulation), expected net benefit, regulation intensity, and preference for corporate credibility. 7.3 For MM, the following can be derived: (1) Factors positively correlated with PUPC include construction cost calculated by Norm and Standard, discount rate of productivity level, reservation profit rate, behavioral cost coefficient of technological innovation, deviation coefficient of quantities, maximum ratio of hiding, and regulation cost coefficient; (2) Factors negatively correlated with PUPC include behavioral cost coefficient of hiding, punishment coefficient, space for design optimization (when $x_0 \leq \frac{1}{2\Phi_1}$), and space for design deepening (when $y_0 \leq \frac{1}{\Phi_2}$).

NO.	Research themes	Comparison of the results of the two research methods and questions from the facilitator (+ indicates a positive correlation with the research theme, - indicates a negative correlation with the research theme. Interview method is abbreviated as "IM", mathematical modelling method of game theory is abbreviated as "MM")	
			7.4 For MM, actively adjusting or optimally selecting exogenous variables that affect PUPC is the basis for the public authority to save PUPC.
		Questions	7.5 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the results of the similarities?
			7.6 Do you agree with the research results in clause 7.2 above? If so, what is the correlation with PUPC?
			7.7 Do you agree with the research results in clause 7.3 above?
			7.8 Do you agree with the research results in clause 7.4 above?
8	Path to save PUPC	Similarities	8.1 The optimal intensity of incentives and the optimal intensity of regulation aim to minimize PUPC.
			8.2 The optimal construction cost savings rate is negatively correlated with PUPC.
			8.3 The optimal opportunism strategy is uncorrelated with PUPC.
			8.4 The six optimal strategies constitute the equilibrium path of the game, and they are in equilibrium with each other.
			8.5 "Independent variable (or subcategory) → six optimal strategies → PUPC" is the path that minimizes PUPC for the public authority.
		Differences	8.6 Optimal level of detail of output specifications aims to minimize PUPC (IM: minimize/uncertain; MM: minimize).
			8.7 Relationship between the optimal tender offer and PUPC (IM: +; MM: uncertain).
		Questions	8.8 Do you agree with the results of the above similarities? Or do you have any questions, additions, or improvements regarding the findings on similarities?
			8.9 Should decisions about the optimal level of detail of output specifications for the public authority aim to minimize PUPC?
			8.10 Can the correlation between the optimal tender offer and PUPC be determined? If so, what is the correlation?