# ACHIEVING PUBLIC AGENCY GOALS IN PUBLIC-PRIVATE PARTNERSHIPS USING INNOVATIVE PAYMENT MECHANISMS

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## Abstract

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Public-Private Partnership (PPP), as an innovative project delivery method, is increasingly used due to its advantages in relieving the capital pressures on project development and involving more life-cycle considerations in project early planning stage. Under a PPP concession contract, the achievement of public agencies goals can be facilitated through linking the contractor's compensation, referred to as payment mechanism, to the realization of stated project performance and achievement of government goals. Payment mechanism lies at the heart of PPP contracts. A good design of the payment mechanism should consider public agencies goals in the project, allocate risks appropriately to stakeholders, and assure satisfactory performance through providing a reasonable compensation to the private developer. While the procedures and recommendations for the design of payment mechanisms have been widely discussed in publications, guidance on how to link the achievement of project objectives with the concessionaires payment is relatively scarce. As such, the concessionaire would be getting compensation without being subject to scrutiny over the achievement of project objectives. In this case, the public agencys goals (e.g. improve roadway safety and availability) may not be fully achieved through PPP. Additionally, the design of payment mechanisms in the existing PPP projects heavily relies on the subjective judgment of decision makers, which is hard to guarantee the trustability of the payment mechanism. To deal

with the these deficiencies as well as to provide a systematic understanding of the design of payment mechanism, this study undertook an in depth literature review on the design of payment mechanisms, conducted a content analysis of several guidance documents regarding payment design from different countries, analyzed the payment-related contractual terms of more than 89 PPP projects and conducted questionnaire surveys to PPP experts from both academia and industry. Based on such works, a practical explanatory framework was developed to assist public owners in designing proper payment mechanisms for transport PPPs. The framework helps in (1) identifying the key considerations, (2) prioritizing project goals, and (3) deciding proper payment schemes and payment type(s). This study further proposed a Stackelberg game theory-based model to determine the optimal amount of payments assigned to each goal. The model searches for solutions that maximize the overall project performance for the sake of social welfare while simultaneously maximize the return for the sake of private investment. A case study based on a real PPP project was discussed to validate the effectiveness of the proposed model. Public agencies would use the framework as a reference to revisit and improve their design of payment mechanisms for their PPP project. Also, the solution provided by the model revealed that the optimal payment mechanism structure could be reached such that it would satisfy the owners requirements for the overall project performance while optimizing the project total payments to the contractor.

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# DEDICATION

***This dissertation is lovingly dedicated to the memory of my beloved grandma, Ren-e Che. You are the reason why I completed this journey.***

# Chapter 1

# INTRODUCTION

## *1.1 Background of the Study*

A number of objectives, such as high-level quality, efficiency, safety, and sustainability, have been set by the public agencies in the current development of infrastructure around the world. The efforts to achieve such objectives were great, and significant successes have been reached through advancement in the engineering and technological aspects that, for example, provided for better building materials and mix design, better structural and geometrical design, optimum frequencies for preventive maintenance, and various maintenance types. However, beyond these engineering methods, little attention was given to investigate other venues for delivering infrastructure with better performance. For that reason, innovative contractual methods represent the subject of the proposed research.

One of the main obstacles for implementing the advanced engineering methods is the availability of funding [1]. A better design that provides for longer and optimum building life cycle would require more initial capital/improvement costs; similarly, an optimum maintenance and repair cycle would require future funding that might not be available, as well. For example, in the transportation sector, it is fair to assume that the roads that lack sufficient funding for regular maintenance and repair are more prone to pavement cracks, rutting, potholes, and some other distresses and deficiencies that all provide for unsafe driving conditions and more traffic accidents. An evaluation report recently rated the United States roads at D level (i.e. Poor or at risk performance) with an estimated \$3.6 trillion investment required by 2020 to improve road conditions and performances, which means \$170 billion needed on an annual basis [68]. Funding for maintenance and repair is usually provided through government tax revenues. However, with the continuing shortage of the government funds, projects may have to compete against each other to get sufficient and timely funding for maintenance and repair.

Another obstacle for improving the life cycle performance of an infrastructure project is the separation between, and the timing of, the capital investment decisions and the repair and maintenance decisions. This separation leads to projects that would be built and then left for future uncertainties about their maintenance and/or repair. For example, most of the current infrastructure projects that are delivered by traditional methods such as Design-Bid-Build (DBB) use the lowest bid criteria for procurement. In such a way, it is hard to ensure the life cycle operation and maintenance needs and requirements of a facility can be fully considered in the project beginning phase. Further, in the traditional contract, the public agency assumes most of the risks in the design and the future performance of a facility. The contractor carries limited risks except for those linked to the materials and workmanship and for a short period of warranty.

The above obstacles and the essential need for better facility performance may require public agencies to expand beyond the engineering and traditional procurement methods by exploring the innovative contracting and alternative project delivery systems. Adding new venues would supplement existing methods by providing better formula to achieve the public agencies goals in infrastructure.

From a contractual perspective, it was not until the advent of the alternative contracting and project delivery methods such as design-build (DB) with its performance warranties, construction manager at risk (CMR) or the construction management/general contractor (GCCM), design build operate maintain (DBOM), design build finance operate maintain (DBFOM) delivery systems that the life cycle issues of construct-ability, repair and maintenance, asset condition, building performance, and safety started to gain more considerations during the procurement process of a facility [34][86]. For example, the life cycle cost for maintenance of pavement has been increasingly used as one of the criteria in the US transportation sector for selecting a builder for DB projects [63].

Eliminating the deficiency of initial capital cost, securing financing for future repair and maintenance, coordinating the decisions and timing of capital procurement and future maintenance, maintaining the facility at a state of good repair, and operating for sustainability are but some of the objectives public agencies can achieve by using the innovative contracting and project delivery systems, generally referred to as public-private partnerships (PPP) [1][28]. The extensive uses of PPP have been demonstrated considerable acceptance in several parts of the world. A public financing database of worldwide projects between 1985 and 2004 shows that 1,121 PPP infrastructure projects (i.e. roads, rails, airports, seaports, water, and buildings), representing $450.9 billion worth of investment, were funded and completed with the majority of the projects being in Europe, Asia, and the Far East [26]. According to the World Bank [107], investment commitments involving private participation in low and middle-income countries for energy, transportation, and water infrastructure totaled $36.7 billion across 132 projects in the first half of 2017 with a 24 percent increase over the same period in 2016. In the United States, the use of PPP has also been on the rise. Thirty-three states and the District of Columbia and Puerto Rico have authorized the use of PPP [65].

## *1.2 Introduction of Public-Private Partners (PPPs)*

Public-Private Partnership (PPP), originated in the UK known as Private Finance Initiative (PFI), is an innovative procurement model for public sector infrastructures, facilities, and services [113]. It can be broadly defined as a long-term agreement, usually over 20 years, between public and private sectors for mutual benefit [13]. PPPs exist in a variety of industry sectors. Each sector offers unique challenges and opportunities for PPPs due to differing in legal, regulatory and investment considerations. According to the World Bank PPPLRC (PPP Legal Resource center) [109], PPP has been widely used in the following main sectors: clean technology, energy, and power, solid waste, information & communication technology, transportation, water, and sanitation. The key successful factor of implementing PPP is to seek the optimal balance of responsibilities, risks, and rewards between the public sector and the private sector. One of the most common ways of implementing PPP in managing infrastructure is through a concession approach, which consists basically in transferring final design, construction, and maintenance and operation of the infrastructure to a private consortium, in exchange for the right to receive profitable compensation by charging fees to the user (e.g. tolls) or to the government on behalf of the user (e.g. shadow tolls) for a period of time contractually agreed in advance [100].

According to the public agency major needs, the approaches of using PPP can be categorized into three groups, including the finance-based approach, the service-based approach, and the mixed approach that combined these two approaches [47][49][96][117]. Finance-based PPP mainly uses a large portion of private capitals to develop the infrastructure and relies on the future usage fees to compensate the private sector. The early PPP projects were predominately finance-based. The motivation of implementing service-based PPP is that to use the techniques, innovation, and management of the private sector to optimize the efficiency (i.e. time and cost) in project development and operation, most common in DBOM and BTO (build-transfer-operate). The third approach is a combination of the first two, which combines the financial need and the technical consideration together. The typical delivery models of this approach include DBFO (design-build-finance-operate) and DBFOM.

There are two major payment strategies can be used in a PPP project, including the demand-based payment and the performance-based payment. In the demand-based payment, the concessionaire will get the compensation based on the actual use of the property, while in the performance-based payment, the concessionaire receives periodic payments from the public agency over the concession term, so long as the performance in accordance with the requirements. With the emergence of services-based and mixed PPPs, the procurement approach is getting evolved from the demand-based approach to the performance-based approach. Such performance-based payments allow the public agency to have more considerations on the life-cycle issues of construct-ability, repair and maintenance, asset condition, and other performance, especially during the procurement phase [86].

Under a PPP contractual system, the project goals, such as safety and sustainability, can be achieved in a number of ways through the technical requirements; while, a more proactive way is to link the contractors compensations to the achievement of the agency goals [88]. In a PPP contract, the way to distribute these compensations is usually referred to as the payment mechanism, which is a package that usually includes one or more different types of payments [74]. In traditional project delivery systems, payment mechanisms provide compensations to the Contractor by using construction capital payments that are usually calculated based on quantities of works, material costs, and labor and equipment hours, without the consideration of project performance. In the alternative PPPs, different types of payments are used to satisfy the different objectives of the government in a project. Common types of payments used in PPP projects have been identified including capital payment, usage/capacity payment, availability payment, operation & maintenance payment, safety payment, user satisfaction payment, quality payment and end of term payment [2]. Such payments can be called functional payments since each of them is selected to achieve a particular goal in a project.

The use of the alternative contractual systems with an innovative payment mechanism is getting momentum in the US. The Federal Government supported these systems, provided several credit facilities to encourage PPPs, and advocated PPPs in 2009 Moving Ahead for Progress in the 21st Century Act (MAP-21). Further, the recent federal Fixing Americas Surface Transportation Act of 2015 provided for the establishment of a National Surface Transportation and Innovative Finance Bureau to help states and private partners move transportation projects forward.

More and more newly issued PPP projects start to adopt performance-based payments in which the private partner would get part of its compensation based on the quality of service performance, such as the availability of lanes and condition/state of the pavement. It can be regarded as the management of PPP projects is evolving to a proactive way. In a proactive way, the private partners compensation should be linked to the achievement of the governments goals [3]. For instance, Okanagan Lake Bridge (OL), BC Canada, is a case that a number of types of payments are selected to achieve particular project goals. Based on a sound expectation for the increasing of traffic demand, the government aimed to optimize traffic capacity and to maintain a good roadway condition. In this respect, the availability payment accounts for 60%-70% of the total payment mechanism in the OL project [2]. The amount of safety payment is also included in the OL project for the consideration of safety improvement. Additionally, a usage payment and a user satisfaction payment are also included in the project and account for 30% and 1% respectively, which aim to encourage the contractor to provide a better road service and attract more traffic volume.

Another example is the case of the Sea-to-Sky (STS) highway, which was a 100 km improvement project, between Vancouver and Whistler (BC), developed under a 25-year DBFOM performance-based contractual agreement with a total cost of $600 million. The project was funded by the BC government without charging tolls. The government had particular objectives for the project and used PPP and particularly the payment mechanism to achieve the objectives:

- Achieving better safety performance particularly in the mountain areas;
- Maintaining the highway in good condition throughout the 25-year agreement;
- Maintaining the availability of the highway and attracting more traffic to the highway; and
- Transferring the asset in good conditions after the expiration of the agreement.

The STS agreement linked the contractors compensation to the achievement of the above agency objectives. The structure of the payment mechanism, shown in Table 1.1, included availability payment with deductions for substandard performance (e.g. pavement condition and performance), vehicle usage payment, safety incentive payments, and end-of-term payment (based on acceptable facility conditions). Every performance measure carries a particular set of deduction points, which carry dollar penalty if benchmark points are reached [2]. The different payment types in the mechanism carried particular percentages (Table 1.1) reflecting the relative importance of the agency objectives in the project.

Table 1.1: STS Highway Payment Mechanism [2]

| Functional Payment | Percentage in Total Annual Payments |
|---|---|
| Availability Payment | 80-85% |
| Vehicle Usage Payment | 10-15% |
| Performance Incentive Payment (Safety) | Not limited to the payment ceiling |
| End of Term Payment | Not exceed a gross amount |

## *1.3 Statement of the Research Problem*

*The lack of appropriate standards and frameworks for guiding and regulating the design of payment mechanism leads the inability of fully addressing and achieving government objectives in PPP concessions.*

Despite the efforts, the US federal and state regulations provided no guidance on how to proactively implement public agency goals in PPP projects (i.e. improving the safety performance of a highway project, improving building sustainability, etc.) through payment mechanism. A payment mechanism, consisting of a set of functional payments, should reflect the governments specific objectives in a project. A well-designed payment mechanism could be used as the government vehicle of transferring the risk and responsibility to the private sector in a proactive way. However, the design of payment mechanism in current PPP projects has not been given enough attention [70]. There were no guidance or mechanisms for selecting payment types based on the project objectives, linking the payment with the performance measures, setting deduction schemes for unsatisfactory performances, and setting the percentage of each payment in the mechanism to reach the optimal outcome [89]. Some example cases include the 2005 Washington State Transportation Innovative Partnerships Act, the Oregon State Innovative Partnerships Program, and the 2015 federal STRR Act.

Moreover, most current agencies decided a payment mechanism arbitrarily based on their past experience and/or familiarity of PPP payment types. For example, most of the PPP highway projects in the US adopted usage payment (relied on toll revenues) in the early stage, and recently moved to use availability payments. However, in both cases there was no clear guidance of how agencies objectives were linked to the payment [88]. For example, in a recent research conducted regarding roadway safety of PPP projects, the author found that safety was one important goal to the highway agencies, but there was no clear articulation on how to enforce that, and no link found between compensation and safety performance [89]. Also, the U.S. Department of Transportation (USDOT) published the PPP best practices suggesting the public owners to link payment mechanisms to the achievement of project goals, yet they failed to provide guidance on how to achieve that [97].

The design of payment mechanisms for PPP projects is also a new area in the academia. Research on the design of performance-based payment regarding aligning project goals with payments are relatively scarce, and most of which focused on specific types of payments, such as availability payment [21][64][72][90] and safety payment [76][99][100]. Only a few studied discussed the design of a payment mechanism by combining different functional payment together into a single package [2][88]. However, the current way to combine different types of payments into a payment mechanism heavily relies on the experience and/or subjective judgment of the public agencies. No study investigated how to scientifically design a payment mechanism by determining the optimal combination (i.e. weights/percentages) of different types of payments.

A good design of the payment mechanism should be able to reflect the owner's goals in the project and to assure satisfactory performance through linking the Contractors compensation to the performance. However, in a recent research, the author found that nearly most of the transportation PPP projects in the US have not articulated the agreements to enforce the project performance (e.g. roadway safety) beyond what is traditionally available on the technical regulation. And none of such PPP projects have provided for linking the achievement of project goals to the contractors compensation [89]. As such, private parties would be operating transportation facilities and getting compensation without being subject to scrutiny over the performance of the facilities. In this case, the public agency objectives in a project cannot be achieved successfully through PPP. Additionally, the motivations driving efficient PPP delivery may be perverted and the effective risk transfer may be undermined [101]. In a worse case, an inappropriate payment mechanism may reversely increase risks to both participants and even lead to project failures, such as projects suffered by bankruptcies (e.g. SR 125) and projects in which private sectors earned super profits (e.g. the Chicago Skyway) [90].

## *1.4 Research Objectives*

In view of the importance of the payment mechanism, this study aims to develop a framework providing reference for the design of payment mechanism for transportation sector. The research objectives can be specifically summarized as follows:

1. Develop a practical explanatory framework for the design of the payment mechanism that can be used for transportation PPP projects. The framework provides for the public agency the process of identifying project goals, selecting appropriate payments, and linking the payments to the performance.

2. Develop a game theory based model for optimizing the design of payment mechanisms by deciding the optimal percentage/weight of each functional payment in the payment package.

Public agencies in the US and other countries global wide are expected to be the main group of users of the proposed framework and the optimization model. By referring to the output of this research, the agency goals in different aspects (i.e. safety, sustainability, etc.) are expected to be achieved in a more efficient way than relying solely on regular contractual terms and traditional payment methods. On the other hand, the framework and the model can also provide references for the private sector to preparing their bidding strategies during the project procurement phase. The current research limits on the transportation projects only, however, in the future study, the proposed framework is expected to be further generalized to fit for other sectors, such as energy and water.

## *1.5 Overview of the Research Methodology*

This section provides a brief overview of the research methodology. The details will be further discussed in the methodology chapter. Overall, the research starts with problem identification and ends by providing the results and marked conclusions. The main process of the research consists of three phases, and each phase has a set of tasks (more details in Chapter 3). The three major research phases are listed in the following:

- Phase 1 - Development of An Explanatory Framework for the Design of Payment Mechanism;
- Phase 2 - Development of a Game Theory Based Optimization Model;
- Phase 3 - Case Study and Validation

The research methods were designed to serve for the aforementioned research objectives and tailored to fit the limitations (e.g., incomplete database) as will be detailed later. Generally, this research uses both qualitative and quantitative methods, including comprehensive literature reviews, the content and comparative analysis, the questionnaire survey, statistical analysis, optimization modeling, and the empirical case study.

## *1.6 Contribution*

The research is expected to make the following major contributions:

1. Establish a systematic understanding in the design of payment mechanisms in transportation PPP projects;
2. Develop an explanatory framework to guide the public agencies in linking the project goals to the payment mechanism; and

3. Develop a model to capture the principal in project contracting and to achieve the optimal payment structure.

This study is beneficial to the public agencies in preparing payment mechanisms for transportation PPP projects. It identifies and quantifies the factors that affecting the design of payment mechanism in PPP and provides guidance for linking the project goals to the payment mechanism. This research also sheds light on the development of optimization in PPP payment mechanism, which provides a quantitative perspective for determining what types of payments and the most appropriate proportion of each payment should be contained in a payment mechanism. Both public sector and private sector can adopt this framework to assess the performance of their PPP payment mechanism. And the results can be employed to compare the risk levels with their counterparts for bench-marking purposes. As a future work, the framework and the optimization models developed in this study can be further translated into Excel plug-in or separate software that can be easily applied in the industry.

## *1.7 Organization of the Dissertation*

This research was organized into nine chapters in total. Chapter 1 provided an overview of the research, including, such as, introduced the general background information, stated the research problem, outlined the research objectives, proposed the research methods, and discussed the significance.

The next chapter, Chapter 2, provided a comprehensive literature review with the intent of providing a systematical understanding of the topics related to this study. Chapter 2 began with a comprehensive introduction of PPP through the first three sections. The payment mechanism used in existing transportation PPPs and the current standards for the design of payment mechanisms were summarized in the end of this chapter.

In Chapter 3, the author presented the details of the methodology utilized in achieving the proposed research objectives. In the following, Chapter 4 and 5 discussed data collection and the preliminary analysis based on the collected data. In Chapter 4, the payment-related contractual documents of the current performance-based PPP projects were collected and analyzed through the content and comparative analysis. The similarities and differences of payment mechanisms used between the US PPP projects and the international projects (represented by Canada) were explored. In Chapter 5, a questionnaire survey was conducted to explore the key factors that should be considered during the design of payment mechanisms for transportation PPP projects. The findings from these two chapters provided a systematical understanding of the design of payment mechanisms, which formed the basis of the proposed framework.

In Chapter 6, based on an in depth review of the published articles, the guidance documents, and the PPP project agreements regarding the design of payment mechanisms as well as the preliminary analysis results from Chapter 4 and 5, the explanatory framework was proposed to assist decision makers in formulating the appropriate payment mechanism that meets the project objectives and characteristics.

By capturing the nature of the PPP contracting and negotiating, Chapter 7 developed a game theory based model to optimize the design of payment mechanism. The model was designed to include the considerations of both the public and private sectors. The solutions provided by the model were expected to maximize the overall project performance for the sake of social welfare while simultaneously maximize the return for the sake of private investment. Chapter 8 provided a real project based case study to validate the practicality and usefulness of the proposed model.

The research was concluded with a detailed discussion in Chapter 9. A summary of the research objectives, procedures, and major findings was included. The current research limitations and the recommended future moves were also provided in Chapter 9.

# Chapter 2

# LITERATURE REVIEW

## *2.1 An Overview*

Public private partnership (PPP) is an alternative procurement delivery system for the development of public facilities and infrastructure [37] [113]. It can also be broadly defined as a long-term agreement, usually over 20 years, between public and private sectors for mutual benefit [97]. The benefits of implementing PPPs have been summarized by Derek and Foster [12] as 1) reducing the role and scope of the government, whilst inviting private sector involvement in this gap left; 2) creating new opportunities for private expansion into traditional areas of the public sector; 3) attracting new capital resource and investment from the private sector; 4) spurring competition by increasing market pressure on services remaining within the government.

## *2.2 PPP vs. Other Delivery Methods*

This section discussed two main questions on (1) how PPP models are similar or different with other project delivery methods; and (2) how various PPP models are similar and/or different with each other. According to a comprehensive literature review, the author proposed a number of factors that help in categorizing the various project delivery methods and identifying the similarities and/or differences among them, summarized in Table 2.1.

These factors can be grouped into three levels of details. The five factors in the first level are majorly used to distinguish between PPP and the other project delivery methods (e.g. design-bid-build). Such factors are useful for decision makers to select the most suitable delivery method based on their project characteristics and requirements. The second level of detail includes two factors that aim to identify the similarities and/or differences among

Table 2.1: The factors used to classify project delivery methods

| **Level of Detail** | **Factor** |
|---|---|
| Level 1 (the general level | a) Project Ownership<br>b) Performance Quality (i.e. schedule and cost)<br>c) Capital Resource<br>d) Owner's Control<br>e) Risk Allocation |
| Level 2 (the project level) | f) Project Financing<br>g) Service and Technique Consideration |
| Level 3 (the contract level) | h) Payment Mechanisms |

various PPP models. The factors in this level could help decision makers to further determine the right PPP model fit for their project once they have decided to adopt PPP rather than other delivery methods. The third level categorizes PPP projects into more detailed types (e.g., performance-based PPP vs. demand-based PPP).

### *2.2.1 Forms of Project Delivery Methods (Traditional vs. Alternative)*

In construction, it is important for the owner to select the most suitable project delivery method since the method will determine the contractual relationships, the ownership, and the project overall cost [5]. A good understanding of choices available is critical to make right decision. Several commonly used project delivery methods have been summarized in the following:

- DBB (Design-Bid-Build), as one type of the traditional project delivery method, typically contains three sequential stages, including a design stage (architectural and engineering services), a bid stage (selection of the general contractor and subcontractors), and a construction stage.

- MP (Multi-Prime) is similar to DBB regarding the three aforementioned stages. However, in the MP, the owner contracts directly with specialty contractors for specific elements of work and there is no a single general contractor.

- In DB (Design-Build), a single entity provides the design and construction of a project and there is only one contract with the owner that combined the design and building services together. In some literature, DB is also considered as one special type of PPP model.

- in CM (Construction Manager) or CM/GC (Construction Manager / General Contractor) method, the owner contracts with a construction manager to manage and construct a project. Such a construction manager participates in the design phase to bring the construction considerations in advanced and takes the general contractor's responsibility during the construction phase.

### *2.2.2 The Comparison between PPP and Other Project Delivery Methods*

There is no agreement within the literature on a precise definition for PPP. FHWA (Federal Highway Administration) defines PPP as a concession that bundles design, construction, finance, operation, and maintenance together and transfer these responsibilities to a private sector during the concession term. By NCSL (National Conference of State Legislatures), PPPs are agreements that allow private sectors to take on traditionally public roles in infrastructure projects, while keeping the public sector ultimately accountable for a project and the overall service to the public. The World Bank defines PPP as a mechanism for government to procure and implement public infrastructure and/or services using the resources and expertise of the private sector. The literature in the field is mired by a terminological ambiguity that has resulted in a large diversity of working definitions [40]. However, this is one thing for sure - that is what a PPP is not: it is not privatization [54]. A common way to interpret PPP is that as a project delivery method in which a private entity takes a part in developing and/or operating a public facility in return for monetary compensation while the ownership still retained by the public agency.

In this subsection, the factors in Level 1 (Table 2.1) are used to facilitate the discussion of the similarities and/or differences between PPP and other project delivery methods.

- **Project Ownership**: PPP and other project delivery methods are different from privatization, where the ownership or title of a public facility is transferred to a private entity. Therefore, for the project ownership, PPP are similar to other project delivery methods which permit the public agency to retain full ownership of an infrastructure project.

- **Performance Quality**: Since a PPP project commonly combines several services, such as architectural and engineering design, construction, operation, and maintenance, under one contract, the owner gains the benefit of having the opportunity to incorporate perspectives from different participants and input to the early planning and design stage. As such, PPP is expected to provide a high-level quality during the project delivery period, because it can efficiently reduce the conflicts between the design and construction. Under this factor, the other delivery methods that are similar to PPP include DB and GCCM. The high-performance quality has become an advantage of the alternative delivery methods (i.e. DB and PPP) when compared with the traditional DBB or MP. In addition, the involvement of private sectors may significantly improve the efficiency of development and/or operation by introducing innovative technologies and managements that the public agency may have difficulty in doing so due to the political, financial or other limitations [4].

- **Capital Resource**: Although it is not necessary to involve private investment in a PPP project, whether to involve private capital is still one of the major differences between PPP and other delivery methods. By involving the private investment into the project, the public sector can postpone payments or leverage future revenues for purposes of fulfilling present demand. As such, the limited federal, state, or local capital resources can be allocated to other important uses. For the consideration of this factor, PPP is expected to perform better than other delivery methods because of its potentials to free public funds for other uses and close the financial gaps.

- **Owner's Control**: Another major difference between PPP and other project delivery methods is the level of owners control for a project. The owner has the least power of control in a PPP project compared to other delivery methods. To this factor, one advantage of the traditional delivery methods (DBB, MP) is that the owner has a significant amount of control over the end product.

- **Risk Allocation**: Generally, the level of control provided to the owner correlates with the level of risk. Since PPP provides the owner the least level of control, the owner then benefits from taking the least level of risks comparing to the other delivery methods. In fact, a strategy in PPP is to transfer certain project risks to the party that is best able to control and manage them [112]. The risks that a private sector in a better position to control than the public sector include design risks, construction risks, and the operation and maintenance (O&M) cost overrun risks. Additionally, for some PPP projects wholly or partially funded by the private sector, financial risk and demand risk (market risk) are also allocated to the private part. The risk allocation parameter, therefore, can be regarded as one important benefit of PPP comparing to other delivery methods.

### *2.2.3 The Common PPP Models*

There are a number of PPP models that are used commonly in the market, including BOT (Build-Operate-Transfer), O&M or OMM (Operations, Maintenance, and Management), DB, DBOM (Design-Build-Operate-Maintain), DBF (Design-Build-Finance), and DBFOM

(Design-Build-Finance-Operate-Maintain) [4] [54] [74].

In a **BOT contract**, the private partner is responsible for building the project and to operate it for a certain time period under a contract with the public agency. At the end of the contract, the project will be transferred to the public agency. In most cases, the private partner will provide some, or all, of the financing for the project development and operation during the contract period. In an **O&M or OMM contract**, a public sector purchases the service from the private sector to operate, maintain, and manage a facility. Under such contracts, the public sector retains ownership of the facility. In a **DB contract**, the public sector provides the financing and procures from a private partner what is traditionally a fixed-fee contract, that is, both the engineering and construction services. In this setup, the private partner assumes the responsibilities and risks that come with completing the project for a fixed fee within a given time-line. The public sector maintains full ownership and financial liability for operation and maintenance. **DBOM** is a significantly more sophisticated PPP model that adds operation and/or maintenance responsibilities to designing and delivering the project. While still financing the project, the public sector procures the design, construction, operation and/or maintenance from the private sector through a single contract. Typically, the public sector continues to assume the full financing burden (inclusive of revenue risks), but also keeps any possible surplus revenue from operations. The **DBF PPP** model combines the partial or full financing of the project with its design and construction through a private sector. However, the public sector retains full responsibility and risk associated with its operation and maintenance. **DBFOM** is an extension of a DBF contract in which the financing, design, construction, operation and maintenance responsibilities are bundled together under one contract with a private sector.

### *2.2.4 The Comparison among PPP Models*

The differences among various PPP models are identified based on the two factors in Level 2 (Table 2.1). There are two major approaches for implementing a PPP project, including the finance based approach and the service based approach [1].

The service based PPP aims to use the expertise, innovations, and management of the private sector to improve the efficiency and qualities of the project, such PPP models include O&M or OMM, DB, and DBOM. The service based PPPs have two main advantages, including (1) allow the public sector to make use of private sector expertise, and (2) introduce an important level of quality and cost control. DBOM can be regarded as a combination of O&M or OMM and DB, which has all the advantages of them plus a few others [79], such as (1) it conditions the private sector to account for maintenance and operation costs early in the design stages; (2) it provides ample opportunities for the private sector to achieve efficiencies while maintaining quality; and (3) it shifts a greater portion of responsibilities and risks to the private partner.

Unlike the service based PPP, the finance based PPP aims to use private financing to satisfy the infrastructure needs [1], such models include BOT, DBF, and DBFOM. There are some important benefits that are associated with such finance based PPPs when compared to those service based PPPs [4]. First, it frees the public funds and allows the public agency to tap into other projects. Second, it fills the gap between the government funding and the infrastructure needs. Third, the financial risks associated with the project can be wholly, or partially, transferred to the private side.

There is no strict distinction between the service based PPP and finance based PPP. A service based PPP contract can allocate part of financial risks to the private sector as well by involving private investment, and a finance based PPP contract can also require the private sector to provide a high quality of development and operation service. A good PPP model should be designed and/or modified based on the particular project requirements. Therefore, it is stated in the National Council For Public-Private Partnership (NCPPP) PPPs come in a variety of forms and no two PPP project are exactly alike.

In additional, due to the different payment methods, the PPP can be divided into demand-based payment and performance-based payment. The contractors revenue highly depends on the market in a demand-based contract and paid by usage (e.g. tolls). Under a performance-based payment, the private partner receives periodic payments from the public agency during the operation and maintenance phase so long as the facility is satisfied for use in accordance with detailed requirements and performance standards set out in the contract. Each PPP model can adopt either of these two payment methods and there is no hard line to distinguish PPP models based on the payment mechanism parameter (Level 3). The details regarding this aspect will be discussed further later

## *2.3 Risk Management in PPPs*

### *2.3.1 The Risks in PPPs*

A significant body of research has been published in risk identification and analysis for PPP projects. Bing et al. [11] identified the risk factors in PPP projects and categorized them into three meta-levels, including Macro level risks (i.e. economic or politic environment), Meso level risks (i.e. project demand/usage, issues in construction), and Micro level risks (i.e. stakeholder relationships). In another research, Xu et al. [110] identified 37 risk factors through a comprehensive literature review and a questionnaire survey. 17 of these risk factors were selected as the critical risk factors fit into 6 categories, including Macroeconomic Risk, Construction and Operation Risk, Government Maturity Risk, Market Environment Risk, Economic Viability Risk, and Government Intervention Risk.

Construction and operation related risks (e.g., delay in construction completion, cost overruns in both construction and operation stages) can be handled well by using advanced technologies and/or contracting out the responsibility. Instead, the market risk (e.g., the uncertainty of project demand/use) is more likely to cause failures in PPP projects. For example, Checherita and Gifford [18] pointed that the demand risk remains the most important risk attached to toll-road infrastructure in the US. In Addition, many other risk factors also need to be considered in PPPs due to the usually long term contract, such as political risks and financial risks. For example, the political risks are mainly caused by the uncertainties of the the political events (e.g., tax code revisions, currency devaluation, export restriction, etc.) [51]. The change of such political events might impact the investment environment and lead to economic losses of the PPP investors. Such risks highly depend on the macroeconomic environment and are hardly controlled by a PPP consortium.

### *2.3.2 Risk Sharing and Mitigation Strategies in PPPs*

One of the main objectives in PPPs is to transfer the project risks to the party that is best able to control and manage it [112]. The risks a private sector is in a better position to assume include design risks, construction risks, and the future O&M risks. On the other hand, the government should retain a set of macro-level risks, such as the political risks, economic or narrowly financial risks. As one of the most important risks in PPP, the allocation of demand risk is subject to several considerations and is discussed detailed in the following.

There are three strategies for allocating the market risks [11], including 1) assumed fully by the private sector (consortium), 2) assumed fully by the government, and 3) shared by the private and public sectors.

Traditionally, a common risk management strategy is to allocate the demand risks to the private sector. Projects with demand risk allocated to the private consortium are generally paid for from project usage and user tolls. For these projects, agreements may provide for substitution clauses that give step-in rights to the lenders in case of default on payments. Further, the agreements usually require insurance and security packages to protect the government in case of developers default. A consequence of such demand risk allocation is that a risk premium will be charged by lenders to cover the demand risk. This premium will show up in the cost of finance, resulting in higher project costs and ultimately in higher toll rates charged to the end users. Additionally, since tolls and project demand are the basis for revenue determination, protection through a no-second facility, absolute-protection-zone, or non-compete clause are important to guarantee project revenues. These clauses, however, could be problematic as they might hinder the governments maintenance, rehabilitation, and road upgrades around the project area.

Another approach for risk allocation comes from the British Columbias and the United Kingdoms real PPP cases. In British Columbia and the UK, the government usually retains all traffic demand risks. In such cases, contractors compensation is paid from the government funds mostly based on the availability of the services and to a much lesser extent on usage (demand). However, in this way, the government will bear an enormous financial pressure and be highly exposed to the risks.

An optimal strategy is to share the demand risks between the public and private sectors in order to achieve better value for money. With part of the demand risk retained by the government, the risk premium in the cost of finance should be largely reduced when compared to the strategy that the private sector assumes all the risk [11]. Consequently, the overall project cost will be reduced. This should eventually give better value for money. In practice, due to the uncertainty of forecasting future traffic demands, the private sector often requests government support to share the financial risk of overestimating project revenues. One of the most popular forms of government support instruments is minimum revenue guarantee (MRG). The government can provide this support to the private sector when the actual toll revenues are lower than anticipated [57]. Hence, MRG is a mechanism for sharing the revenue risk between the concessionaire and government.

The selection of risk mitigation strategies should be based on the risk level (i.e. low risk vs. high risk) of a PPP project. According to the literature [85], a model was developed to assess the risk level to be faced in pursuing the project. Based on the model as well as the major financial risks a PPP consortium may assume in a project, the mitigation strategies can be discussed under three scenarios, including high political risk, high narrowly financial risk, and high market risk situation.

The political risks can be mitigated through seeking assistance from influential individuals or organizations who have a rapport with local government authorities, involving international firms or organizations to create leverage with local government authorities, and seeking government participation [85]. All such strategies have one common purpose that is to obtain government support and guarantees. On one hand, the political support will facilitate the project success. For examples, The Shajiao B Power Project in China was promoted due to the support from an influential Chinese champion and the direct political relationships between the investors and the local governments facilitated the developments of the Paiton I Power Plant Project in Indonesia and the North-South Highway Project in Malaysia. On the other hand, the government guarantees can help project investors to obtain economical financing benefits. This is the case in the Rizhao Power Plant Project in China. The support and indirect guarantees from Chinese authorities helped the project largely reduce the political risks and have a debt-to-equity ratio of 3.40 which only can be achieved in very low-risk projects.

The strategies used to mitigate the narrowly financial risks include the use of international lending institutions, use of debt financing with a fixed rate, denominating loans in local currency, and denominating a portion of the revenue in foreign currencies [85]. The financial risks can be mitigated through using the loans from international lending institutions, because these loans usually have low-interest rates and provide friendly support to the development of developing countries. To adopt a fixed-rate debt can also mitigate the financial risks since it hedges the uncertainty of interest rate changes. To structure local currency loans to match the revenues which are denominated in local currency is useful to mitigate the risk from future exchange rate fluctuation. If a project involved both the local loans and the foreign loans, a way to mitigate the risk of the currency exchange rate is structuring project revenues in both local and foreign currencies.

The market risk can be reduced in an early planning stage by well-designed contractual provisions (i.e. revenue guarantee) and careful estimation of the market demand. However, it cannot be eliminated. When the market issues happen, two ways can be used to mitigate the risks, including structuring the debt repayment schedule and refinancing and/or debt restructure [85]. Since the initial years of operation have a high risk of low revenue, it is useful to mitigate this risk by structuring the debt repayment schedule to start low and escalate later. The refinancing and/or debt restructure will be useful to solve the cash deficiency caused by the underestimated revenue.

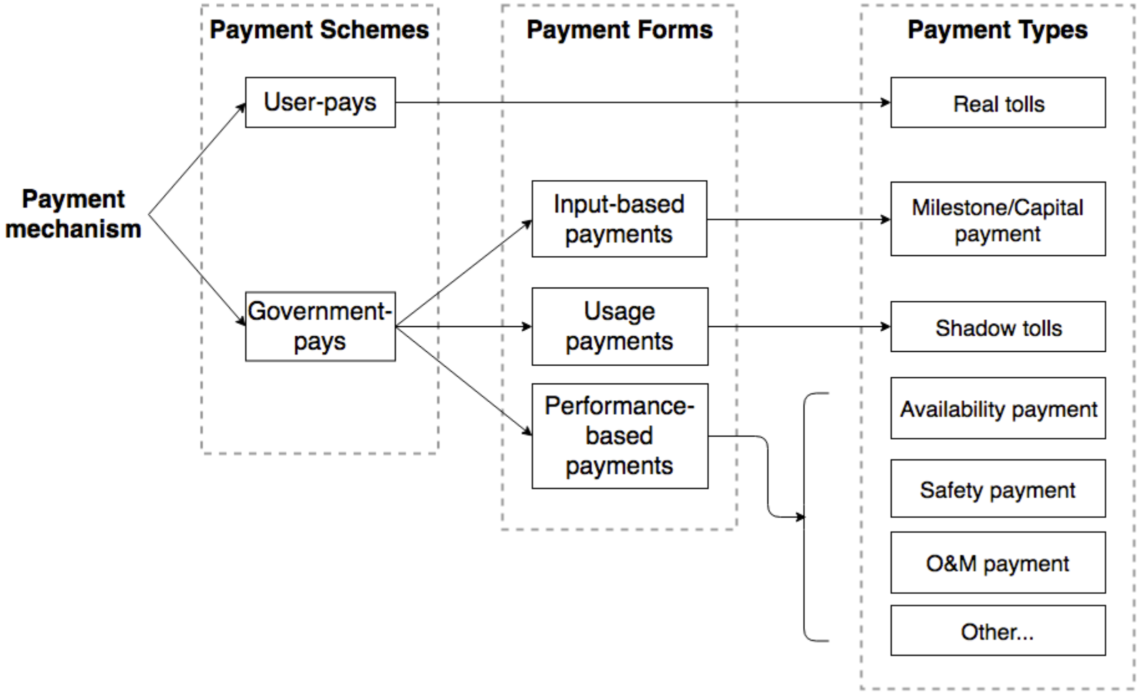


Figure 2.1: The hierarchy of payment mechanisms in PPPs

## *2.4 Payment Mechanism In Transportation PPPs*

A payment mechanism usually has the structure that include one or more payment types (e.g. availability, safety, capital/milestone), a weight or percentage for each payment type, a set of performance measures, and a number of deductions (e.g. deductions for unavailability and substandard performance) [2]. Several types of payments used in current PPP projects have been introduced in the literature. In a variety of different articles, however, the name of each payment is slightly different. In order to enhance the clarity, this paper first provides a unified definition for the different types of PPP payments. Further, based on the review of the PPP guidance documents from several countries and the contractual documents of more than 89 PPP projects, a hierarchy is proposed to distinguish the different payments that could be experienced in PPPs, illustrated in Fig. 2.1.

The revenue regime of PPPs refers to the source of revenues received by the private sector.

According to the revenue regime, two major schemes can be identified, including user-pays payment scheme and government-pays payment scheme [8] [41].

### *2.4.1 User-pays payment scheme*

Under the user-pays payment scheme, the Contractor receives compensation by obtaining the right to collect fees directly from end users of the infrastructure service. This payment scheme is also referred to as user charges in several European PPP standards (e.g. [23] [24]). In transportation projects, it is widely known as real tolls (the World Bank) or toll concession [28].

User-pays schemes are suitable for PPP projects that have the ability to generate stable revenues, particular those projects with guaranteed demand [7]. For example, investors and lenders will have greater confidence in the projects where tolls are used to alleviate congestion, as these projects usually have verified sufficient demand. In addition to demand consideration, the practicality of using user-pays is also important in assessing the suitability of user-pays since some environments may not be practical to use user-pays [23]. For example, collecting tolls may not be cost- effective for the road with many points of entry and egress.

An important concern for user-pays schemes is how user fees will be controlled (e.g. who has the right to regulate and/or setting fees). The toll policy trade-offs and risks have been discussed in several studies regarding tolling principles [80][105]. The details on price setting and adjustment for user-pays PPP concessions have been well studied. For instance, Kerf et al. [47] provides a overview on the design of user-pays PPP; the tariff (for water sector) indexation and resets are discussed by the World Banks toolkit [25]; and the model for price setting is available in the World Banks Body of Knowledge on Infrastructure Regulation [75].

Government subsidies (e.g. capital grant) can be provided if user-pays payments are unlikely to generate sufficient revenues to compensate the Contractor. When government subsidies is needed, such subsidies should be paid similar to government- pays payments, except that any subsidies required from the Authority will be smaller [23].

### *2.4.2 Government-pays payment scheme*

Government-pays payments, also referred as unitary payments by many European PPP guidance (e.g. the UK and Ireland), are the payment by the government to the Contractor for services or assets provided [41]. The government-pays payments used in current PPP transportation projects consist of three major forms, including input-based payments, usage payments, and performance-based payments, shown in Fig. 2.1.

Input-based payments, typically represented by milestone payment or capital payment, are calculated based on the Contractors input (e.g. labor and materials) rather than the output or service performance. Input-based payments play the dominant role in the traditional project delivery systems, such as Design-Bid-Build (DBB). They are also widely used in the US transport PPPs [2][88]. Input-based payments used to pay for PPP projects will be similar to those for traditional delivery systems. Usually, such payments require the Authority to provide significant upfront capital funding during the construction phase and are associated with the achievement of specified construction milestones. Input-based payments are intended to offset but not necessarily cover the entire construction cost in PPPs. For the US transport PPPs, the range of input-based payments constitutes between 37-50% of the project value, and other types of payments can be used to finance the remaining [9].

Usage payments can be expressed in various ways based upon the characteristics of the project. The most common form of usage payment used in transport PPPs is shadow tolls, in which the payment received by the Contractor based on the actual number of users of the roads [28][108]. Usage payments are analogous to user-pays payments, but differ in that the Authority makes the payment to the Contractor. Usage payments can be used as a substitute when user-pays payments are infeasible (e.g. legal viability).

Performance-based payments are set based on the quality of a service, regardless of the amount of inputs for that service and/or the usage of that service. In performance- based payments, the Contractor will be paid subject to meeting predetermined performance standards (e.g. the output specifications) [28]. Deductions will be made if the performance offered by the Contractor falls below the required levels. Availability payment is the most commonly used type of performance-based payment in transport PPPs. This payment fits perfectly for projects that primarily consider the provision of public infrastructure for availability, without which the required services cannot be provided, such as lane availability on the roads [94]. In addition to availability payment, many other types of performance payments exist in current PPP projects, such as safety payment, O&M (Operation and Maintenance) payment, traffic management payment, and user satisfaction payment. These payments can be used as separate payments in a payment mechanism, or as is more common, through performance related deductions within a usage or availability payment [23].

## *2.5 The Design of Payment Mechanisms*

Payment mechanism lies at the heart of the PPP contract [94]. The main purpose of the payment mechanism is to provide sufficient compensation to make the PPP project attractive and to ensure the Contractor provides acceptable services. According to European PPP Expertise Center (EPEC)s PPP Guide to Guidance [24], the payment mechanism is the main vehicle for allocating risks between public and private sectors. The payment mechanism could be used as a vehicle to reflect the Authoritys goals in transferring the risk and responsibility to the Contractor and in achieving specific project performance, such as remedy the congestion [93].

The design of payment mechanism requires inputs from all stakeholders, especially for the Authority and its advisers (e.g. financial, legal, and technical). It is a process of tailoring payment mechanisms to individual projects. Countries or areas with relatively mature PPP experience have gradually developed a number of guidance in the design of payment mechanisms. Based on a review and analysis of such guidance documents and the published literature, the following principles can be distinguished.

### *2.5.1 The underlying principles of designing a payment mechanism*

In traditional development of an infrastructure project, it requires the Authority to provide significant up-front capital funding during the construction phase. By introducing private sector finance, PPP provides an opportunity for the Authority to translate the large amounts of up-front capital expenditure into a flow of periodic payments during the operation phase [106]. Under a PPP contract, the Authority pays more attention on the continuous operation performance rather than the construction of the asset [23]. Therefore, for the design of payment mechanisms, the considerations of PPP projects should be distinguished from those of the traditional projects. The principles that develop the basic structure of a payment mechanism for PPP projects can be distinguished and summarized to include the following:

1. The payment should be based on measures such as usage, availability and other performance, and not on the inputs needed to deliver the service [23][24][87][94]. This principle has been widely recognized in most PPP projects in Europe and Asia. However, input-based payments (e.g. milestone) are an integral part of the payment structure for many of US based PPP projects [9][88].

2. Payment should not commence until the full service is available to the required standard [23][24][41][87][94]. Some exceptions may be applicable. For the brownfield projects, some payments may be made during the construction period to ensure the availability of the existing services (e.g. adding lanes to an existing roads), or payments can be made during construction (e.g. milestone payment) to help in reducing the amount of the future commitments/payments, thus reducing the interest and the total cost of the project.

3. "Measure less but measure well" [23][94]. The payment mechanism should be simple to understand and flexible to different scenarios. Special attention needs to be paid to any practical difficulties in monitoring, measuring and auditing the required performance.

4. The payment mechanism should make deductions for unsatisfactory performance, and the deductions should reflect the severity of failure [2][9][94].

5. The applicability of the different types of payments in a payment mechanism should depend on the particular characteristics of the project concerned, and in particular, the risk allocation between the public and private sectors [9][23][88].

6. Performance-based payments should be based on measurable objectives and outcomes [23][24][41][87][94]. Usually, the design of payment mechanism should be highly dependent on the requirements set out in the output specifications [9][43][50].

7. The payment mechanism should be bankable [23]. Based on the developed payment mechanism, the bidders and the lenders will model their probable revenue and cost streams with reasonable certainty. Only when the project is profitable will they be willing to enter into the contract given the risks allocated to them in the payment mechanism.

8. The payment mechanism should be affordable to the public sector [23][28]. Usually, the Authority will set the payment cap, such as the maximum availability payment.

### *2.5.2 The process of the payment mechanism design*

According to an extensive consolation with the professionals responsible for managing PPP projects, the Scottish government recommended a standard process of developing a payment mechanism for a PPP project [87]. The process is basically consistent with the processes used in most European countries PPP guidance, such as the UK [94] and Ireland [23]. Generally, a process of designing payment mechanism has four major steps, including:

- Identify the objectives of the payment mechanism

- Develop the structure of the payment mechanism

- Calibrate the payment mechanism
- Evaluate and revise the payment mechanism

First, the Authority needs to establish objectives for the payment mechanism based on the characteristics of the project. The objectives of the payment mechanism should be consistent with the project objectives. As mentioned earlier, the payment mechanism is the principal way to allocate risk to the private sector. Therefore, the objectives of the payment mechanism should reflect the desired allocation of risk [41]. Usually, such objectives are highly dependent on the performance requirements specified in the output specification [23]. Project objectives, payment mechanism, and output specification are closely related. A clear identification of the objectives is essential to facilitate iteration between these elements of a PPP.

A common approach to decide the structure of payment mechanism is to start with considering the most cost-effective allocation of demand risk between the public sector and the private sector [23][94]. According to the World Bank PPPIRC (Public-Private Partnership in Infrastructure Resource Center) report [108], the demand risk for the transport projects consists of two types of risks, including traffic risk (the risk of how many vehicles traveled up and down the road) and revenue risk (the risk regarding both traffic volumes / toll rate and collection / enforcement issues). User-pays payment scheme are considered capable of transferring both risks, which means demand risk is fully transferable to the private sector; under government-pays payment scheme, usage payment form represented by shadow toll is seen as transferring traffic risk but not revenue risk, which means demand risk is to be shared between the public sector and the private sector; input-based and performance- based payment forms usually transfer neither of these risks to the private sector, which means the public sector is to retain demand risk. The importance of demand risk in developing the structure of payment mechanism is presented in Fig. 2.2.

The process to tailor the basic payment structure to the particular project characteristics is referred to as calibration [94]. In this process, a large number of deduction points and

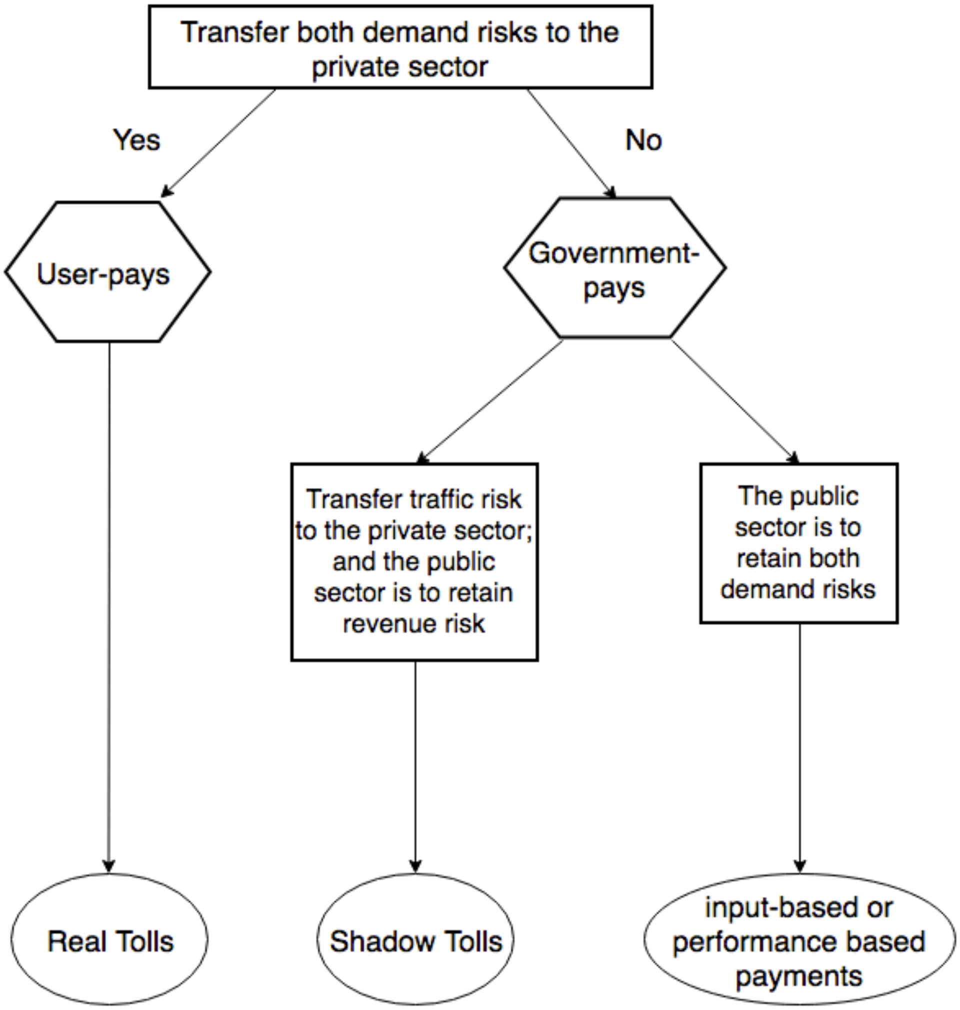


Figure 2.2: The development of the appropriate payment structure

calculation mechanisms are assigned to the various parts of the payment mechanism (e.g. the assignment of weights and related formula to the requirements set out in the output specifications). The calibration is central to the achievement of value for money and the Authoritys objectives in risk transfer [87][94]. Through the calibration, significant performance required in the output specification can feature in, or be linked to, the payment mechanism objectives. During the calibration, the Authority should carefully define the financial impacts of the deductions of substandard performance. The deductions should be sufficient economically enforce the Contractor performs the required standard. However, the deduction should not be too high since it will lead to unnecessary risk pricing by the Contractor or affect the bank-ability of the project [87][113].

The calibrated payment mechanism will be reviewed and negotiated by all stakeholders (e.g. the short-listed bidders and the lenders) during the dialogue period. The negotiation commonly focuses on three areas [87], including service specification (e.g. the performance standards and the associated rectification periods), payment (e.g. the amount of full payment and deduction caps), and warning notices and termination triggers. The payment mechanism may be refined based on the feedback from other stakeholders to achieve better cost-effective risk allocation. However, the Authority should be careful to ensure they are not inadvertently recouping the risks intended to allocate to the Contractor when refining the payment mechanism [23]. Finally, the revised payment mechanism should be evaluated against the project objectives to ensure that all objectives are achieved in a cost-effective way.

### *2.5.3 The design of payment mechanisms in the US transport PPPs*

The design of payment mechanisms for PPP projects is a new area to the US. The public agencies seem to have inadequate experience for designing and evaluating efficient PPP contracts [15][30]. For example, although the new issued PPP laws in many states provide for the use of various payments, they usually contain no guidance in selecting and setting the payment mechanism. The USDOT [97] published PPP best practices where it encourages linking the payment mechanism to the achievement of project goals, yet it failed to provide guidance on how to achieve that. Within this context, most agencies in the US decide payment mechanisms arbitrarily based on their past experience and familiarity of PPP payment types. As such, the public agencys objectives may not be achieved successfully through PPP.

Current research on linking the project goals to PPP payments is also inadequate, most of which focus only on specific types of payments, such as availability payment ([64][72][84][90]) and safety payment ([76][99][100]). Only a few studies discussed the design of a payment mechanism by combining different payments together into a package. Abdel Aziz [2] proposed a framework for developing a payment mechanism with a mixture of payment types. Few further studies continued to introduce the implementation of the mixed payments through case studies and contract analyses [88]. However, the way to combine different types of payments into a payment mechanism heavily relies on the experience and/or subjective judgment of the public agencies. No study investigated how to scientifically design a payment mechanism by determining the optimal combination (i.e. weights/percentages) of different types of payments. Additionally, for those limited studies regarding the design of the payment mechanism, maximizing the project performance through optimizing the payment mechanism has not been valued. Cui et al. [21] provided an attempt by proposing a bi-level stochastic model to maximize the road availability through optimizing the total payment amount and deductions for the design of availability payment. Their model, however, is limited to availability payment and inefficient for a payment mechanism consisting of multiple types of payment.

# Chapter 3

# RESEARCH METHODOLOGY

## *3.1 Introduction*

This section describes the process of this research. The whole research consisted of three phases, and each phase had a set of tasks. The research methods were designed to achieve the research objectives and tailored to fit the limitations of, such as, incomplete data and inaccessible to the database. Generally, this study used both qualitative and quantitative methods, including comprehensive literature reviews, a questionnaire survey, a content analysis, empirical case studies, statistical analysis, and quantitative modeling. The research flowchart is shown in Fig. 3.1, including the deliverable from each phase.

## *3.2 Development of Payment Mechanism Explanatory Framework*

### *3.2.1 Task 1: Conducting a Comprehensive Literature Review*

Starting from the academic point of view, a comprehensive literature review was first and continually conducted to investigate what have been published regarding the general contracting methods and the payment mechanisms in PPPs. The collected information were categorized into several topics, such as discussions on different types of payments, payment structures in PPP contracts, linking payments with project risks and/or performance, performance measures, and other topics in relation to the design of payment mechanisms.

Combining with the practice, this study also reviewed and summarized the current government guidelines, frameworks, and other public documents regarding PPP contracting and the design of payment mechanisms. The major findings from the review have been summarized in the literature chapter.

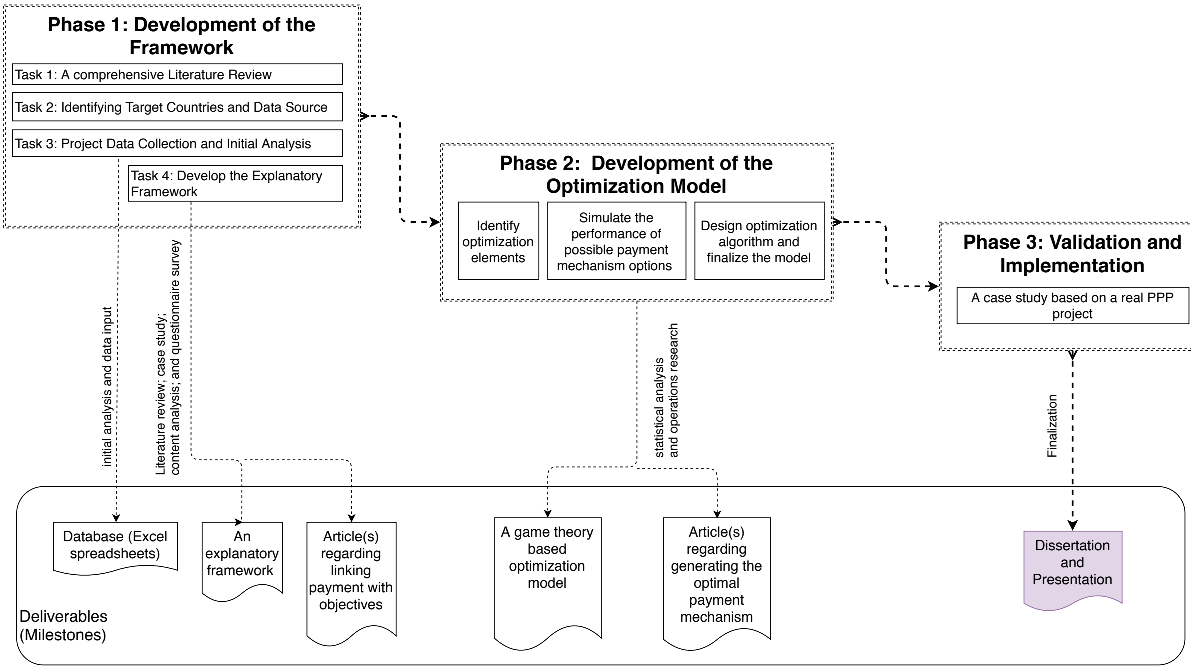


Figure 3.1: The flowchart of the research

### *3.2.2 Task 2: Identifying Target Countries and Source of Data*

This task identified a set of target research countries based on the accessibility of data. Although this research aimed to propose a framework for the design of payment mechanism that could be in line with the international standards, which required a worldwide data collection, it was impossible and not necessary to include PPP cases in every country. This study focused on the countries that have (1) the rich history of using PPP and plenty of PPP cases; and (2) accessible and well organized project information (e.g. contractual documents, financial statements). According to these criteria, the data collection mainly focused on the regions of North America (e.g. the United State, Canada), Europe (e.g. the United Kingdom), and Asia (e.g. China). The following resources were used to identify the target countries and PPP projects in each selected region and to collect contractual data such as the government guidelines and project documents:

- The World Bank private participation in infrastructure database: `https://ppi.worldbank.org/`;
- InfraPPP: `http://www.infrapppworld.com/pipeline-html/database-of-ppp-projects`;
- PPP Forum (UK Infrastructure project): `http://www.pppforum.com/projects`;
- Gujarat Infrastructure Development Board: `http://www.gidb.org/ppp-ppp-project-database`;
- Republic of the Philippines PPP center: `https://ppp.gov.ph/?page_id=26068`;
- Canadian PPP project: `https://infogr.am/canadian_ppp_project_database`;
- Public work financing database: `http://pwfinance.net/projects-database/`; and
- Indian infrastructure: `https://infrastructureindia.gov.in`

### *3.2.3 Task 3: Data Collection and Analysis*

The data collection consisted of two major parts, including the collection of the contractual documents of PPP projects and the collection of PPP experts' opinions regarding the design of PPP payment mechanism through a questionnaire survey.

#### *The collection and analysis of contractual documents*

Over 89 PPP projects were identified from the previous task, and the project data were collected, including, such as, bidding documents (e.g. RFQ and RFP), concession agreements, technical requirements, the government PPP standards or regulations, project value for money reports, and other reports with regards to evaluating the project performance (e.g. safety report). The collection of such data were expected to capture each selected PPP project's: (1) basic information, (2) agency goals, (3) payment structure and payment types, (4) additional provisions for deduction or incentive, (5) performance measures, (6) link between the payments and the goals, and (7) final performance or outcome.

A content analysis was conducted to extract the unstructured contractual information from the collected documents and to convert them into structured data managed in Excel worksheet. A comparative analysis is further conducted to explore the similarities and differences of the payment mechanisms used between different countries. The findings from the comparative analysis were used to generate the best practice in the design of payment mechanism and to develop the framework that serves for the research objective. The types of the collected data were both qualitative (e.g. project information, objective, performance measures, etc.) and quantitative (e.g. safety index, NPV, cash flow, etc.). The details of the analysis has been covered in the next chapter.

#### *The questionnaire survey*

According to the literature review and the analysis of the contractual documents, a number of factors for the payment mechanism design were identified. A Delphi questionnaire survey

[69] was conducted (to the PPP experts in both academic and industry) to evaluate the importance of each factor and identify the most critical ones for the design of the payment mechanism. The survey also helped to investigate the importance of each functional payment on the achievement of different project goals since each payment may have positive effects on one goal but potential negative influences on others. For example, the safety payment has strong impacts on improving roadway safety but may have limited effects on increasing the project demand (i.e. traffic volume). The survey results were used to serve for the establishment of the framework. The introduction of the survey is presented in Chapter 5.

### *3.2.4 Task 4: Develop the explanatory framework for payment mechanism design*

A framework for designing innovative payment mechanisms to facilitate the achievement of public agency's goals in PPPs was proposed based on the findings from the previous steps. This explanatory framework provided guidance on designing payment mechanisms for transportation PPPs. The major components of the framework have been summarized as follow, and the details are described in Chapter 6.

1. Identifying the agency's objectives/goals in the project;
2. Providing recommendations on the selection of functional payments based on the agency's objectives;
3. Identify the priority of the objectives;
4. Providing recommendations on deciding the percentage of each payment in the payment mechanism based on a developed optimization model;
5. Developing the payment adjustment mechanisms (i.e. provision for inflation or escalation);
6. Identifying the performance measures used to evaluate the achievement of each project goal;

7. Developing the deduction and incentive structure, and identifying the cap, if any, on the amounts.

### *3.3 Development of an optimization model for designing the payment mechanism*

The framework proposed from the previous phase is expected to provide for the guidance of the selection of the payments from a qualitative point of view. This framework could assist the decision maker to select the appropriate functional payments based on the project goals and characteristics. An optimization model was further developed to help in the same regard but from a quantitative perspective.

An important aspect for the design of a payment mechanism with a combination of different types of payments is to decide the amount of each type of payment in the total payment structure. For example, if a safety payment is desired, what percentage should it have compared to other payments. Due to the budget limitation, it is not appropriate to blindly increase the amount of one payment. In a payment mechanism with fix budgets, the increase in the proportion of one functional payment means to reduce the proportion of some others. Consequentially, when improving one aspect of the project performance, it may negatively affect the other aspects of the project performance. To achieve the optimal project, it requires a strategy to find the balance between minimization of the drawbacks and maximization of the strong-points of each payment.

However, to the best knowledge of the author, there is no published or known method aiming to determine the percentage of each payment in a payment mechanism used in current PPP projects except empirically or subjectively assigned by the public agencies. This research aimed to fill this gap from a quantitative perspective by proposing an optimization model. The model was developed based on game theory, as decisions are commonly made in a sequential manner in the process of contract negotiation and execution between two parties (the public sector and the private sector) in a PPP project. Generally, the interests of both public and private sectors were reflected in the model through a bi-level objective function. Through changing the ratios of each type of payment in a payment mechanism, the model sought for solutions that maximize the overall project performance for the sake of social welfare while simultaneously maximize the return for the sake of private investment. A variable elimination method and the genetic algorithm were used to solve the optimization model. A detailed description of the model development has been presented in Chapter 7.

## *3.4 Validation and Implementation*

The framework was developed based on the perspective of the public agency and under several assumptions, such as some particular PPP models (e.g. DBFOM or performance-based PPPs). In order to validate the practicability of the framework and the quantitative models, a case study, based on a real PPP project was conducted (see Chapter 8) to examine the applicability of the proposed framework and the model.

# Chapter 4

# CONTENT ANALYSIS OF PAYMENT RELATED CONTRACTUAL DOCUMENTS

## *4.1 Introduction*

Because performance-based PPPs are relatively new in the US, it is not clear whether payment mechanisms used in the US projects would be similar to those used in the PPP international market regarding the payment types, payment structure, performance measures and specifications, penalties, and deduction schemes. To serve for the research goal, that is to provide a systematical understanding about the payment mechanism used in performance-based PPPs, and more importantly, to provide guidance on the design of the appropriate payment mechanism for facilitating the achievement of the project goals, this research investigated the payment mechanisms used in the performance-based transportation PPPs in the US and comparing them to those of the Canadian market. Through a content analysis of the project contracts, the unstructured contractual information is extracted and transformed into structured data. And a comparative analysis is conducted to explore the similarities and differences of the PPP projects between the US and Canada. Public agencies could refer the findings from the comparison to revisit and improve the design of payment mechanism.

## *4.2 The Projects and the Contractual Data Collection*

A total of twenty projects were selected as the research sample, among which ten are from the US while the other ten are from Canada. The US Department of Transportation Federal Highway Administration (FHWA)s database shows 33 transportation projects adopting or adopted PPP approaches, among which sixteen are demand-based by using toll concessions; twelve are performance-based by using availability payment concessions; the other five are

Table 4.1: The Selected USA Project Sample

| **Project** | **State** | **Contract Type** | **Year of Financial Closure** | **Current Status** |
|---|---|---|---|---|
| Eagle Project (EGL) | CO | DBFOM | 2011 | In operation |
| Goethals Bridge Replacement (GB) | NJ | DBFM | 2014 | Construction |
| I-4 Ultimate (I-4) | FL | DBFOM | 2014 | Construction |
| I-595 Improvements (I-595) | FL | DBFOM | 2008 | In operation |
| I-69 Section 5 (I-69) | IN | DBFOM | 2014 | In operation |
| Ohio River Bridges East End Crossing (ORB) | IN | DBFOM | 2013 | In operation |
| Port of Miami Tunnel (PMT) | FL | DBFOM | 2010 | In operation |
| Presidio Parkway (Phase II) (PP) | CA | DBFOM | 2012 | In operation |
| Southern Ohio Veterans Memorial Highway (SOV) | OH | DBFOM | 2015 | Construction |
| State Street Redevelopment Project (SSR) | IN | DBFOM | 2016 | Construction |

long-term lease concessions (concessionaires not involved in the project early development). The ten US projects were selected from the twelve availability payment concessions, which constitute almost the whole population (83%). The Canadian projects were selected that have similarities to the US projects regarding project size (e.g., cost), fiscal year, and concession type (e.g., availability). As such, the projects are comparable between two countries. Table 4.1 and 4.2 show the basic information about the projects in the US and Canada, respectively.

The data sources mainly consisted of the procurement documents (e.g., RFQ/RFP), concession agreements, the value for money reports and case studies, and scholar articles.

Table 4.2: The Selected Canadian Project Sample

| **Project** | **Province** | **Contract Type** | **Year of Financial Closure** | **Current Status** |
|---|---|---|---|---|
| Calgary Southwest Ring Road (CSR) | Alberta | DBFO | 2016 | Construction |
| Eglinton Crosstown LRT (LRT) | Ontario | DBFM | 2015 | Construction |
| Golden Ears Bridge (GEB) | BC | DBFO | 2006 | In Operation |
| Highway 407 East Phase 2 (407) | Ontario | DBFM | 2015 | Construction |
| Iqaluit International Airport Improvement (IIA) | Nunavut | DBFOM | 2013 | In operation |
| Kicking Horse Canyon - Phase 2 (KHC) | BC | DBFOM | 2005 | In operation |
| New Champlain Bridge Corridor (NCB) | Quebec | DBFOM | 2015 | In operation |
| Northeast Anthony Henday Drive (NAH) | Alberta | DBFOM | 2012 | In operation |
| Sea-to-Sky Highway Improvement (STS) | BC | DBFOM | 2006 | In Operation |
| South Fraser Perimeter Road Project (SFP) | BC | DBFO | 2010 | In Operation |

The relevant contractual information about payment mechanisms was extracted from the documents above. Such information was, then, converted into structured data and organized by Excel spreadsheets.

## 4.3 The Content and Comparative Analysis

To achieve the research purposes, a content analysis associated with a comparative analysis was conducted for the potential to explore the existent of, and similarities and differences in the design of payment mechanisms between the US and Canada. The collected data are divided into three components that majorly consisting of a payment mechanism, including a set of payment types, a payment adjustment scheme, and a set of performance measures and specifications. The analysis is conducted for these three components respectively.

### 4.3.1 Payment types used in the projects

The payment types used in the selected projects were first investigated and summarized in Table 4.3. The review of the project contracts showed that capital payments were an integral part of the payment mechanism, particularly for the US projects. The public agency usually made such payments based on a set of construction and completion milestones. The calculation of capital payment is mainly based on the inputs rather than the performances. Capital payments can be made as a lump sum or, a maximum amount associated with an adjustment formula, particularly for some brownfield projects, to keep the continuity of service availability during the construction phase [9].

An availability payment (AP) is typically used, after the projects substantial completion, to pay for the remaining construction costs and the new O&M costs based on the operational availability. This payment is determined by a formula in the form of Eq. 4.1 as an example from the I-69:

$$AP = MAP - UA - NA - OA \tag{4.1}$$

Table 4.3: Payment Types Used in the Selected Projects

| | **Project Name** | **Payment Type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Capital Payment | Usage Payment | Avaiability Payment | O&M Payment | Traffic Management Payment | Safety Payment | End of term payment | Rehabilitation Payment |
| US | EGL | x | | x | | | | | |
| | GB | x | | x* | | | | | |
| | I-4 | x | | x | | | | | |
| | I-595 | x | | x | | | | | |
| | I-69 | x | | x | | | | | |
| | ORB | x | | x | | | | | |
| | PMT | x | | x | | | | | |
| | PP | x | | x | | | | | |
| | SOV | x | | x | | | | | |
| | SSR | x | | x | | | | | |
| CA | CSR | x | | x | x | | | x | x |
| | LRT | x | x | x | x | | | | |
| | GEB | | | x | x | | x | | |
| | 407 | x | | | x | | | | x |
| | IIA | x | | x | x | | | | |
| | KHC | x | x | x | | | x | x | |
| | NCB | x | x | x | x | | | | x |
| | NAH | x | | x | x | | | x | x |
| | STS | | x | x | | x | x | x | |
| | SFP | x | | x | | | | | |

Note: X* means the terminology of the paymnt is different in the project

Where MAP is the maximum availability payment set by the public agency and subject to adjustments, UA is unavailability adjustment, NA is noncompliance adjustment, and OA is the other adjustment.

Generally, most of the other selected projects adopted a similar formula as Eq. 4.1. Also, the definition of availability payment in the selected projects was almost the same. However, some projects may use other terminologies to represent availability payment. In this research, if the definition and calculation of the payment are consistent with the availability payment defined in other projects, it is considered as availability payment during the data transformation. For example, marked in Table 4.3, the Goethals Bridge Replacement Project (US) called its payment as O&M payment but followed an availability payment definition and calculation.

In all of the selected US projects, O&M related payments are integrated into the availability payment. Thus, these two terminologies (i.e. O&M payment and availability payment) are sometimes interchangeable in the US. However, Canada shows a clearer separation between these two types of payments. Over half of the selected Canadian projects separated an O&M payment from availability payment. In this way, O&M payment will be calculated in a specific formula similar to availability payment while emphasizes more on the quality of operations & maintenance.

Surprisingly, usage payment (which is a typical payment used in demand-based PPPs) is also used in the payment structures of 4 Canadian projects constituting a range between 3 to 20% of the project values. However, the US projects strictly isolated the usage payment from availability payment. In the US, the main criterion used to distinguish the nature of a PPP project (demand-based vs. performance-based) is whether the project adopts availability payment or usage payment.

Many Canadian projects also adopted a number of other functional payments. These functional payments are introduced to serve for the various project goals and usually constitute a small proportion of the total payment. For example, a traffic management payment was introduced in the project of STS for encouraging the contractor to maintain good traffic flow during the construction; a safety payment associates the payment with the road accident rate; an end of term payment is used to incentivize the contract to hand back the project in an acceptable conditions; and a rehabilitation payment is set for encouraging contractor to provide periodic repairs.

### *4.3.2 Payment adjustments used in the projects*

In addition to the above payments, the contractors compensations in the performance-based PPP are subject to adjustments. A construction deduction used to adjust the capital payments if nonconformity events occur during the construction phase. Such events commonly include but not limited to construction closure (in brownfield projects), construction availability fault, construction O&M violations, and construction delay.

In the operation phase, the adjustments used in most of the studied projects consisted of two major components, including the unavailability deduction and the noncompliance deduction. The unavailability deduction (UD) is enforced on the contractors if unavailability events occur, such as the lane closure. This deduction is calculated by the following formula as an example from the project of SOV:

$$UA_{total} = \sum_{h=1}^{q} UD_h \tag{4.2}$$

Where $UD_h$ is the unavailability deduction for a single unavailability event; q is total number of unavailability events; and h is a single unavailability event.

Commonly, to take the impact of the event into consideration, the unavailability adjustment for a single event is the product of the segment factor that assigned to different road segments based on the traffic flow.

The noncompliance deduction (ND) is used for deducting the O&M nonconformities that are defined by the noncompliance performances set out in the contract. This deduction, concerning each noncompliance event whose noncompliance point adjustment, is applied in or occurs during each fiscal year after the substantial completion, will be determined by the following formula as an example from SOV:

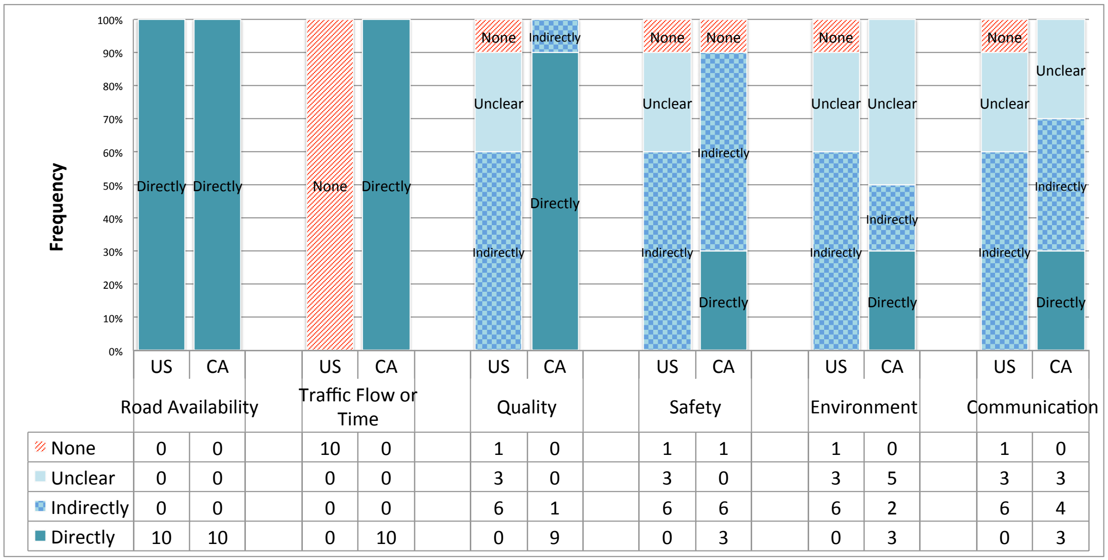
$$ND_{total} = NCPV \times \sum_{x-1}^{n}(NCP) \times IE \tag{4.3}$$

Where NCPV is the value for each noncompliance point of $5,000; NCP is the accrued number of noncompliance points; and IE is the indexation.

Most of the studied projects also included a hand-back condition deduction by setting a retention payment the end of concession. The retention is called hand-back reserve account in the US and asset condition retention in Canada. The public agency will hold such payment for a certain time after the concession to ensure the hand-back condition is acceptable. Also, a variety of other adjustments are introduced in some projects to complement the payment structure, particularly in Canada. For example, some Canadian projects contain safety adjustments for encouraging the safety performance, which have a calculation similar to safety payment. Some projects, in both the US and Canada, set the performance incentives for outstanding performance. For example, GBR and STS have the O&M overall performance incentives; ORB set incentives for the fast construction; and LRT introduced energy-saving incentives to improve sustainability.

### *4.3.3 Performance measures used in the projects*

Performance measures are set out to complement the payment structure and the adjustments to quantify the desired performances and linking them to the payment. Commonly, public agencies require contractors to install and maintain the measurement equipment and to self-monitor the performance. This subsection discusses the investigation of the performance measurements used in the studied projects and how well these performances were linked to the contractors compensation through the payment mechanism.



| | Road Availability | | Traffic Flow or Time | | Quality | | Safety | | Environment | | Communication | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | US | CA | US | CA | US | CA | US | CA | US | CA | US | CA |
| ▨ None | 0 | 0 | 10 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| ■ Unclear | 0 | 0 | 0 | 0 | 3 | 0 | 3 | 0 | 3 | 5 | 3 | 3 |
| ▦ Indirectly | 0 | 0 | 0 | 0 | 6 | 1 | 6 | 6 | 6 | 2 | 6 | 4 |
| ■ Directly | 10 | 10 | 0 | 10 | 0 | 9 | 0 | 3 | 0 | 3 | 0 | 3 |

Figure 4.1: Linking performance measurement to the payment mechanism

According to the review of the contracts, this research groups the performance into the following major dimensions, including road availability, traffic flow and traffic time, project quality, safety, environmental impact, and communication (e.g. the periodic report). During the data extraction, this study used four levels to identify the link situation for each project in each dimension, including (1) direct link, which means the project explicitly linked the performance measurement to the payment mechanism through a particular payment or adjustment; (2) indirect link, which means performance is not directly is not linked to the payment mechanism by a separate payment or adjustment, but as an O&M noncompliance points belonged to the O&M deduction; (3) unknown link, which means the performance measurement is required in the contract but failed to link to the payment mechanism neither directly nor indirectly; and (4) no link, which means the performance is not required to be measured in the contract. To visualize the result of the content analysis, as shown in Fig. 4.1, this study used clustered and stacked columns to indicate the number of projects in each link level for each performance between the US and Canada.

The first paired columns show the result that all the selected projects directly included road availability into the payment calculation. This indicates that road availability is the core indicator in the current performance-based PPPs. The second paired columns, however, shows an obvious difference between the two countries regarding the traffic performance. Although most of the US projects included the traffic control as one criterion for evaluating the project performance, none of them quantified the traffic performance by using traffic flow or traveling time, and consequentially, none of them linked the traffic factors to the payment. In contrast, all the selected projects in Canada linked the traffic flow or time to either a payment or deductions. For the other four performances, the US projects usually integrated them into the O&M performance and indirectly linked the performances to the payment through the O&M noncompliance points. In term of quality, unlike the US projects, most of the selected Canadian projects chose to separate it from the O&M performance by using specific calculations. In terms of safety, environment, and communication, however, most of the Canadian projects also integrated them as part of the O&M performance and used the method similar to the US to deduct the unsatisfactory performances on the payment. Due to the acceptance of a variety of functional payments in Canada, there are still projects linking these performances directly to the payment by specific payments or deductions.

## *4.4 Findings from the US and Canadian PPPs*

The content analysis of the studied projects reveals the similarities and, more importantly, differences in the payment mechanisms used in the performance-based PPPs between the US and Canada. First, as shown in Table 4.3, PPP projects in the US tend to have fewer payment types than those in Canada. In fact, the studied projects in the US were exclusively limited to capital payment and availability payment, which are the two core payments used in current performance-based PPPs. In contrast, many Canadian projects studied in this research have a hybrid payment mechanism with a variety of functional payments. Such functional payments are introduced to serve for the particular project goals and can be calculated separately from the availability payment formula.

Capital payment can be excluded from the payment mechanism. Although capital payment is widely used in most of current performance-based PPPs, it is not necessary to be an integral part of the payment mechanism for every case. As shown in Table 4.3, two projects, the Sea-to-Sky (STS) Highway, and Golden Ears Bridge (GEB) projects, used no capital payments in the construction phase. The whole compensation for the contractors, in these two projects, is determined based on the project performance in the operation phase, among which the availability payment constituted a great proportion of the total payment amount (85% in STS and 93% in GEB). This means the contractors income is heavily associated with the project operational performance regardless of the inputs in the development. By excluding capital payment from the payment mechanism, most of the risks can be transferred to the private side. However, it is not suitable for all the cases as this potentially makes the contractors lose their enthusiasm and charge more for the risk premiums.

Usage payment can be adopted in the performance-based PPPs to complement availability payment to encourage contractors to provide better services. In the studied US projects, usage payment is strictly isolated from the performance-based PPPs. Some of the Canadian projects, however, used this payment as an incentive to increase the traffic demand. The calculation of usage payment is based on traffic volume multiplied by user unit fee. As such, an increase in the traffic volume will potentially increase the overall project revenue. The implementation of usage payment, on the one hand, will potentially stimulate the contractor to provide better services to attract more users, thereby increasing their own compensation. On the other hand, the implementation of usage payment may partially ease the government financial burden on infrastructure development, which is one of the major considerations for using PPP. In performance-based PPPs, the funding of paying for the availability payment is majorly derived from the government tax and bonds. Even if the payment is spread over a long concession term, the government still needs to bore the huge amount that can consequently lead the government to high financial pressure. Adopting a proportion of usage payment into performance-based PPPs can be a good strategy for the financial consideration. To these points, usage payment and availability payment are not mutually exclusive but are complementary.

The US projects usually adopted a relatively simple formula for the calculation of availability payment. As shown in Fig. 4.1, except for road availability, all other performances are indirectly linked to the payment by noncompliance deductions that calculated by Eq. 4.3. The benefit of taking such calculations is to make the overall payment mechanism simple and easy to follow. However, one of the drawbacks is that the deductions for some performances can be difficult and inaccurate, which leads that the non-compliant performance cannot be penalized accurately. For example, in term of safety, due to the lack of indicators to quantify safety performance, the unsatisfactory safety cannot be accurately reflected through the payment by simply assigning noncompliance points in most of the US projects. By contrast, some Canadian projects set up a specific formula with quantified safety performance (e.g. the fatal rate) as parameters to calculate the safety payment and adjustment. To this extent, the payment calculations used in the studied Canadian projects are generally more sophisticated than those used in the US projects. However, it is expensive to measure each performance quantitatively and to design specific formula for each of them. This research recommends that the performance measurements and the design of calculation formulas could be based on the priority of the project goals. Particular payments can be added to achieve the major project goals, while the existing deduction formula, such as Eq. 4.3, can be retained for the noncompliance of other performances.

# Chapter 5

# IDENTIFY THE KEY FACTORS FOR PAYMENT MECHANISM DESIGN: A QUESTIONNAIRE SURVEY

## *5.1 Introduction of the Questionnaire Survey*

This chapter introduces the questionnaire survey used to explore the key factors that determine the design of the payment mechanism and clarifies their current practice and implementation in transportation PPP projects to serve for the establishment of the framework proposed. The overall process is illustrated in Fig. 5.1. First, an initial list of the factors were identified based on an in depth literature review regarding the design of payment mechanisms and a content analysis of the payment-related contractual documents of more than 89 PPP projects. Next, the listed factors were further tested through a questionnaire survey to PPP researchers, professionals, and stakeholders. The survey also helped to identified additional factors that were missed in the literature. According to the survey results, the key factors in the design of PPP payment mechanisms were uncovered and ranked based on their importance.

The developed questionnaire survey consisted of three major sections. The first section was assigned to collect the basic information of the survey respondents' roles and experiences with PPP projects. The second section captured a comprehensive opinion about the general design of a payment mechanism. The last section investigated the factors in determining the payment schemes. The questionnaire also included a request to provide any additional considerations. A copy of the questionnaire is provided in Appendix A.

The questionnaire survey was conducted from April 2018 through December 2018. A total of 207 questionnaires were sent out by e-mail and Linkedin Inmail, among which 17 were completed and returned. The effective return rate (8.2%) was slightly lower than prior

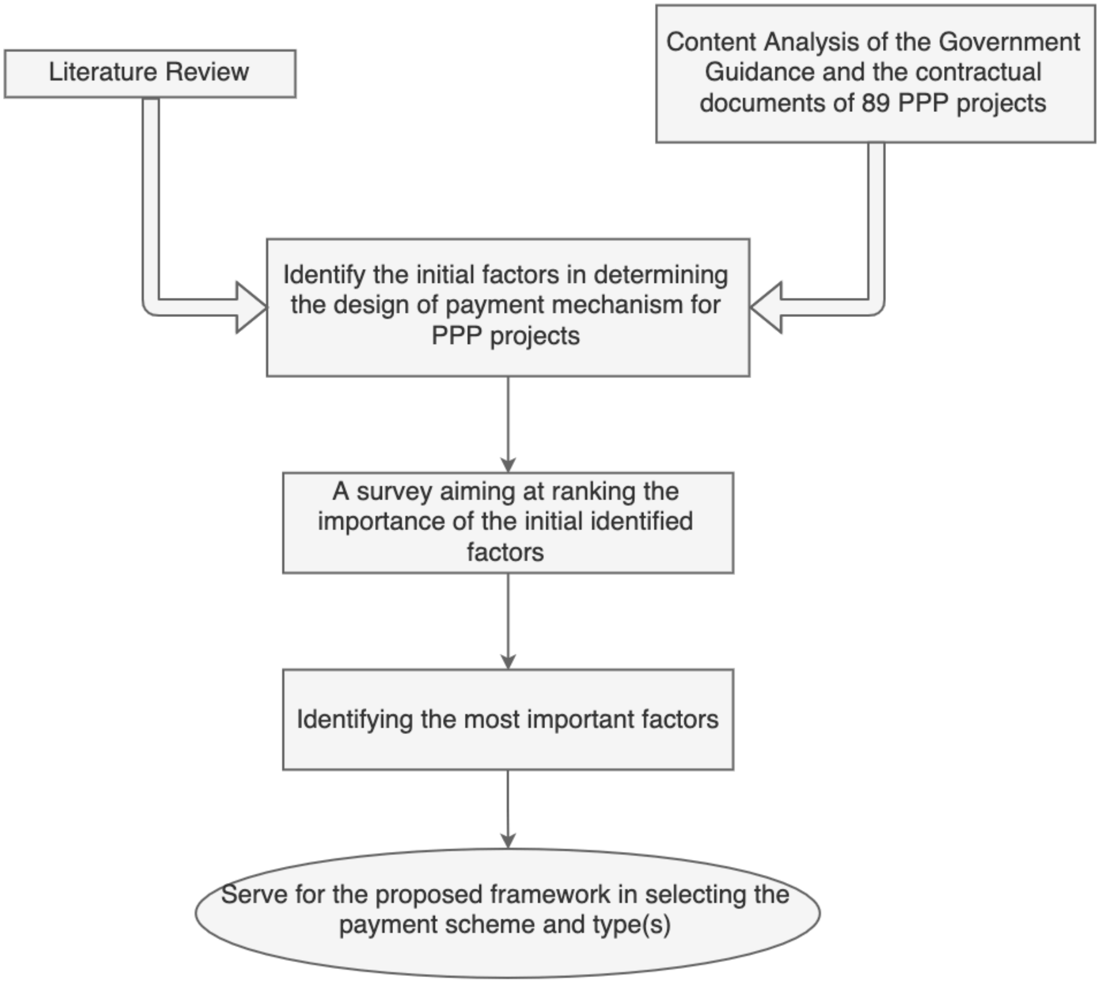


Figure 5.1: The process of the questionnaire survey

PPP-related surveys, such as a response rate of 13.02% from Yuan et al. [115], 12% from Li et al. [55] and 9.4% from Salman et al. [83]. Such a response rate may not be sufficient to meet the needs of data analysis. Therefore, the current research phase will only provide for the exploratory analysis of the survey data. In the future research with more supports, the survey will be conducted to a wider population.

## 5.2 The Background of the Respondents

The respondents were from different organizations in various countries and regions and could be classified into several groups, including (1) academia, which refers to researchers in the field of PPPs; (2) public agency (i.e. the government and public owners that have participated in PPPs); (3) construction contractor, which refers to the project developers with PPP experience; (4) operation and maintenance contractor, which refers to the contractors who are particular responsible for the operation and maintenance of PPP projects; and (5) consultants, which refers to the third parties that hired by the owner to provide services for PPP projects. Table 5.1 describes the roles of the respondents in PPP projects. Fig. 5.2 illustrates the regions where the respondents' PPP projects are located. Noted that the summation of the responses in Fig. 5.2 is higher than the total number of the respondents, which is because the respondents may have PPP experience in more than one region.

## 5.3 Key considerations for the general design of the payment mechanism

In the second section of the questionnaire survey, an initial list of the considerations regarding the general design of PPP payment mechanisms are summarized in the following.

1. Owner goals/objectives in the PPP project

2. Availability of the public funding

3. Project ability to generate revenues (e.g. sufficient demand)

Table 5.1: Survey respondents' roles in PPP projects

| Respondent | Information of questionnaires sent out | | Information of questionnaires returned | | | Effective returned rate |
|---|---|---|---|---|---|---|
| | Number | Percentage | Number | Number of usable responses | Percentage | |
| Academia | 86 | 41.55 | 8 | 7 | 41.18 | 8.14 |
| Public Agency | 39 | 18.84 | 6 | 6 | 35.29 | 15.38 |
| Construction Contractor | 53 | 25.60 | 3 | 3 | 17.65 | 5.66 |
| O&M Contractor | 12 | 5.80 | 0 | 0 | 0.00 | 0.00 |
| Consultants | 17 | 8.21 | 2 | 1 | 5.88 | 5.88 |
| Total | 207 | 100.00 | 19 | 17 | 100.00 | 8.21 |

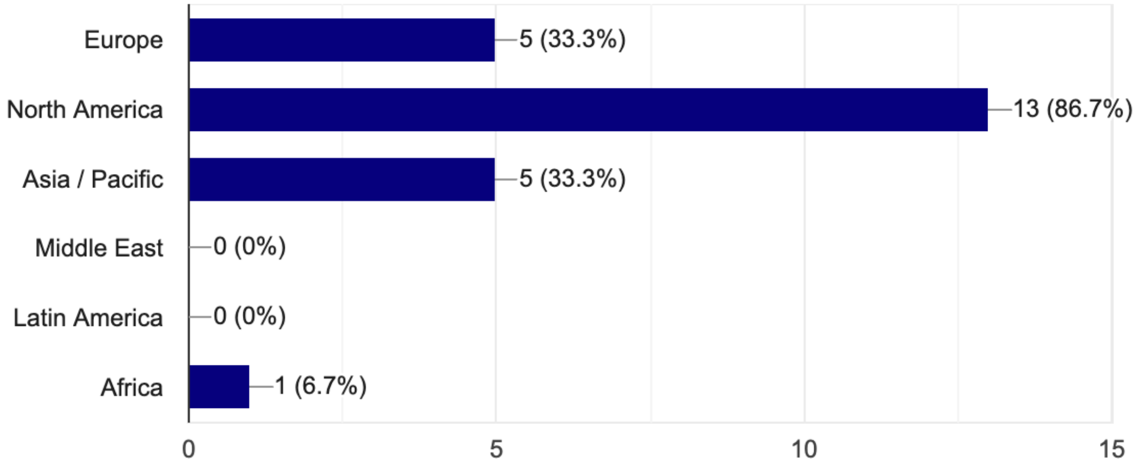


Figure 5.2: The regions of the respondents' projects located

4. Project expected revenue amount
5. Project total cost
6. Risks to be transferred to the concessionaire
7. Bankability/Profitability of the payment mechanism to the concessionaire
8. Owner's & Stakeholder's knowledge of the different payment types
9. Owner's knowledge of PPP models (e.g. DBF, DBFOM, BOT)
10. The simplicity of a payment mechanism (e.g. time & cost needed for payment calculations)
11. Owner's ability to monitor project/concessionaire performance
12. Ability to design performance measures that reflect owner/project requirements
13. Local and general economy
14. Availability of permitting law allowing the use of alternative payment types (e.g., performance, usage, etc)

A set of Likert-style rating questions, using a five-point scale were used to identify the most significant considerations among the initial list. The five scale intervals consist of (1) not relevant or can be ignored; (2) less important; (3) moderate; (4) important; and (5) most important. Due to the low response rate, the respondents are not classified into different groups. An overall level group is used to provide a preliminary understanding of the opinion from PPP experts in this research phase. The scores and rankings of these initially identified considerations are shown in Table 5.2.

Table 5.2: The scores and rankings of the considerations for the general design of PPP payment mechanisms

| | Considerations | The overall group (with all the respondents) | | |
|---|---|---|---|---|
| | | Mean | S.D. | Rank |
| C1 | Owner goals/objectives in the project | 4.67 | 0.32 | 1 |
| C2 | Risks to be transferred to the concessionaire | 4.35 | 0.56 | 2 |
| C3 | Bankability/Profitability of the payment mechanism to the concessionaire | 4.22 | 0.46 | 3 |
| C4 | The simplicity of a payment mechanism (e.g. time & cost needed for payment calculations) | 4.07 | 0.82 | 4 |
| C5 | Project total cost | 3.95 | 0.55 | 5 |
| C6 | Availability of the public funding | 3.88 | 0.65 | 6 |
| C7 | Project expected revenue amount | 3.79 | 0.86 | 7 |
| C8 | Project ability to generate revenues (e.g. sufficient demand) | 3.75 | 0.91 | 8 |
| C9 | Ability to design performance measures that reflect owner/project requirements | 3.52 | 1.07 | 9 |
| C10 | Owner's ability to monitor project/concessionaire performance | 3.48 | 0.94 | 10 |
| C11 | Availability of permitting law allowing the use of alternative payment types (e.g., performance, usage, etc.) | 3.31 | 1.14 | 11 |
| C12 | Owner's & Stakeholder's knowledge of the different payment types | 3.28 | 1.02 | 12 |
| C13 | Local and general economy | 2.87 | 0.84 | 13 |
| C14 | Owner's knowledge of PPP models (e.g. DBF, DBFOM, BOT) | 2.59 | 1.01 | 14 |

In Table 5.2, the mean represents the respondents' average opinion about the importance of one consideration. And the S.D. (i.e. standard deviation) represents the variance of the respondents' opinions, which indicates the agreement level of the respondents regarding the score and ranking of one consideration. For the 14 considerations offered to respondents, the mean response rating values range from 4.67 down to 2.59. Owner's goals/objectives in the project (C1) is the only factor with mean value score that fell into the 'very important' ($> 4.50$) category, and no factor mean values scores fell into the 'not relevant' ($< 1.50$) category. This indicates that all of the 14 considerations are important for the design of the payment mechanism in PPP projects.

The preliminary survey result shows that the owner's goals (C1) should be significantly considered when designing the payment mechanism for a PPP project, which further implies that the payment mechanism should appropriately reflect the owner's project objective (or linking the performance of such objectives to the contractor's compensation). It should also be noted that the variance of the respondents' opinions regarding this consideration (owner's goal) is the lowest one among the 14 considerations ($S.D. : 0.32$), which indicates that most respondents reach an agreement regarding the score and ranking of this consideration. Risk allocation (C2), bankability to the contractor (C3), and simplicity of the payment mechanism (C4) are other three considerations that have the mean scores higher than 4, which means they should also have very higher priorities to be considered during the design of the payment mechanism.

Noted that, the consideration of legislation permission (C11) has the highest variance, which implies that the respondents have different opinions regarding the importance of such consideration. This can be explained by the various regions of the respondents' PPP experience. Some countries or regions may have the legislation limitation for the use of specific types of payment in PPPs and the others may have no or less legislation limitation.

## *5.4 Key factors in determining the selection of payment scheme*

The last section of the survey aimed to identify the key factors in the design of payment mechanism. The process of designing a payment mechanism for PPP projects can be divided into two main steps, including the selection of the payment scheme and the selection of payment types (see the details in Chapter 6). As the selection of the specific types of payments heavily depends on the project goals, this section of the survey focused mainly on identifying the key factors in affecting the selection of payment scheme.

The potential factors in determining the appropriate payment scheme (user-pays vs. government pays) have been identified and presented in Table 5.3. Similar to the previous section, Likert-style rating questions using a five-point scale were used to identify the most critical factors among the initial group. The score and ranking of each factor is shown in Table 5.4.

The survey results illustrate that nine of the identified factors fell into 'moderately important' (> 2.50) category or higher and one factor (F4) is less important. PPP model (F1) has the highest mean score and the lowest variance, which indicates that the respondents agree that the PPP model (e.g. DBFOM, and DBF) would importantly determine the payment scheme. Additionally, legal viability (F2) and government policy (F3) are two factors that fall into (or almost fall into) 'very important' (> 4.50) category. This indicates that the government's macro support would play an important role in determining the selection of the payment scheme for PPP projects. The other factors that have scores close to or higher than 4.0 are F6, F7, and F9. F9 represents the financial feasibility, and F6 and F7 together reflect the use demand of the PPP project, which further implies the profitability of the project. The ranking of these three factors indicates that after the political factors, the economic factors would also be important in determining the payment scheme selection. Likewise, F4 is the least important factor, which implies that the potential competition might not be a factor that determines if a PPP project should use user-pays or not.

Table 5.3: Core Factors (CFs) in Determining the Payment Scheme

| Step 1: Project Characteristics | | Step 2: Allocation of Demand Risk | |
|---|---|---|---|
| Factor | Description | Factor | Description |
| $F_1$: PPP model | PPP includes different models such as DBF and DBFOM. If the model does not include O&M in the contract (e.g. DBF), the Contractor will be unable to collect tolls since they have no responsibility for operation. Therefore, the user-pays payment scheme may not be practical to use in such models. | $F_6$: Elasticity of demand | This factor considers the extent to which user-pays would dissuade potential users from using the project. It considers the relationship between user fees and expected level of use. |
| $F_2$: Legal viability | The application of user-pays to PPP projects will be dependent on the legal powers of Authorities and Contractors to charge users of services. | $F_7$: Ability to forecast demand | This factor will determine the extent to which the Contractor is likely to accept demand risk on the project, and the extent to which the private finance can be secured in a cost effective way. |
| $F_3$: Government policy | The application of user-pays must reflect government policy on user charging. | $F_8$: Practicality of collecting tolls | In some instance, it may not be practical to collect tolls. As such, it may not be cost effective to apply user-pays. |
| $F_4$: Number of availability alternative roads | The application of user-pays on a project may discourage potential users and result in them using other available alternatives. This could have a significant impact on the ability of the project to deliver the benefits for which was designed. | $F_9$: Financial viability of user-pays | The user-pays should be proved financial feasible to use. |
| $F_5$: Public opinion on user-pays | The public opinions about user-pays may influence the decision. | $F_{10}$: Intention to transfer the responsibility of operating the toll system | The Authority may have different levels of intention to operate the toll system (e.g. monitoring, maintaining, and collecting tolls). |

Table 5.4: The scores and rankings of the factor in determining the selection of payment scheme

| Factor | | The overall group (with all the respondents) | | |
|---|---|---|---|---|
| | | Mean | S.D. | Rank |
| F1 | PPP model | 4.70 | 0.13 | 1 |
| F2 | Legal viability | 4.63 | 0.33 | 2 |
| F3 | Government policy | 4.44 | 0.87 | 3 |
| F9 | Financial viability of user-pays | 4.21 | 0.52 | 4 |
| F6 | Elasticity of demand | 4.04 | 0.77 | 5 |
| F7 | Ability to forecast demand | 3.95 | 0.29 | 6 |
| F5 | Public opinion on user-pays | 3.43 | 0.72 | 7 |
| F8 | Practicality of collecting tolls | 3.37 | 0.65 | 8 |
| F10 | Intention to transfer the responsibility of operating the toll system | 2.64 | 1.02 | 9 |
| F4 | Number of availability alternative roads | 2.05 | 0.89 | 10 |

# Chapter 6

# THE EXPLANATORY FRAMEWORK FOR THE DESIGN OF PAYMENT MECHANISM IN TRANSPORTATION PPPS

## *6.1 The Overview of the Framework*

The framework aims to assist decision makers in formulating the appropriate payment mechanism that meets the project objectives and characteristics. The main contribution of this framework is twofold. First, the framework identifies the factors that need to be taken into account when deciding a payment mechanism. The payment mechanism design of PPP projects is more difficult than that of traditional infrastructure projects since long-term contracts should account for future uncertainties and risk allocation between participants. The proposed framework provides for the decision makers objectives to be considered in the design of the payment mechanism and for the link between the compensation and the management of the allocated risks to be realized. Second, the framework allows the use of quantitative methods, such as machine learning (ML), the Analytical Hierarchy Process (AHP), and optimization modeling, to standardize and automate the decision-making in quantifying the priorities of the project goals, and in determining the different payment types and the corresponding percentages.

The proposed framework is presented in Fig. 6.1, consisting of four key phases, and each phase includes a set of detailed steps. The four phases are:

1. Selecting the appropriate payment scheme;
2. Selecting the appropriate payment type(s);
3. Optimizing the payment mechanism; and

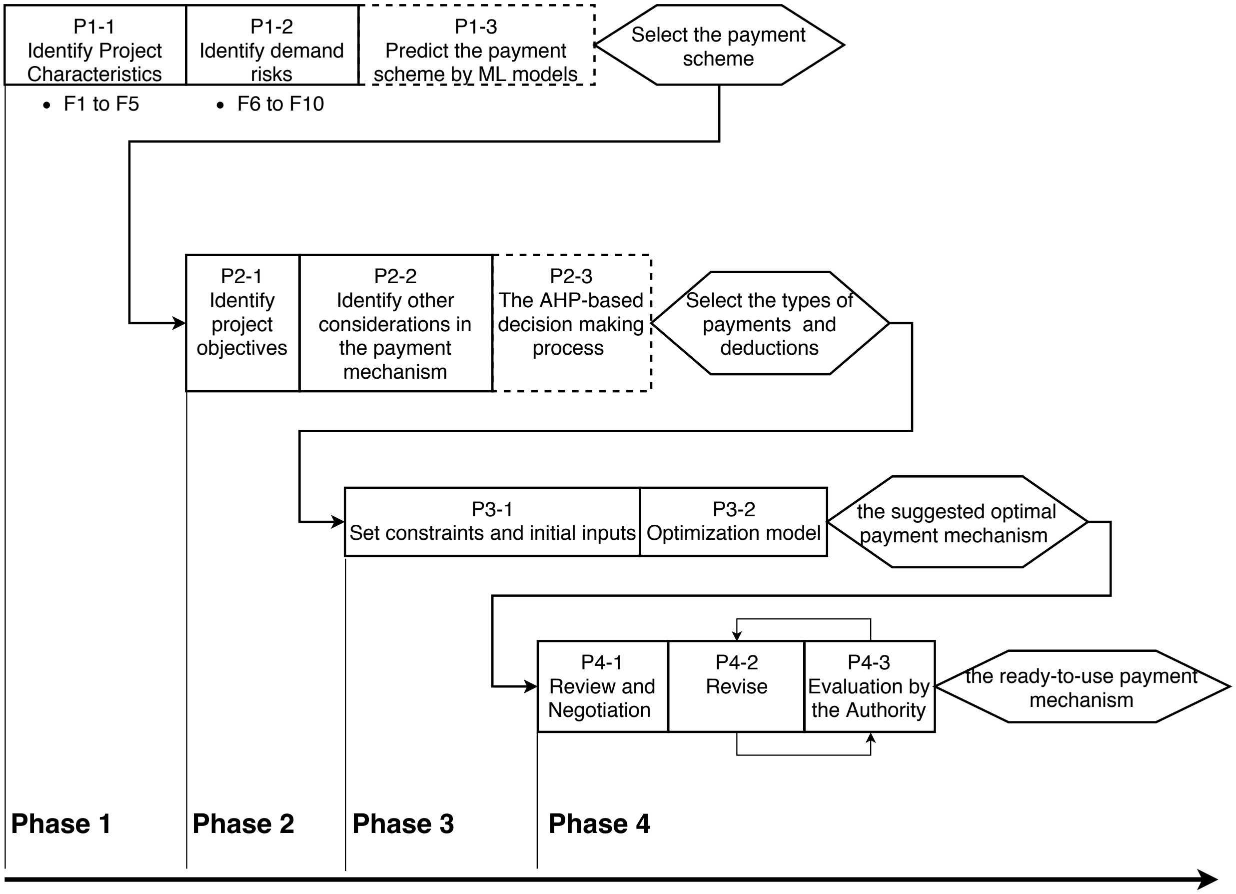


Figure 6.1: The Explanatory Framework for the Design of Payment Mechanism

4. Negotiating and evaluating the suggested payment mechanism.

## *6.2 Phase 1 - The selection of payment scheme*

The framework starts with selecting the appropriate payment scheme, in other words, to determine user-pays versus government-pays (as discussed in 2.4.1 and 2.4.2). The selection should be based on the allocation of demand risk between the public owner and the contractor. All demand risk is transferred to the private sector in user-pays scheme, while demand risk is shared between two participants or to be retained by the public sector in government-pays scheme. According to FHWA [28], about half of the US transportation projects anticipating using PPPs (those projects that have not yet reached the transaction launch phase and in which PPP is a candidate delivery method) may adopt user-pays payments. This even-handed split between two payment schemes indicates that payment mechanism is dependent on the government's preferences and the particular risk profile for the project [7].

In general, Phase 1 of the framework identifies the key factors in determining the payment scheme. By referring to such factors, the framework could help the public owner in selecting the appropriate payment scheme based on the project characteristics. This phase consists of three steps (see Fig. 6.1), including:

- Identify the project characteristics;
- Consider the allocation of demand risk; and
- Predict the appropriate payment scheme using classification machine learning models (optional).

The selection of user-pays or government-pays might come into difficulty when each scheme can be equally selected. In order to deal with this challenge, the framework provides for the analysis of historical PPP projects to help in the selection process.

First, according to the comprehensive review of guidance documents and several PPP projects, a number of factors in determining the payment scheme have been identified and summarized in Table 5.3. The importance of these factors has been examined through the questionnaire survey (see Chapter 5), and the result is shown in Table 5.4. The first two steps in Phase 1 ($P_{1-1}$ and $P_{1-2}$) helps the decision-makers to identify such factors for their projects and ensure the key factors are fully considered during the scheme selection.

The design of payment mechanism should be evolutionary, and the public sector should draw on experience of similar projects taking into account differences in project objectives and characteristics [23]. The selection of the payment schemes (user-pays vs. government pays) can be regarded as a binary classification problem. As such, by analyzing the past projects, classification machine learning models (e.g. logistic regression and gradient boosting) could be used to provide statistical inference on determining the appropriate payment scheme for a new project ($P_{1-3}$). To do so, a PPP database used for determining the payment scheme has been established. The core factors (identified from the aforementioned two steps) of each project were collected as the predictors. In the initial stage, a total of 89 projects have been included in the database, covering all PPP transport projects in the US [28] and the vast majority of Canadian PPP transport projects [16]. As the current scope is to explain the theoretical scope, the establishment of such classification models will be considered as a future research step. Conceptually speaking, the machine learning models will explore the similarity between the new project and the projects in the database by going through the key factors (see Table 5.3). The payment scheme will be recommended to the new project based on which used in the most similar project(s).

### *6.3 Phase 2 - The selection of payment type(s) and deduction(s)*

Once the main payment scheme is determined, the next phase is to identify the appropriate type(s) of payment and deduction for meeting the project objectives. Since the Authority may be financially free standing in user-pays payment schemes, this phase mainly considers for the government-pays scheme or the government subsidies used in the user-pays schemes.

The government-pays payment scheme can be structured based on one major payment type (e.g. availability payment) with a set of deductions [90], or it can be composed of multiple types of payments into a payment package [2]. Since the 1980s, availability payment became more prominent in the United Kingdom, Canada, and Australia, and in the US, the adoption of availability payment is also growing rapidly [7]. For the current PPP transport projects, the most common way is to use availability as the main payment type, and a set of other service performance are attached to it in the form of deductions. In addition to availability, a transport project may also have many other significant goals. For example, in the accident-prone circumstance, the public agencies may desire to improve road traffic safety through the issued PPP projects, and in this case, a particular safety payment can be set to facilitate the public agencies goal. As introduced in the literature review chapter, many particular types of performance payment have been developed to serve for the particular focuses of a PPP project. Irwin [42] discussed some of the trade-offs between different types of payment and provided suggestions on how governments can decide the appropriate one. Abdel Aziz [2] provided more detailed description of the different types of payment, and Yescombe [113] further discussed their implications for risk allocation and bank-ability. The Authority can refer to the application of any existing types of payment in other projects (e.g. the calculation formula and the measures), or they can develop a new payment to fit their needs.

In Phase 2, the framework provides for a comprehensive consideration in determining the appropriate payment type(s) based on the project objectives. Further, the framework suggested a decision-making process based on AHP (Analytic Hierarchy Process) can be used to quantify the priorities of the Authoritys objectives and to decide the relative weights or percentage of each payment in the payment mechanism. The AHP is a structured technique to handle multi-criteria analysis for complex decision-making problem. It provides a simple way for weighting decision elements that cannot be enumerated directly [45]. The details of the technical process of the AHP based decision making have been given in Appendix B.

The AHP-based approach for deciding the payment mechanism can be divided into four steps, illustrated in Fig. 6.2. This method can assist the decision makers to recognize their understanding pertinent to the importance of the considerations for selecting payment types.

First, the framework would ask the public owner to clearly define their objectives and expectations for the project ($P_{2-1}$ in Fig. 6.1). Once the project objectives have been identified, the framework would help in selecting the appropriate payment structure ($P_{2-2}$ in Fig. 6.1). This step aims to solve two major questions: (1) what payment structure should be used (i.e. one main payment with a set of deductions or a combination of different types of payments) and (2) which type(s) of payment should be used. A number of determinants in developing the payment structure have been identified through the questionnaire survey

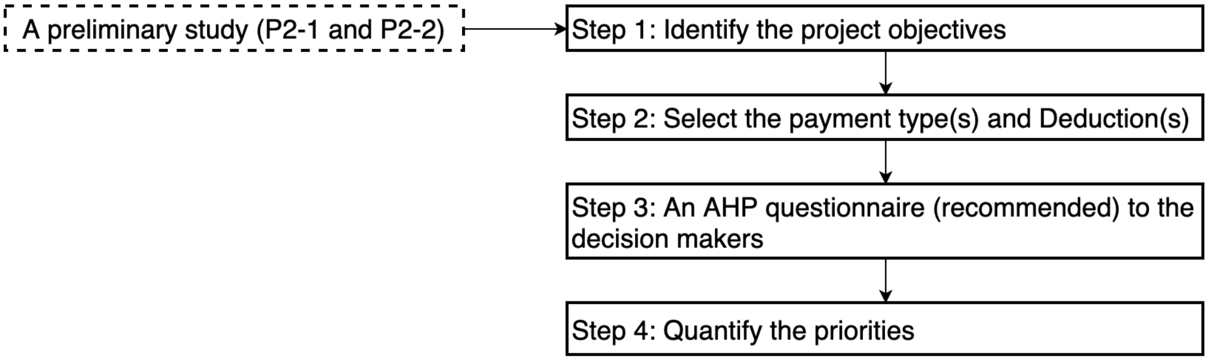


Figure 6.2: The AHP-based decision-making process

introduced in Chapter 5. According to the analysis of the survey responses, in addition to the project objective, many other factors are also expected to influence the Authoritys decision in selecting payment types, such as the stakeholders knowledge of different types of payment; the complexity of the payment mechanism; and the owners ability and/or required efforts/costs to monitor project performance. Such identified determinants will provide for the public owner a comprehensive consideration in determining the payment structure fits best for their preference.

Next, the appropriate type(s) of payment (e.g., availability and safety) can be selected based on the major objectives and other considerations. In government-pays scheme (or government subsidies in user-pays scheme), the particular payment(s) can be assigned to the first-priority objectives in a PPP project, and other project objectives can be reflected by means of performance deductions within the main payment(s). For example, availability and safety are both important objectives in the project of I-595, however, that project decided to have a type of payment for the availability purpose without having a separate payment for safety, instead, it used performance deductions to account for the safety purpose. The determination of the appropriate payment(s) should be subjected to other decision elements. For instance, when the simplicity of payment mechanism is a key consideration (first-priority) for a project, the selection of payment may have to be limited to one or two types even if there may be more than two first-priority objectives.

Once determined the payment type(s) and the deduction(s), the framework will help the owner prioritize each project goal in order to properly distribute payments. In this step, an AHP based method is recommended. A number of pairwise comparisons will be used in the AHP method to identify the owner's preferences on respective project goals. The owners opinions will be incorporated into the scoring of the pairwise comparisons, and AHP matrices can be constructed to compare the relative importance of respective project goals.

Finally, based on the pairwise comparison, the priority (weight) of each project goal can be calculated. These quantified priorities or weights are used in the optimization model (in Phase 3) to provide for the optimal proportion of various payments in a payment mechanism.

## *6.4 Phase 3 - Optimization of the payment mechanism*

Once the payment schemes and payment types are selected, the framework provides for the determination of the optimal percentage of each payment in the payment mechanism structure. Since there are multiple objectives to be considered in reach out the optimal payment mechanism, the framework provides a game theory based optimization model in suggesting the optimal payment mechanism by adjusting the proportion of various types of payment in the payment mechanism. The interests of both public and private sectors are considered and reflected by a bi-level objective function. The model aims to search for solutions that maximize the overall project performance for the sake of social welfare while simultaneously maximizing the return for the sake of private investment. The details of the model will be described in Chapter 7.

## *6.5 Phase 4 - Evaluation of the payment mechanism*

PPP requires the public owner to work closely with all stakeholders. It is important to have the opinions from all participants in the design of payment mechanism. Phase 4 provides a chance for the whole owner team and consultant specialists hired by the owner to review and provide feedback for the payment mechanism derived from former phases. Based on the feedback, the payment mechanism may be refined to provide more cost-effective ways to achieve objectives and allocate risks.

The revised payment mechanism should be evaluated by the public owner to verify it meets all project objectives and presents the best value for money. The evaluation could focus on the following points:

- All project objectives should be reflected in the payment mechanism by the corresponding payment(s) and/or deduction(s);
- Each stakeholder should clearly understand and fully agree with the payment mechanism (e.g. the calculation of each type of payment, the penalty conditions, etc.);
- Output specification should be compatible with the payment mechanism, and each performance standard should be assigned a corresponding payment (deduction) point. Any requirements in the output specification which do not feature in the payment mechanism should be challenged or should be brought into the payment mechanism [94];
- A risk assessment should be conducted to ensure risks are allocated through the payment mechanism to the party best able to manage them at the lowest cost.

## *6.6 Summary of the chapter*

Payment mechanism lies at the heart of the PPP contract, which can be used to reflect the public goals in allocating risks and achieving required project performance in a cost-effective way. The design of payment mechanism is the process of tailoring payment mechanism to individual projects based on the particular project objectives. While the procedures and considerations in developing payment mechanisms have been well established, guidance of aligning project objectives with the payment is relatively scarce and the selection of payment methods highly relies on the empirical judgment of decision makers.

To deal with these deficiencies, this research proposes an explanatory framework to assist decision makers in developing the appropriate payment mechanism for PPP transport projects. The framework consists of four main phases, including (1) the selection of payment scheme; (2) the selection of payment types; (3) the optimization of payment mechanism; and (4) evaluation and revision.

First, based on an in depth review of the guidance documents and PPP project agreements regarding the design of payment mechanism, key factors in determining the payment scheme are identified. A database consisting of such key factors is established, which includes the transport PPP projects in the US and Canada. This database is used to build a set of classification machine learning models for the prediction of the appropriate payment scheme (user-pays vs. government-pays) for a new project.

Second, the framework suggests an AHP-based decision-making process to assist the decision makers to identify the priority of respective project objectives. Particular type(s) of payment can be selected to meet the first-priority objectives in a PPP project, and the other project objectives can be reflected by means of performance deductions within the main payment(s).

Third, once the main type(s) of payment and deductions are determined, the framework proposes a multiple-objective optimization model to provide the optimal payment mechanism by adjusting the proportion of various type(s) of payment and deductions in the payment mechanism. The optimal payment mechanism will seek to maximize the achievement of all project objectives within an affordable price and maximize the overall profit for the private sector simultaneously.

Last, the payment mechanism derived from the framework will be reviewed and evaluated with all stakeholders. Refinements may be made based on the feedback. The revised payment mechanism will be evaluated by the Authority before the implementation to ensure it meets all project objectives and presents the best value for money.

This framework sheds light on using quantitative methods to achieve the optimal payment mechanism based on the project objectives and other characteristics. Both public sectors and private sectors can benefit from this framework. In the future, a test will be conducted and presented for the purpose of comprehensively validating the practicability of the proposed framework.

# Chapter 7

# STACKELBERG GAME THEORY BASED OPTIMIZATION MODEL

## *7.1 Overview*

Payment mechanisms lie at the heart of public-private partnership contracts. As mentioned previously, a good design of the payment mechanism should consider the owners goals in the project, allocate risks appropriately to stakeholders, and assure satisfactory performance through providing a reasonable compensation to the private developer. In view of the needs for proper allocation of risks, optimizing performance, and attaining reasonable rewards, this chapter proposes a Stackelberg game theory-based model to assist public agencies in designing payment mechanisms for PPP transportation projects. The interests of both public and private sectors are considered in the model and reflected by a bi-level objective function. The model aims to search for solutions that maximize the overall project performance for the sake of social welfare while simultaneously maximize the return for the sake of private investment. A variable elimination method and the genetic algorithm are used to solve the optimization model. The solutions provided by the model reveal that the optimal payment mechanism structure could be reached such that it would satisfy the owners requirements for the overall project performance while optimizing the project total payments to the contractor.

The remainder of the chapter is organized as follows. First, an introduction of Stackelberg game theory is presented to help the readers have a better understanding of the model. After that, a detailed discussion of model development in the context of payment mechanism design is given. Next, a genetic algorithm based heuristic approach used to solve for the proposed optimization model is discussed. Further discussions concerning the limitations of the model and implications are given in the end of this chapter.

## *7.2 Stackelberg Game Theory*

In the process of the PPP contract negotiation and execution, the two main participants, the public sector and the private sector, usually have different objectives or considerations. The model used for optimizing the design of PPP payment mechanisms, therefore, should capture the various objectives from different participants, which is known as a multi-objective optimization problem. A multi-objective problem is an optimization problem that involves two or more conflicting objective functions [62]. Several methods have been developed to solve for multi-objective optimization problems, such as the weighted sum methods ([59] [48]), Pareto optimal frontier ([22] [32] [66]), and game theory methods ([78] [31]). This chapter gives a focus on solving the optimization problem in the design of payment mechanism by using the game theory-based method due to the nature of the problem which will be covered in details later.

In a typical game theory problem, each player has his or her own objective. All players aim to improve their own benefits through collaborating or competing with each other. There are three common game theory modes, including cooperative game, non-cooperative game, and sequential game [31]. In cooperative game, the players know the decisions chosen by others and collaborate with each other to achieve a Pareto optimal solution (i.e. a solution satisfies each player). In non-cooperative game, the players make their own decisions without knowing the decisions chosen by others. A classic non-cooperative game is the prisoners dilemma in which two prisoners decide whether to confess or not. Sequential game, also known as Stackelberg game, is a particular case of non-cooperative game in which the decisions are made sequentially. This research focuses on using Stackelberg game method as decisions are commonly made in a sequential manner in the process of contract negotiation and execution in a PPP project.

A Stackelberg game commonly has two main groups of players: a leader and a follower. Either of them has their own strategy aiming to optimize their respective objectives, which are usually different and even conflicting. The leader moves first by choosing a strategy, and the follower chooses the optimal strategy given the knowledge of the leaders move. The leader can predict the followers reaction (or strategy) by rationally assuming that the follower always optimizes their strategy under a given strategy of the leader. By the awareness of the followers potential moves, the leader can maximize their objective function through revising their strategy.

The Stackelberg game theory problem, especially for the bi-level objectives optimization, has been studied widely. Sinha et al. [91] summarized the basic principles and discussed the practical uses of bi-level optimization based on a comprehensive literature review. Brotcorne et al. [14] proposed a bi-level model for optimizing toll setting. In their model, the leader is the facility operation firm that aims to maximizing revenues from tolls set, while the follower is represented by the road users travelling on shortest paths with respect to a generalized travel cost (time and money). Hearn and Ramana [39] and Larsson and Patriksson [52] developed bi-level optimization models to minimize urban congestion by controlling tolls. The other applications of Stackelberg game-based optimization include, such as, management of hazardous materials [46], road network design ([53] [58] [19]), and airline price setting [20].

## *7.3 Problem Nature of the Design of Payment Mechanism*

The design of a PPP payment mechanism requires taking the considerations of both the public and private sectors into account. The public sector aims to achieve a good performance level of project within budget while the private sectors aims to maximize the return. The success of a PPP project depends not only on the detailed contract terms regulated by the public sector but also depends on the private sectors strategy in development, operation, and maintenance (DOM) [21]. Instead of forcing the contractor to execute the contract through a set of prescriptive technical requirements, a more proactive way of developing and managing a project is to encourage the contractor to deliver a good service by linking the payment with the project performance.

In order to provide incentives for the contractor to achieve the project goals, each goal should be linked to a payment or part of it. In a performance-based contract, the contractors revenue will be determined by three parts, including the maximum payment assigned to each project goal, the expected cost of the selected DOM strategy on achieving each goal, and the deduction for the non-compliant performance. A deduction for the non-compliant performance can be set in a proportion between 0 to 100% of the maximum payment assigned to the corresponding goal based on the wishes of the public authority. The authority might allow deduction to reach 100% if the contract is fully performance-based and mainly for services being rendered by the contract. Alternatively, the owner might select a maximum percentage deduction considering the remainder of the payment reimburses the basic capital inputs of the contractor (e.g., material costs).

Given a contract, it is rational to assume that the private contractor will choose the strategy that controls the costs while maintaining an acceptable performance so as to avoid high noncompliance deductions. Therefore, the decision of the public agency regarding the payment structure, amount and deductions will affect the contractors DOM strategy, which will have a corresponding impact on project performance. By having knowledge of the contractors reaction in advance, the owner can adjust the amount of maximum payment assigned to each project goal based on the priority of each goal so as to maximize the overall project performance. Fig. 7.1 illustrates the relationship among the maximum payment, the strategy, and the performance.

## *7.4 The Optimization Model*

Based on Stackelbery game theory discussed above, this research proposes an optimization model including two hierarchical objectives, which is also known as a bi-level optimization problem. The model aims to search for solutions that maximize the overall project performance for the sake of social welfare while simultaneously maximizing the overall profit for the sake of private investment. From the perspective of the public sector, the model will provide guidance for the design of the payment mechanism by quantitatively determining the optimal proportion of each type of payment in a payment mechanism. From the perspective of the private sector, the solution of the model can be used as a reference for the contract

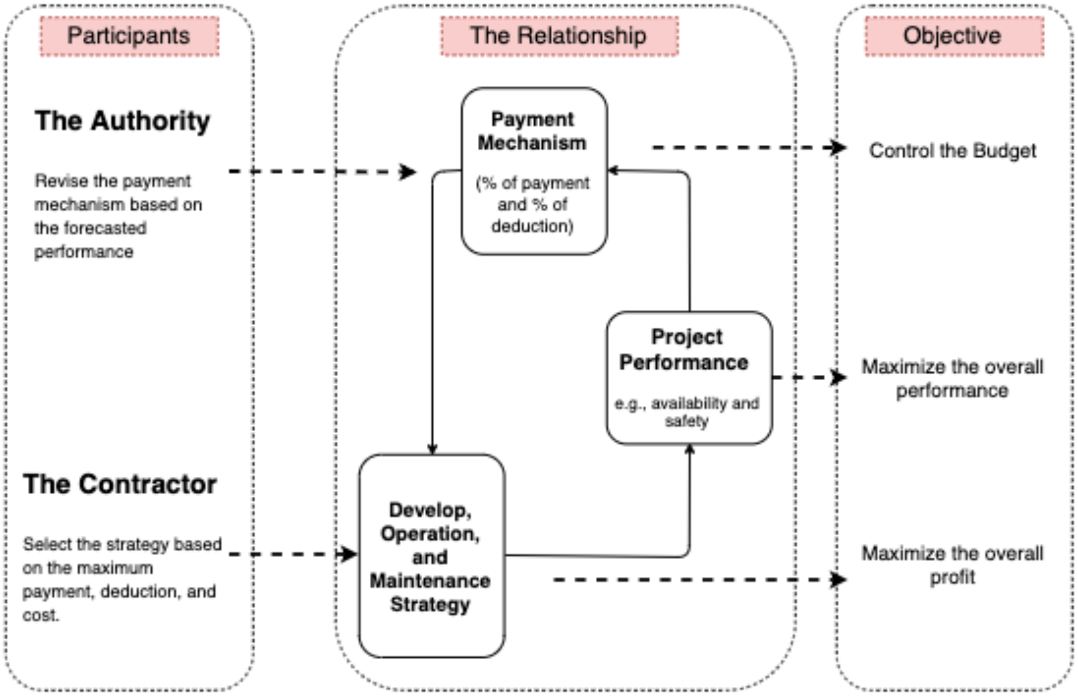


Figure 7.1: The PPP Payment System Relationships

negotiation.

### *7.4.1 The Objective Function*

In the process of contract negotiation and execution, the decision between the public and the private sectors is made in a sequence, which follows the Stackelberg game problem. The authority (as the leader) decides on payment design and the contractor (as the follower) follows by changing project delivery strategy (e.g., efforts spent to achieve each project goal). By capturing the objectives of both parties, this paper proposes a Stackelberg game based bi-level optimization model. The model is presented as follows.

$$\text{(UL)} \quad \underset{x}{\text{Max}} \sum_{i}^{n} [(P(y_i) \times \alpha_i - x_i \times \beta \times \alpha_{money}] \tag{7.1}$$

subject to

$$0 \leqslant x_i \leqslant budget \tag{7.2}$$

$$\sum_{i}^{n} x_i \leqslant budget \tag{7.3}$$

where $y_i$ are obtained by solving

$$\text{(LL)} \quad y_i \in \underset{y_i}{\text{argmax}} \sum_{i}^{n} [x_i - \frac{100 - P(y_i)}{100} \times x_i \times \mu - c_i \times y_i] \tag{7.4}$$

subject to

$$y_{min} \leqslant y_i \leqslant y_{max} \tag{7.5}$$

$$\sum_{i}^{n} (c_i \times y_i) \leqslant \sum_{i}^{n} x_i \tag{7.6}$$

$$P(y_i) = Performance_i = \frac{100}{1 + e^{-(ay_i - b)}} + \lambda \tag{7.7}$$

The model contains two decision variable vectors the owners payment mechanism (X) and the contractors DOM strategy (Y). X is a vector consisting of $n$ variables (e.g., $x_1$, $x_2$, $x_n$), where n is the total number of project goals the owner aims to achieve through

PPP. Each variable ($x$) is the amount of payment assigned to the corresponding goal in a payment mechanism (X). Y is also a vector of $n$ variables representing the contractors strategy. Each variable ($y_i$) is the strategy selected to achieve the corresponding project goal $i$. For the calculation purpose, these strategies are quantified as the effort the contractor put on achieving the project goals. For convenience, the model assumes that each strategy $y$ represents a percentage from 0 to 100, where 0 means the contractor spends no effort on achieving the project goal and 100 means the contractor offers the best. The strategy $y_i$ for achieving goal $i$ determines the corresponding project performance either linearly or non-linearly, which will be discussed in details later. But in general, it is reasonable to assume that the higher the $y$ (e.g., the more DOM actions are taken), the better performance a project will have. The other factors in the proposed model include:

- $i$ The project goal $i$;
- $n$ The total number of project goals;
- $P(y_i)$ The relationship function relating project performance to the contractors DOM strategy for achieving goal $i$;
- $\alpha_i$ The priority of goal $i$;
- $\beta$ A normalization factor to scale the payment and the performance to the same unit, where $\beta = \frac{100}{\sum x_i}$;
- $\mu$ The maximum deduction percentage;
- $c_i$ The unit cost of DOM strategy for achieving goal $i$, which equals the estimated cost that achieves goal $i$ with a platinum level performance divided by 100 (the maximum of $y$);
- $a$ and $b$ The parameters in the performance function;

- $\lambda$ A stochastic variable to reflect the uncertainties that affect the performance and the measurement error.

The model has two hierarchical objective functions the upper level (UL) and the lower level (LL). The UL function, presented in Eq. 7.1, reflects the public authoritys objective in maximizing the overall project performance while minimizing the total payment. As shown in the first part of Eq. 7.1, the overall project performance is a sum of the weighted performance of each goal. The weights represent the authoritys priority for achieving each project goal. The priority of the project goals can be quantified through an AHP (Analytic Hierarchy Process) based survey to the public agency ([116] [98]). In the literature review chapter, using AHP to quantify the priority of project goals has been discussed. The second part of Eq. 7.1 reflects the owner's objective in controlling budget, which is also adjusted by multiplying a weight to reflect the priority in minimizing the total payment ($\alpha_{money}$). A normalization factor ($\beta$) is used to scale the payment and the performance to the same unit.

The contractors objective is represented by the LL function, Eq. 7.4. Given a contract with a determined payment mechanism, the model assumes that the contractor will act rationally to maximize the overall revenue (the value of LL function) through adjusting the DOM strategy ($y_i$) to minimize the corresponding expenses and the deduction for the noncompliance.

Model constraints are listed in Eq. 7.2, 7.3, 7.5 and 7.6. Eq. 7.2 guarantees no single payment exceeds the project budget, and Eq. 7.3 ensures the total amount of the payment mechanism is within the budget. Eq. 7.5 limits the contractors strategy within a range of 0% to 100% as mentioned previously, and Eq. 7.6 ensures the total payment will at least cover the contractors total cost, otherwise the contractor may decide not to take the project.

### *7.4.2 Assumption of the Performance Function*

The performance, which reflects the achievement of each project goal, is an essential part in the model. On one hand, it is the main component that the UL objective function aims to maximize. On the other hand, it determines the amount of deduction in the LL function, which further determines the contractors overall profit. The performance can be quantified by several indices. For example, Cui et al. [21] used the pavement condition index (PCI) to reflect the road availability. Rangel et al. [77] used crash, injury, and fatal rates to reflect the road safety performance. For the sake of simplification, in this paper, all the project performances are represented respectively by dummy indices in the range of 0 to 100, where 100 means the project goal is fully achieved.

The performance function (Eq. 7.7) reflects the relationship between the contractors DOM strategy and the corresponding performance, represented by an index. In manufacturing, a higher level of manufacturing strategy/process has been proved to be associated with higher product performance/quality [38]. In construction industry, the project performance is also confirmed to be positively correlated to the contractors effort on project development and maintenance. Chan et al. [17] indicated that the actions of project management are one of the key factors affecting the success of a construction project. Meng [61] stated that a good supply chain maintained by the contractor has the significant influence on project performance. However, no research has provided a clear quantitative explanation for the relationship between the contractors DOM strategy and the project performance. Cui et al. [21] assumed the project performance (e.g., road availability) has a linear relationship with the contractors effort (e.g., O&M actions). However, this linear assumption may not fully reflect the real case. Harter et al. [38] found that the product quality is nonlinear with the manufacturers effort, but no specific relationship function is given.

This paper presents a nonlinear relationship between the contractors strategy and the project performance by using a sigmoid function to convert the linear function assumed by the previous study [21] to nonlinear, exhibited in Fig. 7.2. The nonlinear performance function is expected to be better in capturing the relationship. Intuitively, when the contractors contribution or effort is below a certain level, it becomes insufficient to provide the basic functions or the required performance in the project. This is reflected through the low performance region in Fig. 7.2. When the effort increases to a certain range, the efficiency

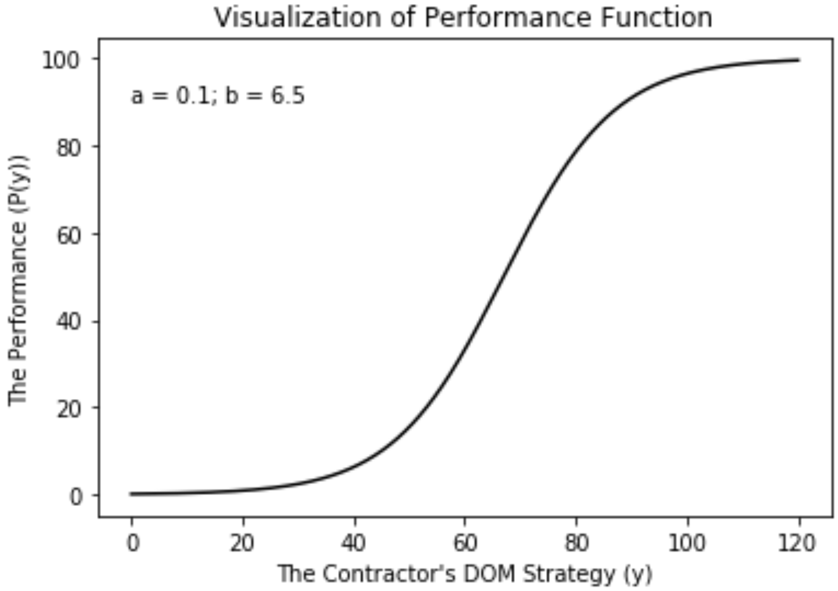


Figure 7.2: Visualization of Performance Function

in improving the performance becomes significant; and as the performance tends to reach the maximum, the improvement brought by the increased efforts becomes almost leveled. For example, if the contractor puts little effort in providing smooth and quite pavement, as measured by ruts that are greater than 0.4 inches, the performance will be low as measured by the non-conformance deduction points and the subsequent dollar deductions. As the contractor increases the effort, the smoothness and the performance will improve steadily (middle in Fig. 7.2). However, once the smoothness reached the perfect level, it is hard to provide a further or significant increase in the performance with more contractor's effort.

The relationship between the contractors strategy and the performance is reflected in the first part of Eq. 7.7, and the shape of the function is determined by two parameters ($a$ and $b$). The second part of Eq. 7.7 ($\lambda$) is a stochastic term presenting the uncertainties during the process of project development and the error of performance measurement. For the purpose of simplification, the model assumes all project goals follows the same performance function (i.e., the same $a$ and $b$). However, in practical uses, the performance function of each project goal can be modified respectively to reflect the real situation.

### *7.4.3 Solving for the Bi-level Optimization Model*

A variable elimination method based on Kuhn Tucker approach is used to solve for the model ([35] [10]). In a Stackelberg problem, a solution pair ($x$ and $y$) is considered to be optimal if neither of the participants have an incentive to revise their strategy [31]. According to the theory of Stackelberg game, the leader chooses the optimal solution(s) by solving the UL function, and then the follower optimizes their own problem by replacing the leaders variables in the LL function with the fixed value obtained from the UL function. From an implementation point of view, the Stackelberg problem can be solved by backward induction. It starts with optimizing the LL function by assuming the leaders (owner) variables are fixed (i.e., as constant parameters). Through varying the leaders variables, the relationship function between the followers (contractor) optimal solutions and leaders variables is obtained. Then the followers variables in the UL function can be substituted by this relationship function, and the UL function becomes an optimization problem with only the leaders variables. The steps of solving a Stackelberg game problem are illustrated in Fig. 7.3.

The key point in solving Stackelberg game-based optimization is to obtain the relationship function between followers optimal solution (the optimal $y$) in the LL objective function and the corresponding value of the leaders variable ($x$). In the following, the variable elimination process of the proposed model is discussed. For the sake of explanation, the problem is simply assumed to have only one goal associated with one type of payment (i.e., one $x$ variable and one $y$ variable) and there is no stochastic term in the performance function. In this case, the LL objective function can be simplified as follows:

$$LL = x - \frac{100 - \frac{100}{1+e^{-(ay-b)}}}{100} \times x \times \mu - c \times y \tag{7.8}$$

In Eq. 7.8, the $P(y_i)$ part in the original LL function (Eq. 7.4) is replaced by the full performance function in Eq. 7.7. By assuming $x$ is fixed (e.g., \$120 million), the relationship

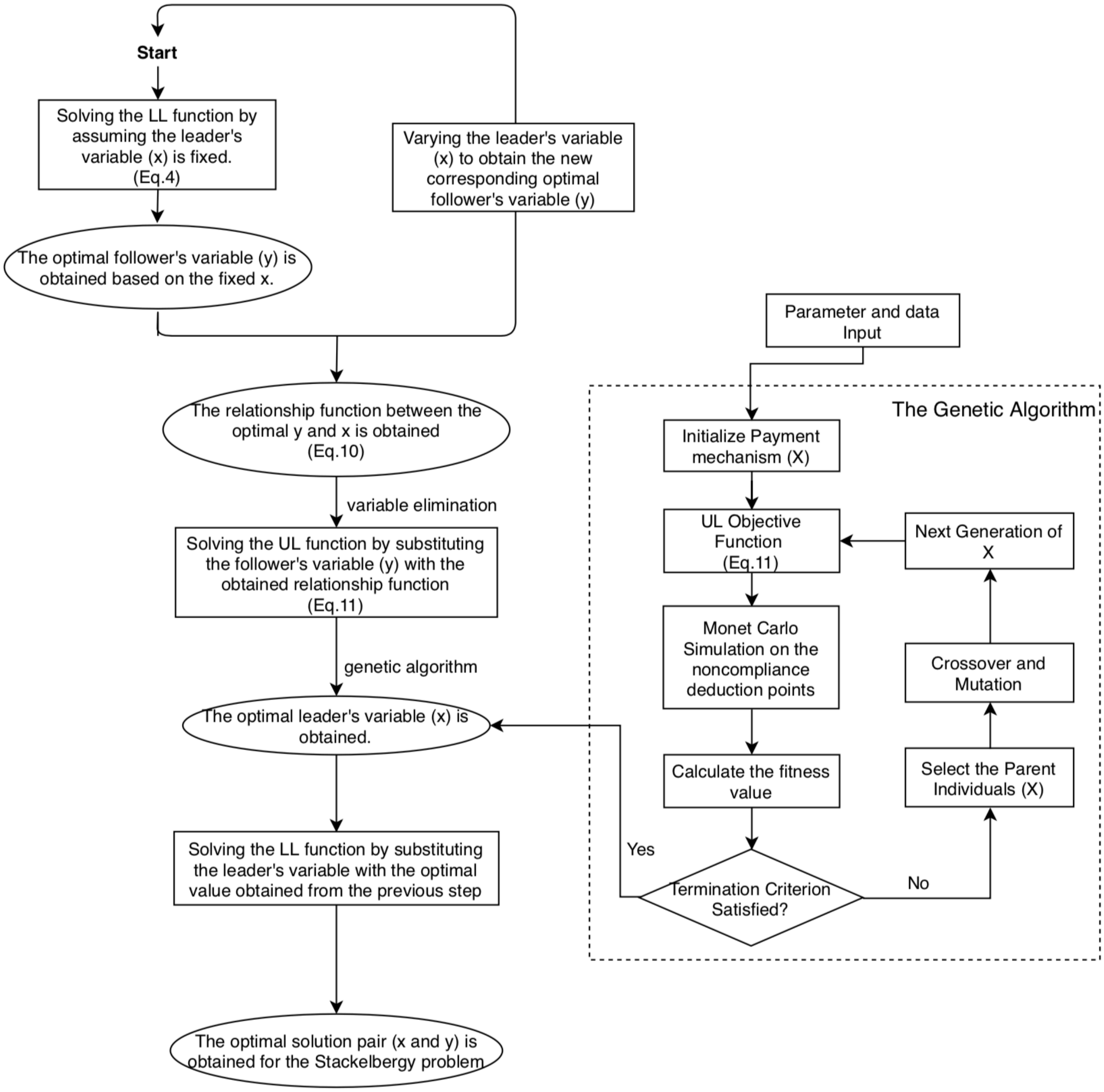


Figure 7.3: The Steps of Solving Stackelberg Problems

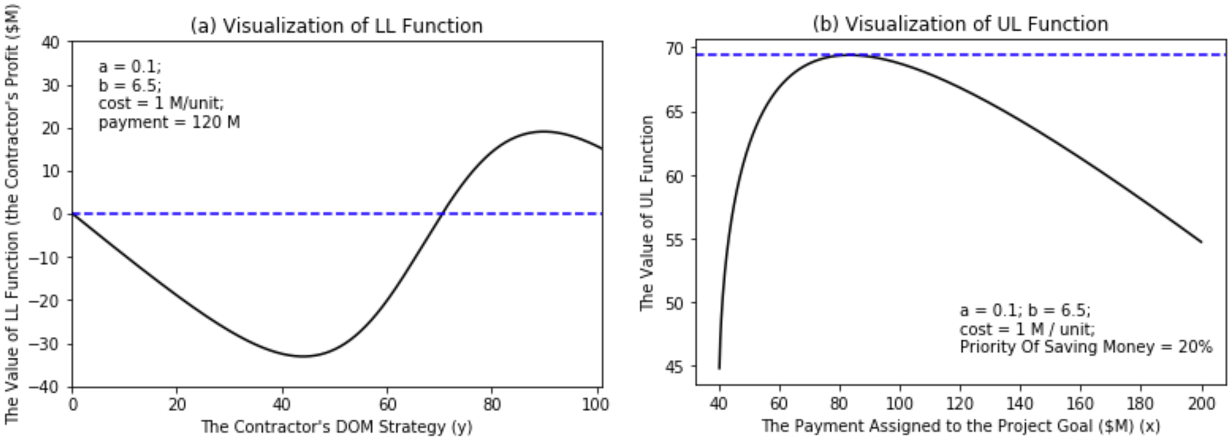


Figure 7.4: The Shape of (a) the LL Function and (b) the UL Function

between $y$ and the value of the LL objective function is illustrated in Fig. 7.4(a).

As shown in Fig. 7.4(a), the LL objective function in the model has a convex portion and a concave portion in the feasible range of y (the strategy) variable. In the concave part, as the contractor's effort in a strategy $y_i$ increases and reaches a certain level (e.g., 70), the profit increases to a positive value. In the convex part, the more effort, the better the reward until a maximum point is reached, after which it would cost the contractor by spending more effort for no further gains. The LL function (Eq. 7.4) tries to obtain the effort or the effort range that will generate the maximum value of the contractor's profit (reward). Fig. 7.4(a) exhibits that there is one global maximum point in the feasible range, which can be obtained by solving the function parametrically (e.g., derivative). For example, given the performance function (e.g., $a = 0.1$ and $b = 6.5$) and the financial parameters (e.g., cost = \$1M per DOM strategy unit and payment = \$120M), the contractor will get the most profit when providing the contribution around 90%. When the LL function reaches the maximum point, the corresponding $y$ is called the optimal reaction of the follower based on the $x$ determined by the leader. In practice, the contractor's effort $y$ for a particular goal $i$ could reflect the contractor's strategy that includes such as a particular work/operation plan, mix of labor and equipment hours, and particular working hours, which in total comes at the cost $c_i$.

As mentioned previously, in Stackelberg problem, the optimum value of the followers variable ($y$) is given as a function of the leader variable ($x$). Such a function can be obtained by solving the derivative of the LL function as presented in Eq. 7.9. The relationship function (substitution function), presented in Eq. 7.10, is derived by setting Eq. 7.9 equals to 0. It is noted that, for the calculation convenience, instead of substituting $y$ in the UL function, the whole performance function is replaced by a function of $x$, as $y$ exists in the UL function in the form of the performance function.

$$\frac{dLL}{dy} = \frac{a \times \mu \times x \times e^{(b-ay)}}{(e^{(b-ay)}+1)^2} - c \tag{7.9}$$

$$z = e^{(b-ay)} = \frac{x - \sqrt{x} \times \sqrt{x - \frac{4c}{a \times \mu}}}{\frac{2c}{a \times \mu}} - 1 \tag{7.10}$$

By substituting the performance function part in the UL function with the relationship function (Eq. 7.10), the UL function can be rewritten as follows.

$$\text{(UL)} \quad \underset{x}{\text{Max}} \; \frac{100 \times \frac{2c}{a \times \mu}}{x - \sqrt{x} \times \sqrt{x - \frac{4c}{a \times \mu}}} \times \alpha_1 - x \times \beta \times \alpha_{money} \tag{7.11}$$

Where $\alpha_1$ equals to 1 since there is only one goal in the function.

Fig. 7.4(b) exhibits the shape of the UL function based on the assumption of a set of parameters as listed in the graph. The UL objective function shows convexity within the reasonable range, which implies that the model will converge to the global optimal solution of $x$. The corresponding $y$ will be obtained by substituting the $x$ in the LL function with the optimum value. The convergence of the optimal solution pair ($x$ and $y$) will hold when generalizing to multiple project goals (a vector of $x$ and a vector of $y$) since summation will not change the convexity.

## 7.5 Genetic Algorithm

From the above discussion, the proposed model has been proved to be convex and solvable theoretically. Through a variable elimination method based on Kuhn Tucker approach [6], the LL objective function is converted to a constraint of the UL function, which determines the relationship function between the respective decision variables of two participants (i.e. $x$ and $y$). Thus, the proposed bi-level model can be converted to an optimization model with a single objective function and a single decision variable/vector the UL objective function (Eq. 7.11) and the payment mechanism ($x$ variables) respectively.

This research utilizes a standard genetic algorithm (GA) to practically solve the problem. The GA is a heuristic approach inspired by natural selection, which uses a stochastic search for solving optimization problem based on genetic processes of biological organisms [104]. The possible solutions of the optimization problem are treated as genetic coding groups. Through a simulation of natural selection, crossover, and mutation, the better solutions are generated from the previous generation (parents solutions). Through the iterative search for solutions, the solutions eventually gets converged to the optimal region.

The GA has been demonstrated to have advantages in dealing with the stochastic search and the robustness to find the global optimum ([67] [60] [114] [21]). Additionally, it is also able to capture the pattern of solution changes by recording the solution from each generation. It is worth noticing that, the proposed model never intended to provide a single contracting solution for the public agency on its own, instead, the practical implication of the model is to give recommendation/reference for the agency in payment mechanism design. Thus, it is more important to analyze the evolving trend of the potential solutions and to explore the reason behind the recommended solutions. The property of capturing the evolving trend makes GA well fit for the purpose of the model.

In execution, the model provides users with two sets of calculation environments - the deterministic environment and the stochastic environment. The deterministic environment assumes all the input parameters are fixed, while the stochastic environment assumes the parameters follow certain probability distributions to capture the uncertainties during the long-term process. The Monte Carlo Simulation is integrated into the calculation of fitness value in the GA to reflect the stochastic environments. The proposed optimization model with the GA approach is carried out using Python. The program code is provided in Appendix C.

# Chapter 8

# CASE STUDY

## *8.1 Background*

The applicability of the proposed model is validated based on a real project undergoing operation with a performance-based PPP contract, the I-595 Corridor project in Florida, USA. Some data used in the model are taken from the project, while others are assumed from a broader perspective.

The I-595 Corridor is a major east-west artery for southeast Florida located in central Broward County and first opened to the public in 1989 [71]. In early 1990s, the daily traffic increased significantly due to the economic development along the corridor, population shifts triggered by disaster, and the change of driving patterns. The Interstate 595 Freeway Operation Analysis Report in 1994 suggested an expansion of the corridor in order to satisfy the increasing traffic demand [71].

The I-595 Corridor Improvements project consisted of the reconstruction and expansion of the mainline and all associated improvements to frontage roads and ramps, for a total length of approximately 10.5 miles. A major part of the improvements project is to develop three at-grade reversible express toll lanes known as 595 Express. The lanes are operated with variable tolls to mange traffic flow and reverse direction in peak travel times [29].

The project used a performance-based PPP contract between FDOT and a private concessionaire, Floridas Turnpike Enterprise. The concessionaire is responsible to design, build, finance, operate, and maintain the roadway for a 35-year contract. FDOT supervises the contract execution. The responsibilities of installing, testing, operating and maintaining all tolling system are retained to FDOT. FDOT is also responsible for setting the toll rates and retains the toll revenue. FDOT agrees to pay the concessionaire \$1,833.6 M (in 2009 dollars) in the form of the final acceptance and availability payments.

## *8.2 Calculation Assumption*

Some assumptions and simplifications are made to simplify the calculation.

- In the model, the achievement of each goal will be measured by dummy Performance Indices in the range from 0 to 100, where 100 means the goal is fully achieved;
- The model assumes the contractors expenses are linear to the DOM strategy (i.e. effort put on achieving the corresponding project goal);
- The LL objective function (Eq. 7.4) assumes that the payment assigned to each goal will be evenly distributed each year during the concession period;
- For simplification, the model assumes a static operation scenario, which means the contractors operation strategy will not change over the concession.

## *8.3 Model Inputs*

The model inputs can be categorized by two kinds of data: the project basic information and the project goal related data. The project basic information is summarized in Table 8.1.

The deduction threshold in Table 8.1 limits the maximum the owner can deduct for the noncompliance performance, which would be determined based on the negotiation between the owner and the contractor. For the I-595 improvements, this parameter is not available in the agreement, and the case study assumes the parameter is 80% by referring to the similar projects. The intention to save money reflects the owner's priority of budgetary consideration, which is represented as a weight from 0 to 1 and 1 means the budget is significantly considered. For example, in some projects, the owners may have a very high priority in reducing the total prices, in which cases, a high weight (e.g. close to 1) should be assigned to the parameter of intention to save money; in other projects, the owners may

Table 8.1: General Parameters

| | Parameter | Values |
|---|---|---|
| Parameters for the general project information | Budget | 1833.6M |
| | O&M Period | 30 years |
| | Deduction Threshold ($\mu$) | 80% |
| | Priority for Saving Money ($\alpha_{money}$) | 20% |
| Parameters for the genetic algorithm | Generation size | 800 |
| | Population size | 150 |
| | Crossover Probability | 0.45 |
| | Mutation Probability | 0.35 |

not have strong intentions to reduce the price so long as the total cost is within the budget. As such, a low weight should be assigned to this parameter. The weights of this parameter (intention to save money) can be decided based on the owner's preferences and their current financial situation. This case study assumes FDOT (the owner)s intention for saving money is 0.2 based on the statement of project goals in the RFP document showing that saving money is not a significant goal so long as the total payment is within the budget.

Unlike a normal process of PPP planning and preparation, the use of the proposed model requires the decision makers to take an additional step to obtain the project goal related information (as the inputs). These inputs are summarized in Table 8.2, consisting of (1) the priority of each project goal and (2) the estimated expense of fully achieving each project goal. The priority of each project goal is presented in the form of weight coefficient (sum to 1) in the UL objective function. As mentioned earlier, these weights can be obtained by an AHP-based survey (e.g. [33]) for the decision makers. The estimated cost for achieving each project goal can be obtained based on the owner's experience as most of the Departments of

Table 8.2: Parameters for the Project Objectives

| Parameter | Availability | Safety | Environment | Communication | Others |
|---|---|---|---|---|---|
| Estimated Cost | 676M | 238M | 182M | 0.2M | 141M |
| The Priority of Goal | 55% | 25% | 10% | 5% | 5% |

Transportation (DOTs) have construction & operation division that can help in obtaining the estimate. For a PPP project, the owner usually develops an output specification to specify the project goals and requirements in the RFP document. These output specifications can be grouped into the corresponding project goal. By estimating the expenses to complete each requirement, the total cost of achieving a project goal can be obtained by summing the costs of the corresponding specifications that belongs to such project goal.

According to the Agreement and Value for Money report [71], the I-595 Improvements project consists of five major project goals, including availability, safety, sustainability, good communication, and others. As the concept of quantifying the priorities of the project goals is relatively new to the industry, no such data is available in the project documents. Therefore, the assumptions are made for the purpose of model validation. These assumptions will not affect the models applicability and replication. Table 8.2 summarizes the project goal related inputs for the I-595 improvement case study. In this case study, the finance-related parameters, such as the costs for achieving project goals, are given as deterministic values; while the performance indices ($\lambda$), as presented in Eq. 7.7, are assumed to be stochastic following a normal distribution to capture the uncertainties in construction.

The study sets up 800 generations (iterations) for the GA in the model. The other parameters used in the GA are summarized in Table 8.1.

## *8.4 Model Results*

With generation evolving, the model obtains 800 solutions. As mentioned earlier, the heuristic approach such as GA can capture the trend that evolves towards a better solution through evolving, which allows us exploring the reasons behind the optimal solutions.

### *8.4.1 The Fitness Value*

The substituted UL objective function (Eq. 7.11) is set as the fitness function for the GA optimization. The fitness value of each generation, which represented the owners perspective, has been recorded and exhibited in Fig. 8.1. The solutions have converged to a stable fitness value region with a rapid rate. The fitness value is a composite value of the project overall performance and the normalized project total payment as formulated in Eq. 7.1. From a practical point of view, the changes of the fitness values imply that the owners overall objective in a PPP project will be better achieved with the improvement in the design of payment mechanism. Eventually, the fitness value converges to a stable region around 75 and is hard to be improved by more evolving.

### *8.4.2 Project Overall Performance vs. Project Total Payment*

By splitting the UL function into a performance portion and a payment portion, Fig. 8.2 exhibits the overall performance and the total payment ($\sum x_i$) of each of the 800 GA generations. As mentioned earlier, the overall performance is the weighted value of each performance multiplied by the corresponding priority (Eq. 7.1). As shown in Fig. 8.2, with contract improves, the overall project performance is increased and tends to be stable with a little fluctuation around 95. On the other side, the total payment continuously decreases in the first 200 generations and starts to converge to a region around 1300M after that. This implies that it is not necessary to blindly increase payment to improve project performance. With the better design of payment mechanisms, the model achieves an improvement in project overall performance while a reduction of the total payment. Noted, the total payment here

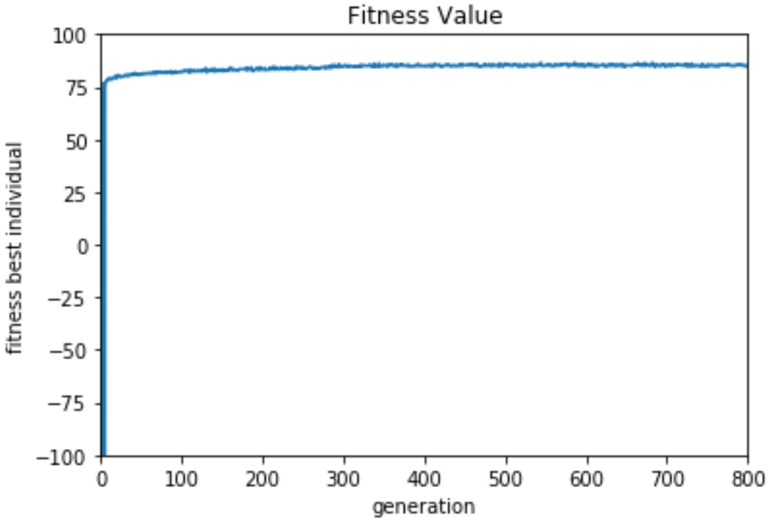


Figure 8.1: Changes of Fitness Value

is the actual payment the owner will pay, which equals to the maximum payment minus the noncompliance deduction. Due to the effects of randomness of performance measures, the payment and the overall performance are not straight lines that tend to be smooth, but rather curves that fluctuate slightly up and down converging regions.

### *8.4.3 Performance vs. Payment of Each Project Goal*

Fig. 8.3 (a to e) represents the evolving trends of the payment assigned to each goal versus the corresponding performance (from the 800 GA generations). In general, the change of each performance is consistent with that of payment assigned to each project goal. With more payment assigned to a project goal, the corresponding performance will get improved, and vice versa. Noted that, the dramatic changes of each payment in the first few generations are caused by the random initialization.

Fig. 8.3(a) exhibits the changes of the payment and the performance for the goal of availability. With evolving, the availability (Goal 1) is getting improved and becomes stable around 98. Consistent with the performance trend, the payment assigned to availability

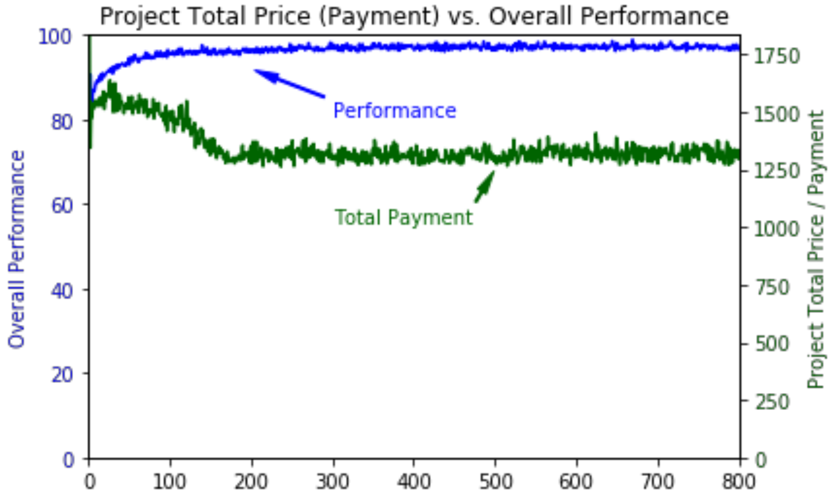


Figure 8.2: Changes of Project Total Payment and Overall Performance

(e.g., availability payment) is continuously increasing and converges around 810M. The high amount of payment is assigned to Goal 1 to ensure a good availability. This is because the availability has the highest priority, the performance of which will significantly affect the overall project performance. Another reason for the high payment is due to the corresponding high cost of achieving availability. Fig. 8.3(b) shows that the safety performance (Goal 2) increases and converges to a region around 96 after 200 generations. The payment assigned to safety (e.g., safety payment) also increases and tends to be stable around 290M. This means the better contracts will also ensure a good performance in safety due to its high priority. Fig. 8.3(c) exhibits that the environment-related performance (Goal 3) has a relatively stable trend around 93. The corresponding payment assigned to achieve environment fluctuates up and down around 200M. For the goal of communication (Goal 4), as shown in Fig. 8.3(d), although the payment assigned to this goal has a dramatic decline with evolving, the performance still maintains around 99 due to the extremely low cost. The performance of the other project goals (Goal 5), presented in Fig. 8.3(e), fluctuates around 90 and the payment assigned to these goals is stable around 130M.

The results shown in Fig. 8.3 implies that as the improvement of the contract, some

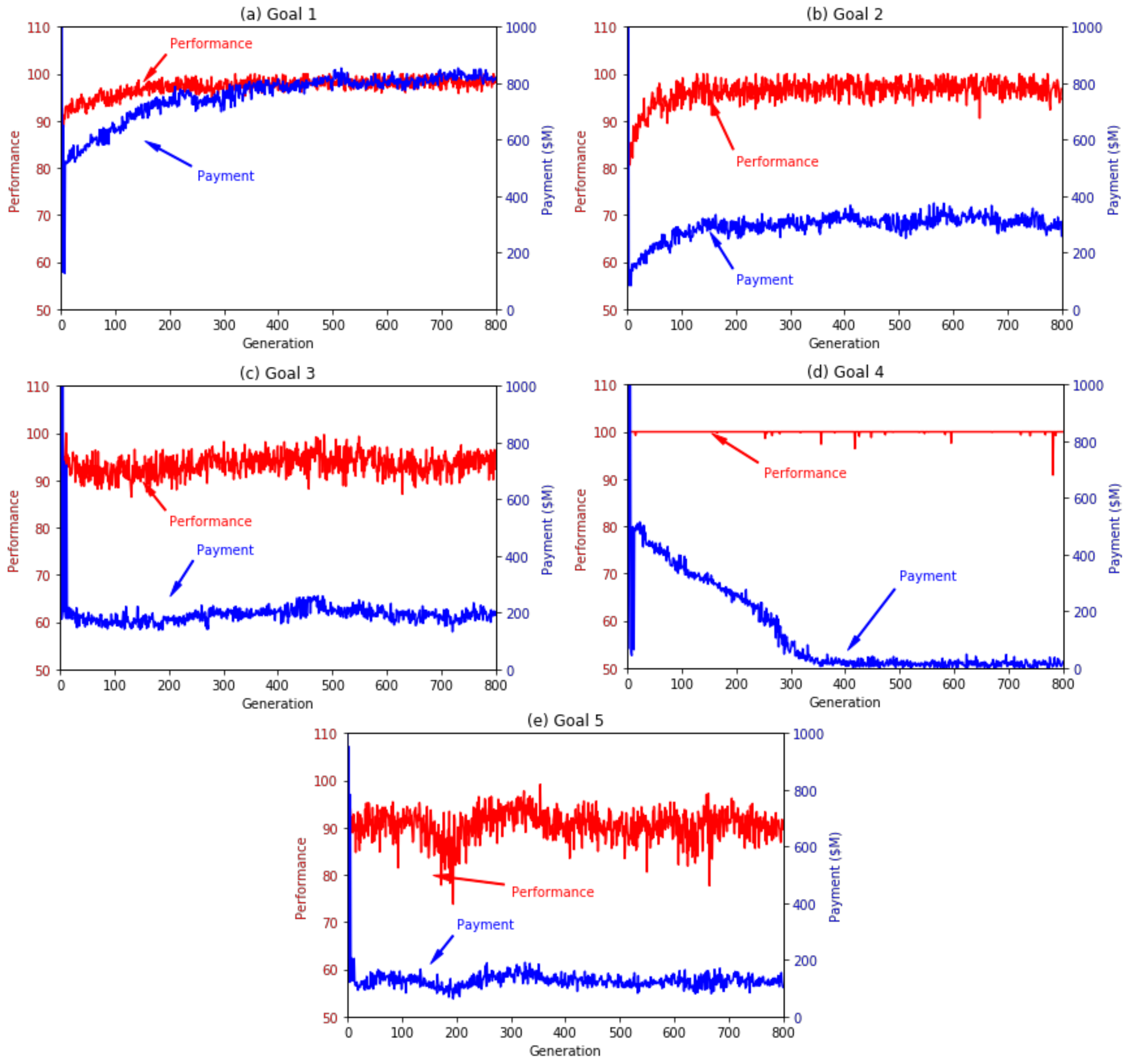


Figure 8.3: Changes of Performance vs. Payment of Each Project Goal

resources (i.e. payment) belonging to lower-priority goals are allocated to those goals that have higher priority (e.g., availability) and have relatively lower delivery cost to maximize the overall performance of the project. It is worth noticing that, although the availability has the highest priority (Table 8.2), the model does not blindly assign more payment to guarantee its best performance (i.e. 100) due to the corresponding high cost for achieving availability. This reflects the ability of the model to capture the non-linear relationship between payment, priority and cost for each project goal. Noted that, the sum of these payments (in Fig. 8.3) is higher than the total payment (shown in Fig. 8.2), which is because the total payment has deducted the noncompliance penalty.

### *8.4.4 Payment Mechanism*

As the generation evolving, these payments converge to certain ranges, as shown in Fig. 8.3. The payments generated from the last 100 out of 800 generations are recorded and box-plotted to discover the optimal solution region. Fig. 8.4 presents the solutions for the amount of the maximum payment assigned to each project goal generated by the model. As shown in Fig. 8.4, the payment amount assigned to the goal of availability (goal 1) are suggested in the range around 820M (about 52% of the total payment); the payment assigned to the second goal (safety) is from 285 to 310 (about 23%); the payment assigned to environment (goal 3) is from 190 to 200 (about 15%); the payment assigned to communication is from 10 to (about 1%); and the payment assigned to the other goals is around 123 (about 9%). It is to be noted that the intention was not to show if these payments match with the actual payment mechanism used in the I-595 project, but rather to show how to come up with such payments. The I-595 experienced an availability payment with the achievement of the other goals being implemented using performance deductions, not separate payments.

Based on the model output, the highest payment is allocated to the goal with the highest priority, which is consistent with the expectations. However, a better contract does not blindly assign higher payments to higher priority goals. Instead, the optimal contracts will achieve a balance among the project goals with a trade-off between the priority and cost.

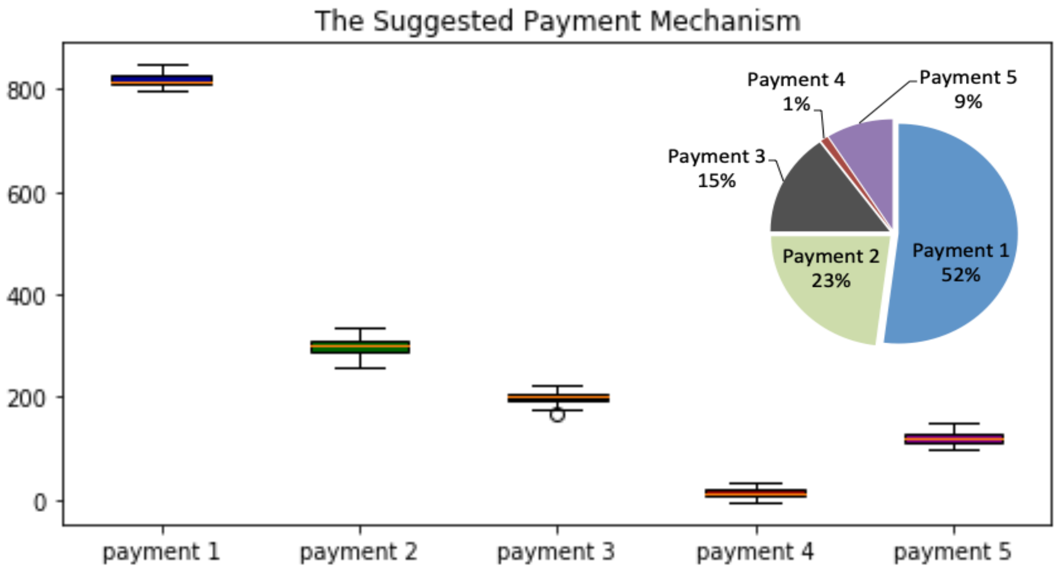


Figure 8.4: The Solution Region of Payment Mechanism

### *8.4.5 Contractor's Profit and Expense*

Fig. 8.5 shows the contractors profit (as modeled by Eq. 7.4) gradually declines with generation evolving, and eventually stabilizes at around 300M. The decreasing trend is consistent with the decline of the owners total payment. This implies the first mover advantage in Stackelberg game theory [56]. However, as the contractors total cost to deliver the project (i.e. the sum of the cost of each strategy) stabilizes at approximately 1100 M, the contractor can still achieve a yield of around 27.3% (= 300M / 1100M), which is greater than the modified internal rate of return for most of the contractors.

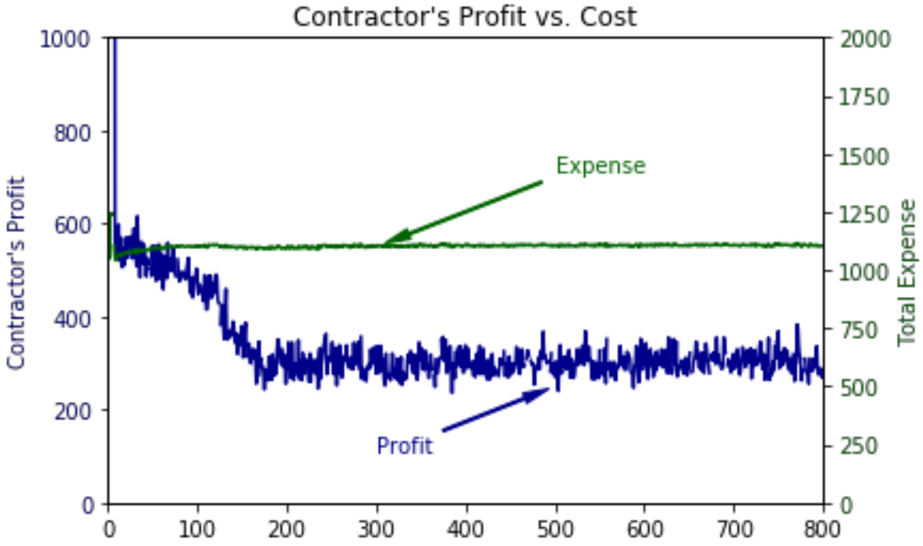


Figure 8.5: The Changes of contractor's Profit and Expense

# Chapter 9

# DISCUSSION, CONCLUSION AND RECOMMENDATION

## *9.1 Overview*

The purpose of this research was to develop a framework for the design of payment mechanisms for transportation PPP projects. The research purpose was derived from the current knowledge gap that there is no guidance for developing or regulating the payment mechanisms to fully address and achieve government objective in a PPP contract. Two specific research goals were summarized in Chapter 1, including (1) developing a practical explanatory framework for providing the decision maker a comprehensive understanding of the design of payment mechanisms in PPPs and providing for the guidance such as the process of identifying project goals, selecting appropriate payments, and linking the payments to the payments; and (2) developing an optimization model for providing quantitative suggestions on determining the payment mechanism (i.e. the optimal percentages / weights of the payments assigned to each project goal in a payment package.

Both qualitative and quantitative research methods were adopted and tailored to serve for the research objectives. Generally, the research methods include comprehensive literature reviews, content and comparative analysis of the PPP contract documents and the government guidance, questionnaire surveys, and optimization modeling.

In the rest of the final chapter, the author summarized the findings of the research, presented conclusions, and identified implications for the practical use. Additionally, the current limitation in the study was discussed and the recommendations for future research were proposed.

## 9.2 Major Findings

### 9.2.1 The general design of payment mechanism

A payment mechanism can be referred as a package that consists of one or more types of payments, the weight or percentage for each payment, a set of performance measures to assess the achievement of project goals, the corresponding deductions for the non-compliant performance, and the incentives for good performance (optional) [9]. In Chapter 2, the types of payments used in current transportation PPPs have been summarized based on a comprehensive literature review. However, in various articles, the payments are called slightly different. The research first provides a unified definition for the different types of PPP payments. A hierarchy is further proposed to distinguish the different payments that could be experienced in PPP projects (see Fig. 2.1).

According to the revenue regime (i.e. the source of revenues received by the private sector), two major payment schemes can be identified, including the user-pays payment scheme and the government-pays scheme. Under the user-pays scheme, the contractor receives compensation by obtaining the right to collect fees directly from end users of the infrastructure service. This scheme is also referred to as user charges in some European PPP projects. In transportation, the payment type under this scheme is usually known as real tolls (called by the World Bank) or toll concession (called by FHWA). The government-pays scheme, also referred as unitary payments by some European PPP guidance, is payments provided by the government to the contractor for services or assets. This scheme consists of three major forms, including input-based payments (based on the input rather than the output or service performance), usage payment (based on the actual usage of the project), and performance-based payments (based on the quality of the services or performances). Chapter 2 also summarized the specific types of payments that can be used under each payment scheme.

The general process and the underlying principles of the design of payment mechanism for PPPs were proposed respectively based on the review of the PPP guidance documents and the published literature (see section 2.5 of Chapter 2). In a summary, the general process of designing a payment mechanism for PPP projects consists of (1) identifying the objectives of the payment mechanism, (2) developing the structure, (3) calibrating, and evaluating and revising. And the principles include the following points:

1. Payment should be calculated based on measures such as usage, availability and other performance, and not on the quantities of the inputs.
2. Payment should not commence until the full service is available to the required standard, although some exception may be applicable.
3. Measure less but measure well.
4. Payment mechanism should include deductions for unsatisfactory performance, and such deductions should reflect the severity of failure.
5. The applicability of the different types of payments should depend on the project characteristics and the preference of risk allocation between the public and private sectors.
6. Performance-based payments should be calculated based on measurable objectives and outcomes.
7. Payment should be attractive to the contractor.
8. Payment should be affordable to the public agency.

Furthermore, in Section 5.3 of Chapter 5, an initial list of the considerations regarding the general design of PPP payment mechanisms were summarized. A questionnaire survey was conducted to identify the most important considerations among the initial list, and the result was shown in Table 5.2.

According to the survey result, the owners goals in a PPP project should be significantly considered during the design of the payment mechanism. In addition, risk allocation, bankability to the contractor, and simplicity of the payment mechanism are other three considerations that should have higher priorities to be considered during the design.

The proposed process, principles, and the identified considerations are the basis used in developing the framework for the design of the payment mechanism for transportation PPPs.

### *9.2.2 The payment mechanisms used in current PPP projects*

In order to provide a systematical understanding about the current use of the payment mechanisms (especially for the performance-based transportation PPPs) and to provide guidance on the design of the appropriate payment mechanism for facilitating the achievement of project goals, in Chapter 4, the research compared the payment mechanisms used in the US transportation PPP projects to those used in the Canadian projects. A content analysis of the project contracts was conducted to extract the unstructured contractual information and converted them into structured data stored in Excel worksheet. A comparative analysis then explored the similarities and differences of the uses of payment mechanisms between the US and Canada.

The findings from the content and comparative analysis revealed that PPP projects in the US tend to have fewer payment types than those in Canada. For example, the ten selected performance-based PPP projects in the US were exclusively limited to capital payment and availability payment. In contrast, many Canadian projects had a hybrid payment mechanism with a variety of functional payments to serve for the particular project goals.

The analysis also found that the US projects usually adopted relatively simple formulas for the computation of performance payments. For instance, except for road availability, all other performances were indirectly linked to the payment through noncompliance deduction in the US projects. The benefit of using a simple computation is to make the overall payment simple and easy to follow. However, the main drawback is that the deductions for some performances can be difficult and inaccurate, which leads that the non-compliant performance cannot be penalized accurately. By contrast, the payment calculations used in Canadian project were generally more sophisticated through including a set of specific formulas for various functional payments. However, sometimes, it may be expensive to measure each performance quantitatively and to design specific formula for each functional payment.

Based on the findings, some recommendations were given in terms of the design of payment mechanisms. First, capital payment could be excluded from the payment mechanism. By excluding capital payment and replacing with more performance-based payments (e.g., availability payment and O&M payment), the contractors income would be heavily associated with the project performance regardless of the inputs in the development. Thus, the project risk could be allocated to the private sector through such a shift of payment structure.

Second, usage payment could also be adopted in performance-based PPPs to encourage the contractor to provide better services by assuming that better quality of the project would lead to more usage. In the studied US projects, usage payment is strictly isolated from the performance-based PPPs. Some of the Canadian projects, however, used such payments as incentives to increase the traffic demand. The use of usage payment, on one hand, will potentially stimulate the contractor to provide better services to attract more users, thereby increasing their own compensation. On the other hand, usage payment might partially relieve the financial pressure of the government. To these senses, usage payments and performance-based payments are not mutually exclusive but complementary.

In terms of the performance measures and the payment calculation, the study further recommended that the performance measurements and the design of calculation formulas should be based on the priority of the project goals. Particular payments can be developed and added to serve for the major (high priority) project goals, while the existing deduction formula (e.g., Eq. 4.3) can be retained for the noncompliance of the less important goals.

### *9.2.3 The proposed framework for the design of payment mechanisms*

Based on the depth review of the guidance documents and PPP project agreements, an explanatory framework was proposed in Chapter 6 to assist decision makers in the design of payment mechanisms for transportation PPP projects. The proposed framework (Fig. 6.1) consists of four major phases, including 1) selection of the appropriate payment scheme, 2) selection of the appropriate type(s) of payment(s) based on the priority of the project goals, 3) optimization of the payment mechanisms, and 4) evaluation and modification of the suggested payment mechanism.

The first phase of the framework provides for the key factors in determining the selection of the payment scheme. In section 5.4 of Chapter 5, ten potential factors (see Table 5.3) were first identified through a depth review of the guidance documents and the published literature in terms of the design of payment mechanism in PPPs. The questionnaire survey introduced in Chapter 5 helped to identify the most critical factors. The importance of each factor was presented in Table 5.4. The results revealed that nine out of the ten identified factors are at least moderately important for the selection of payment scheme. Among them, the selected PPP model (e.g. DBFOM or DBF) was the most important factors in determining the selection. Legal viability and government policy are the next two most important factors, which indicates that the governments macro support or strategy would play an important position in determining if the project should be user-pays based or government-pays based. Additionally, financial feasibility and the use demand, which can be referred as economic factors, are also important but after the political factors. The survey results also indicated that the market competition might not be an important factor that determines if a PPP project should adopt user-pays scheme or not.

By referring to such factors and considering their own project characteristics, this phase would help to decide which payment scheme (user-pays vs. government pays) is a better fit for the project.

In the second phase, the framework proposed an AHP-based decision-making method to assist the decision to identify the priority of the project goals. Then, the particular type(s) of payment(s) would be suggested for the main (or high priority) goals. The other project goals could be reflected by means of performance deductions within the main payment(s) based on the simplicity principle.

Once the main type(s) of payment are determined, the framework further proposed a game theory based optimization model to determine the optimal proportion of each type of payment in the payment mechanism. The optimal solution aims to maximize the achievement of the overall project objectives (maximizing the performance) within an affordable price while providing an attractive return for the contractor.

The payment mechanism derived by the framework would be reviewed and evaluated with all stakeholders. Refinements would be made based on the feedback. The revised payment mechanism would be evaluated again by the public agency to ensure it meets all project goals and presents the best value for money before the implementation.

### *9.2.4 The game theory based optimization model for the design of payment mechanism*

In view of the importance of the payment mechanism in satisfying the public agencys as well as the private contractors objectives in PPPs, in Chapter 7 the research proposed a Stackelberg game theory based model to assist the owner in designing payment mechanisms for PPP transportation project. The interests of both sectors are reflected through two hierarchical objective functions. A Kuhn Tucker approach-based variable eliminating method and a standard genetic algorithm method are utilized to solve the proposed optimization model. Through optimizing the decision variables, including the owners payment mechanism and the contractors delivery strategy, the model aims to maximize the overall project performance for the sake of social welfare while maximizing the profit for the sake of private investment.

In Chapter 8, the developed model is validated through a real project based case study (the I-595 Corridor Improvements). The results demonstrated that the solutions provided by the model were continuously improved with the generation evolving and eventually converged to an optimal region. The evolving trend exhibited that the project performance was increased and remained at a satisfactory level while the total project payment was significantly decreased with a better design of payment mechanism. Although the contractors profit was decreased with the contract evolving due to the leaders advantage in Stackelberg game theory, the return still remained at a satisfactory level. Both sectors are expected to be benefit from the solutions provided by the model in effectively developing and negotiating the payment mechanism for PPP projects.

## *9.3 Value and Implication of the Research*

The design of an appropriate payment mechanism has been recognized as the crucial factor for the success of PPP projects ([1] [28] [108]). Although the guidance in developing payment mechanisms have been well established, past studies mainly focus on the procedure and considerations in the design while leaving the selection of specific payment structures to the empirical judgment of the decision makers. Additionally, past studies has rarely involved how to link payments to achieving project objectives. As such, the public objectives in a PPP project may not able to be fully achieved. This research proposed a framework with an optimization model to assist the decision maker in developing the payment mechanism that fits best for their project characteristics. The proposed framework is expected to provide contributions to both academia and industry.

For theoretical implications, the framework establishes a systematic understanding of the link between the payment mechanism and the project objectives. From an objective point of view, it explores the modifications required in the design of payment mechanism based on the priorities of project objectives and the project characteristics.

For practical implementations, the framework can be tailored and utilized by both public and private sectors for their respective purposes. The framework provides a good reference for the public sector. By using the framework, the design of payment mechanism can provide a more reasonable risk allocation and better value for money in a more efficient way than relying solely on regular contractual terms and traditional guidance. The private sector also can use the outcome derived from the framework as the baseline for the negotiation with the Authority during the dialogue period.

Further, the optimization model, proposed as part of the framework, sheds light on using quantitative methods to achieve the optimal design of payment mechanisms from an objective way.

Although the framework is developed based on transport PPP projects, it can be applied to other sectors through appropriate tailors. In the future, the framework can be further developed as Excel plug-in or separate software that can be easily applied in the industry.

### *9.4 Limitations*

Several limitations were noticed whilst conducting this research. In the questionnaire survey (see Chapter 5), the number of the survey responses limited the credibility and usefulness of the survey result.

The optimization model, as part of the framework proposed in Chapter 7, bears with two main limitations. First, in order to simplify the model for the sake of conceptual explanation, the effect of inflation is not included in the objective function. Thus, the actual total payment and the contractors DOM (Development, Operations, and Maintenance) cost may be slightly higher than the values calculated by the model. A modified LL objective function, shown in Eq. 9.1 can be used to substitute the original LL function to reflect the inflation over the concession period.

$$\text{(LL)} \quad y_i = \underset{y_i}{\operatorname{argmax}} \sum_{i}^{n} [\sum_{t=1}^{m} \frac{x_i - \frac{100 - P(y_i)}{100} \times x_i \times \mu - c_i \times y_i}{m \times (1+r)^{t-1}}] \tag{9.1}$$

In Eq. 9.1, $r$ is the inflation rate and $m$ represents the concession term (e.g., years). This modified LL function assumes that the owners payment is distributed evenly each year over the concession period. By replacing with the modified function, the time factor can be captured, which will better reflect the long-term life-cycle of PPP projects.

Another limitation is that the proved convexity of the model heavily relies on the assumption of the performance function (Eq. 7.7). Due to the complex interaction of the leader and the follower, changing the assumption of the performance function will easily convert the model to a complicated non-convex problem, which is difficult to obtain the global optimum [111]. As such, a variable elimination method may be limited to solve for the problem. A number of various algorithms have been developed to deal with the difficulty in Stackelberg problems.

Due to the limitations, this framework by no means intends to solve the complex design of payment mechanism in its entirety, but rather to provide quantitative and scenario-based recommendations for public and private sectors in contract negotiation.

### *9.5 Recommendations for Future Research*

In Chapter 4, the authors evaluated the design of payment mechanism in the US transportation PPPs and stated that the current payment mechanism might not be able to fully reflect project objectives [88]. To the best of authors' knowledge, only a few studies have investigated the relationship between each type of payment and the project objectives. Harding et al. [36] evaluated the performance of availability and service based payment mechanisms in PPP road traffic project and provided limited advice on selecting payments based on the project objectives. In order to enrich this area of research, in a future study the author suggests to investigate the effectiveness of different types of payment in achieving the project objectives in PPPs through. By such studies, the links between the payments and the objectives will be clearly established. Based on the links, the type(s) of payment can be selected based on the major project goals.

Future studies are also recommended to continue to explore the deeper mechanisms and enhance the robustness of the optimization model by further relaxing the underlying assumptions. A set of optimization methods regarding sequential nested genetic algorithm ([60] [67] [114]) will be examined to reduce the reliance on the assumption of the performance function and to solve the problem robustly. Instead of converting a bi-level model to a single objective function optimization model using a variable elimination approach, such algorithms use GA twice to solve two objective functions (UL and LL) directly in a sequence - one for solving all x variables in the UL function and the other for solving the entire y variables in the LL function based on the fixed x obtained from the UL GA solution. These improved algorithms are expected to be robust to solve for non-convex problems [67].

Additionally, in current phase, the model assumes the Contractors DOM strategy is static, which means the strategy will be determined in the beginning of the concession and not change during the operation. However, the optimal revenue of the Contractor most likely happens under a dynamic scenario, where the Contractor can modify their operation strategy based on the current performance conditions. For illustration, the Contractor may reduce their inputs on achieving the availability if the current pavement condition performs well. The saved resources can be allocated to improve the other performances that caused high deductions due to the noncompliance. The problem of project operation and maintenance has been demonstrated to have a lot of similarities to the Economic Order Quantity inventory problem in supply chain management [90]. By comparing the process of project operation with the inventory management, the methods of dynamic modeling used in inventory models can be utilized to solve for the optimization problems in the design of payment mechanism. In the future research, the model can be adjusted to integrate the effects of dynamic changes during the concession period.

## 9.6 Summary

Chapter 9 served to provide a discussion of the findings of this research, a presentation of conclusions, an identification of values and implications, the current limitations, and the recommendations for next steps.

The purpose of this research is to develop a framework that provides for a systematical understanding and practical reference for the design of payment mechanism for transportation PPPs. Both sectors will benefit from the solutions provided by the model in effectively developing and negotiating payment mechanism for PPP projects. In the future, the proposed framework can be generalized to fit for various sectors, such as energy and water.

# BIBLIOGRAPHY

[1] Ahmed M Abdel Aziz. Successful delivery of public-private partnerships for infrastructure development. *Journal of construction engineering and management*, 133(12):918–931, 2007.

[2] Ahmed M Abdel Aziz. A survey of the payment mechanisms for transportation dbfo projects in british columbia. *Construction Management and Economics*, 25(5):529–543, 2007.

[3] Ahmed M Abdel-Aziz and Alan D Russell. A structure for government requirements in public private partnerships. *Canadian Journal of Civil Engineering*, 28(6):891–909, 2001.

[4] Akintola Akintoye, Matthias Beck, and Mohan Kumaraswamy. *Public private partnerships: a global review*. Routledge, 2015.

[5] Mohammed I Al Khalil. Selecting the appropriate project delivery method using ahp. *International journal of project management*, 20(6):469–474, 2002.

[6] Gemayqzel Bouza Allende and Georg Still. Solving bilevel programs with the kkt-approach. *Mathematical programming*, 138(1-2):309–332, 2013.

[7] Aon Infrastructure Solutions. *Payment Mechanism: The First Form of Risk Transfer in Public-Private Partnerships*, 2014.

[8] APMG International. *Public Private Partnership Certification Program*, 2018.

[9] Ahmed M Abdel Aziz and Khaled Abdelhalim. Comparative analysis of p3 availability

payments in the usa and canada. Proceeding of the 2nd International Conference on Public-Private Partnerships, 2015.

[10] Jonathan F Bard and James T Moore. A branch and bound algorithm for the bilevel programming problem. *SIAM Journal on Scientific and Statistical Computing*, 11(2):281–292, 1990.

[11] Li Bing, Akintola Akintoye, Peter J Edwards, and Cliff Hardcastle. The allocation of risk in ppp/pfi construction projects in the uk. *International Journal of project management*, 23(1):25–35, 2005.

[12] Derek Braddon and Deborah Foster. *Privatization: Social science themes and perspectives.* Dartmouth Pub Co, 1996.

[13] Great Britain. *A new approach to public private partnerships.* HM Treasury, 2012.

[14] Luce Brotcorne, Martine Labbé, Patrice Marcotte, and Gilles Savard. A bilevel model for toll optimization on a multicommodity transportation network. *Transportation science*, 35(4):345–358, 2001.

[15] Jeffrey N Buxbaum and Iris N Ortiz. Protecting the public interest: The role of long-term concession agreements for providing transportation infrastructure. Technical report, Keston Institute for Public Finance Policy and Infrastructure Policy , 2007.

[16] The Canadian Council for Public-Private Partnerships. *The Canadian transportation PPP project database*, 2018.

[17] Albert PC Chan, David Scott, and Ada PL Chan. Factors affecting the success of a construction project. *Journal of construction engineering and management*, 130(1):153–155, 2004.

[18] Cristina Checherita and Jonathan Gifford. Risk sharing in public-private partnerships:

general considerations and an evaluation of the us practice in road transportation. Technical report, 2007.

[19] Isabelle Constantin and Michael Florian. Optimizing frequencies in a transit network: a nonlinear bi-level programming approach. *International Transactions in Operational Research*, 2(2):149–164, 1995.

[20] Jean-Philippe Côté, Patrice Marcotte, and Gilles Savard. A bilevel modelling approach to pricing and fare optimisation in the airline industry. *Journal of Revenue and Pricing Management*, 2(1):23–36, 2003.

[21] Qingbin Cui, Xinyuan Zhu, and Alex D'Alessio. Public-private partnership: A design issue. In *2017 IEEE Symposium Series on Computational Intelligence (SSCI)*, pages 1–6. IEEE, 2017.

[22] Kalyanmoy Deb. Multi-objective optimization. In *Search methodologies*, pages 403–449. Springer, 2014.

[23] Department of The Environment and Local Government, Ireland. *Public Private Partnership Guidance Note*, 2000.

[24] EIB (European Investment Bank). *The guide to guidance: How to prepare, procure and deliver PPP projects*, 2011.

[25] Public-Private Infrastructure Advisory Facility. *Approaches to private participation in water services: A toolkit.* World Bank Publications, 2006.

[26] Federal Highway Administration (FHWA). *Design-Build Effectiveness Study*, 2006.

[27] Federal Highway Administration (FHWA). *Washington Highway Safety Improvement Program 2014 Annual Report.*, 2014.

[28] Federal Highway Administration (FHWA). *FHWA Public Private Partnerships Toolkit*, 2018.

[29] Federal Highway Administration (FHWA). *Project Profile: I-595 Corridor Roadway Improvements*, 2018.

[30] Michael J Garvin. Enabling development of the transportation public-private partnership market in the united states. *Journal of Construction Engineering and Management*, 136(4):402–411, 2009.

[31] Ehsan Ghotbi. *Bi-and multi level game theoretic approaches in mechanical design*. PhD thesis, University of Wisconsin Milwaukee, 2013.

[32] Tushar Goel, Rajkumar Vaidyanathan, Raphael T Haftka, Wei Shyy, Nestor V Queipo, and Kevin Tucker. Response surface approximation of pareto optimal front in multi-objective optimization. *Computer methods in applied mechanics and engineering*, 196(4-6):879–893, 2007.

[33] Klaus D Goepel. Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises–a new ahp excel template with multiple inputs. In *Proceedings of the international symposium on the analytic hierarchy process*, volume 2013, pages 1–10. Creative Decisions Foundation Kuala Lumpur, 2013.

[34] John Hallin. *Guide for pavement-type selection*, volume 703. Transportation Research Board, 2011.

[35] Pierre Hansen, Brigitte Jaumard, and Gilles Savard. New branch-and-bound rules for linear bilevel programming. *SIAM Journal on scientific and Statistical Computing*, 13(5):1194–1217, 1992.

[36] Jochen Harding, Heribert Bodarwé, and Ivan Cadež. Evaluation of availability and service performance based payment mechanisms for ppp road traffic infrastructure projects. Technical report, 2010.

[37] Oliver Hart. Incomplete contracts and public ownership: Remarks, and an application to public-private partnerships. *The Economic Journal*, 113(486):C69–C76, 2003.

[38] Donald E Harter, Mayuram S Krishnan, and Sandra A Slaughter. Effects of process maturity on quality, cycle time, and effort in software product development. *Management Science*, 46(4):451–466, 2000.

[39] Donald W Hearn and Motakuri V Ramana. Solving congestion toll pricing models. In *Equilibrium and advanced transportation modelling*, pages 109–124. Springer, 1998.

[40] Graeme Hodge and Carsten Greve. 10. the ppp phenomenon: performance and governance insights. *Collaborative Governance*, page 93, 2008.

[41] Elisabetta Iossa, Giancarlo Spagnolo, and Mercedes Vellez. Contract design in public-private partnerships. *Report for the World Bank*, 2007.

[42] Timothy Irwin. *Public Money for Private Infrastructure: Deciding When to Offer Guarantees, Output-Based Subsidies, and Other Forms of Fiscal Support.* The World Bank, 2003.

[43] Arshad Ali Javed, Patrick TI Lam, and Patrick XW Zou. Output-based specifications for ppp projects: Lessons for facilities management from australia. *Journal of Facilities Management*, 11(1):5–30, 2013.

[44] Jang-Hyeon Jo, Jong-Sung Lee, Yanfeng Ouyang, and Fan Peng. Integrated decision support for roadway safety analysis. *Journal of Computing in Civil Engineering*, 25(1):50–56, 2010.

[45] Seunglim Kang and Seongkwan Mark Lee. Ahp-based decision-making process for median barrier installation. In *Proceedings of the 2007 ASCE International Workshop on Computing in Civil Engineering*, pages 452–464, 2007.

[46] Bahar Y Kara and Vedat Verter. Designing a road network for hazardous materials transportation. *Transportation Science*, 38(2):188–196, 2004.

[47] Michael Kerf, R David Gray, Timothy Irwin, Celine Levesque, Robert R Taylor, and Michael Klein. *Concessions for infrastructure: a guide to their design and award.* The World Bank, 1998.

[48] Il Yong Kim and OL De Weck. Adaptive weighted sum method for multiobjective optimization: a new method for pareto front generation. *Structural and multidisciplinary optimization*, 31(2):105–116, 2006.

[49] Mohan M Kumaraswamy and David A Morris. Build-operate-transfer-type procurement in asian megaprojects. *Journal of construction Engineering and Management*, 128(2):93–102, 2002.

[50] PTI Lam, APC Chan, and SH Chan. A best practice framework of output specifications for ppp projects. In *Proceedings of TG72–Special Track held at the 18th CIB World Building Congress, Salford, CIB TG72-Public Private Partnership*, pages 10–13, 2010.

[51] Larry HP Lang. *Project finance in Asia*, volume 6. North-Holland, 1998.

[52] Torbjörn Larsson and Michael Patriksson. Side constrained traffic equilibrium modelstraffic management through link tolls. In *Equilibrium and advanced transportation modelling*, pages 125–151. Springer, 1998.

[53] Larry Joseph Leblanc. Mathematical programming algorithms for large scale network equilibrium and network design problems. 1974.

[54] Sidney M Levy. *Public-private partnerships: Case studies on infrastructure development.* 2011.

[55] Bing Li, Akintola Akintoye, Peter J Edwards, and Cliff Hardcastle. Perceptions of positive and negative factors influencing the attractiveness of ppp/pfi procurement for

construction projects in the uk: Findings from a questionnaire survey. *Engineering, Construction and Architectural Management*, 12(2):125–148, 2005.

[56] Marvin B Lieberman and David B Montgomery. First-mover advantages. *Strategic management journal*, 9(S1):41–58, 1988.

[57] Cledan Mandri-Perrott. Mobilizing private capital and management into infrastructure development. *World Bank, Washington, DC*, 2006.

[58] Patrice Marcotte. Network design problem with congestion effects: A case of bilevel programming. *Mathematical programming*, 34(2):142–162, 1986.

[59] R Timothy Marler and Jasbir S Arora. The weighted sum method for multi-objective optimization: new insights. *Structural and multidisciplinary optimization*, 41(6):853–862, 2010.

[60] R Mathieu, L Pittard, and G Anandalingam. Genetic algorithm based approach to bi-level linear programming. *RAIRO-Operations Research-Recherche Opérationnelle*, 28(1):1–21, 1994.

[61] Xianhai Meng. The effect of relationship management on project performance in construction. *International journal of project management*, 30(2):188–198, 2012.

[62] Kaisa Miettinen. *Nonlinear multiobjective optimization*, volume 12. Springer Science & Business Media, 2012.

[63] GC Migliaccio, GE Gibson, and JT Oconnor. Procurement of design-build services: Two-phase selection for highway projects. *Journal of Management in Engineering*, 25(1):29–39, 2009.

[64] Goran Mladenovic and Cesar Queiroz. Assessing the financial feasibility of availability payment ppp projects. In *T&DI Congress 2014: Planes, Trains, and Automobiles*, pages 602–611, 2014.

[65] National Conference of State Legislatures. *Public-private partnerships for transportation: a toolkit for legislators*, 2016.

[66] Patrick Ngatchou, Anahita Zarei, and A El-Sharkawi. Pareto multi objective optimization. In *Proceedings of the 13th International Conference on, Intelligent Systems Application to Power Systems*, pages 84–91. IEEE, 2005.

[67] V Oduguwa and R Roy. Bi-level optimisation using genetic algorithm. In *Proceedings 2002 IEEE International Conference on Artificial Intelligence Systems (ICAIS 2002)*, pages 322–327. IEEE, 2002.

[68] American Society of Civil Engineers. 2013 report card for america's infrastructure. American Society of Civil Engineers, 2013.

[69] Chitu Okoli and Suzanne D Pawlowski. The delphi method as a research tool: an example, design considerations and applications. *Information & management*, 42(1):15–29, 2004.

[70] Lukumon O Oyedele. Avoiding performance failure payment deductions in pfi/ppp projects: model of critical success factors. *Journal of Performance of Constructed Facilities*, 27(3):283–294, 2012.

[71] Jeffrey A Parker et al. Inc.(2009). i-595 corridor roadway improvements: Value for money analysis, 2009.

[72] M Parker. Availability payments and other forms of p3s for surface transportation. *Funding and*, 2011.

[73] Bhagwant Naraine Persaud. *Statistical methods in highway safety analysis.* Number Project 20-5 FY 1999,. 2001.

[74] PPP Knowledge Lab. *PPP Reference Guide*, 2018.

[75] Public Utility Research Center. *Body of Knowledge on Infrastructure Regulation*, 2018.

[76] Thais Rangel, José Manuel Vassallo, and Blanca Arenas. Effectiveness of safety-based incentives in public private partnerships: Evidence from the case of spain. *Transportation research part A: policy and practice*, 46(8):1166–1176, 2012.

[77] Thais Rangel, José Manuel Vassallo, and Israel Herraiz. The influence of economic incentives linked to road safety indicators on accidents: The case of toll concessions in spain. *Accident Analysis & Prevention*, 59:529–536, 2013.

[78] Singiresu S Rao and TI Freiheit. A modified game theory approach to multiobjective optimization. *Journal of Mechanical Design*, 113(3):286–291, 1991.

[79] Alexandru V Roman. Public procurement specialists: They are not who we thought they were. *Journal of Public Procurement*, 15(1):38–65, 2015.

[80] Jan Rouwendal and Erik T Verhoef. Basic economic principles of road pricing: From theory to applications. *Transport policy*, 13(2):106–114, 2006.

[81] Thomas L Saaty. A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology*, 15(3):234–281, 1977.

[82] TL Saaty. The analytic hierarchy process. mcgrawhill international. *New York*, 1980.

[83] Ahmed FM Salman, Mirosław J Skibniewski, and Ismail Basha. Bot viability model for large-scale infrastructure projects. *Journal of Construction Engineering and Management*, 133(1):50–63, 2007.

[84] Peter Sandborn, Amir R Kashani-Pour, Xinyuan Zhu, and Qingbin Cui. A new availability-payment model for pricing performance-based logistics contracts. Technical report, MARYLAND UNIV COLLEGE PARK CENTER FOR ADVANCED LIFE CYCLE ENGINEERING (CALCE), 2014.

[85] John E Schaufelberger and Isr Wipadapisut. Alternate financing strategies for build-operate-transfer projects. *Journal of construction engineering and management*, 129(2):205–213, 2003.

[86] Sidney Scott. *Best-value procurement methods for highway construction projects*, volume 561. Transportation Research Board, 2006.

[87] Scottish Government. *Briefing Note 1 Payment Mechanisms In Operational PPP Projects*, 2007.

[88] Luming Shang and Ahmed Abdel Aziz. The usa ppp payment mechanisms: A comparison to the canadian ppp systems. In *Construction Research Congress 2018*, pages 129–138, 2018.

[89] Luming Shang, Ahmed Abdel Aziz, and Giovanni Migliaccio. An investigation of the traffic safety performance of ppp transportation projects in the united states. Technical report, 2017.

[90] Deepak Sharma and Qingbin Cui. Design of concession and annual payments for availability payment public private partnership (ppp) projects. In *Construction Research Congress 2012: Construction Challenges in a Flat World*, pages 2290–2299, 2012.

[91] Ankur Sinha, Pekka Malo, and Kalyanmoy Deb. A review on bilevel optimization: from classical to evolutionary approaches and applications. *IEEE Transactions on Evolutionary Computation*, 22(2):276–295, 2018.

[92] Bojan Srdjevic, Matija Pipan, Zorica Srdjevic, Bosko Blagojevic, and Tihomir Zoranovic. Virtually combining the analytical hierarchy process and voting methods in order to make group decisions. *Universal Access in the Information Society*, 14(2):231–245, 2015.

[93] Her Majesty Treasury. PFI: Meeting the Investment Challenge (London), 2003.

[94] Her Majesty Treasury. Standardisation of PFI contracts. *Crown, London*, 2007.

[95] Evangelos Triantaphyllou and Stuart H Mann. Using the analytic hierarchy process for decision making in engineering applications: some challenges. *International Journal of Industrial Engineering: Applications and Practice*, 2(1):35–44, 1995.

[96] UNIDO. Guidelines for infrastructure development through build-operate-transfer (bot) projects, 1996.

[97] US Department of Transportation (USDOT). *Successful Practices for P3s A Review of What Works When Delivering Transportation via Public-Private Partnerships*, 2016.

[98] Omkarprasad S Vaidya and Sushil Kumar. Analytic hierarchy process: An overview of applications. *European Journal of operational research*, 169(1):1–29, 2006.

[99] JM Vassallo, T Rangel, P Pérez de Villar, and B Arenas. Do ppp contracts improve road safety? *Research paper. EIB University Research Sponsorship Programme. Politechnic University of Madrid*, 2009.

[100] José M Vassallo and Juan Gallego. Risk sharing in the new public works concession law in spain. *Transportation Research Record*, 1932(1):1–8, 2005.

[101] Aidan R Vining and Anthony E Boardman. Public-private partnerships in canada: Theory and evidence. *Canadian public administration*, 51(1):9–44, 2008.

[102] Thomas R Warne. Design build contracting for highway projects: A performance assessment. *Tom Warne & Associates, LLC*, 2005.

[103] Paul Weist. An ahp-based decision making framework for it service design. *MWAIS 2009 Proceedings*, page 11, 2009.

[104] Darrell Whitley. A genetic algorithm tutorial. *Statistics and computing*, 4(2):65–85, 1994.

[105] Reini D Wirahadikusumah, Betty Susanti, Biemo W Soemardi, et al. Risk in governments estimate for toll road: Based on investors perspective. *International Journal on Advanced Science, Engineering and Information Technology*, 8(2):475–482, 2018.

[106] World Bank and Public-Private Infrastructure Advisory Facility (PPIAF). *Toolkit for Public-Private Partnerships in Roads and Highways*, 2009.

[107] World Bank Group. *Private Participation in Infrastructure (PPI) Annual Report*, 2017.

[108] The World Bank Group PUBLIC-PRIVATE-PARTNERSHIP LEGAL RESOURCE CENTER. *Public-Private Partnerships in Roads*, 2018.

[109] World Bank Group Public-Private Partnership Legal Resource Center. *Public-Private Partnerships by Sector*, 2019.

[110] Yelin Xu, John FY Yeung, Albert PC Chan, Daniel WM Chan, Shou Qing Wang, and Yongjian Ke. Developing a risk assessment model for ppp projects in chinaa fuzzy synthetic evaluation approach. *Automation in Construction*, 19(7):929–943, 2010.

[111] Hai Yang, Sam Yagar, Yasunori Iida, and Yasuo Asakura. An algorithm for the inflow control problem on urban freeway networks with user-optimal flows. *Transportation Research Part B: Methodological*, 28(2):123–139, 1994.

[112] Athol Yates, Bill Sashegyi, et al. Effective risk allocation in major projects: Rhetoric or reality?: A survey on risk allocation in major wa construction projects. *Effective Risk Allocation in Major Projects: Rhetoric or Reality?: A Survey on Risk Allocation in Major WA Construction Projects*, page ii, 2001.

[113] Edward R Yescombe. *Public-private partnerships: principles of policy and finance.* Elsevier, 2011.

[114] Yafeng Yin. Genetic-algorithms-based approach for bilevel programming models. *Journal of transportation engineering*, 126(2):115–120, 2000.

[115] Jingfeng Yuan, Alex Yajun Zeng, Miroslaw J Skibniewski, and Qiming Li. Selection of performance objectives and key performance indicators in public–private partnership projects to achieve value for money. *Construction Management and Economics*, 27(3):253–270, 2009.

[116] Fatemeh Zahedi. The analytic hierarchy processa survey of the method and its applications. *interfaces*, 16(4):96–108, 1986.

[117] XueQing Zhang and Mohan M Kumaraswamy. Procurement protocols for public-private partnered projects. *Journal of Construction Engineering and Management*, 127(5):351–358, 2001.

# Appendix A

# THE SURVEY QUESTIONS

# Survey on the Design of Payment Mechanisms for Transportation PPPs

This survey is part of a research project at the University of Washington on “Achieving Public Agency Goals in Public-Private Partnerships (PPPs) using Innovative Payment Mechanisms”. The survey solicits the opinions of professionals in the contracting industry, consulting, academia, and public owners on what should be considered for the design of payment (compensation) mechanisms.

The survey has two major sections:
(1) The key factors that affect the design of payment mechanism for transportation PPPPs; and
(2) The effectiveness of the different types of payments in achieving the public agency’s goals in PPP projects.

The survey may take approximately 15 to 25 mins. The survey data will be used only for research purposes.

If you like to get a copy of the results or the relevant materials, I could be reached at ls3053@uw.edu (Luming Shang).

## Section 1: Survey Demography

1. **1.1 The role(s) that your organization has in PPPs include:**
   *Check all that apply.*

   ☐ Academia
   ☐ Public Agency
   ☐ Contractor (Construction)
   ☐ Contractor (Operation and Maintenance)
   ☐ Consultant for design, engineering, environmental, and transportation
   ☐ Consultant for legal, financial/economic, accounting, and bidding (RFQ/RFP management)
   ☐ Other: ____________________

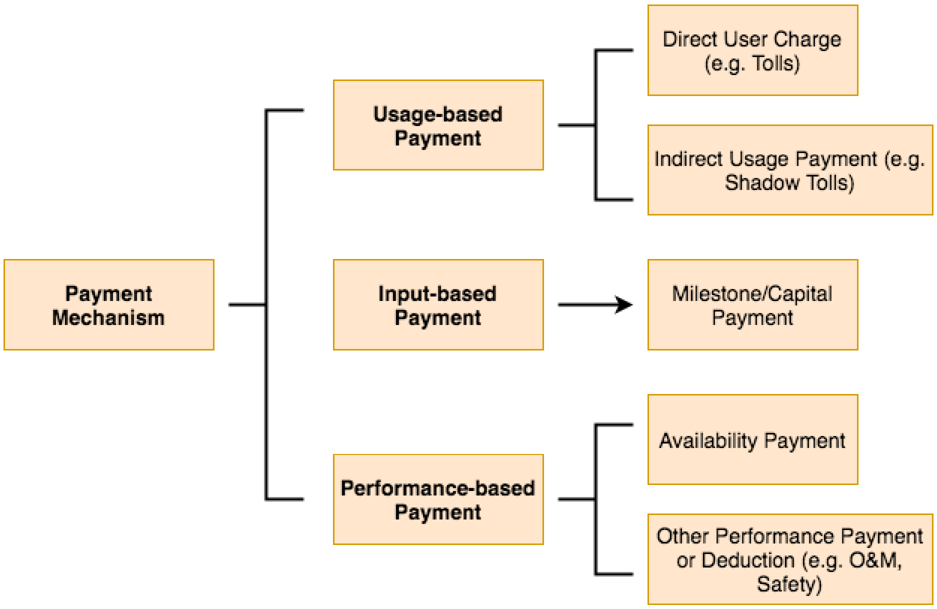
2. **1.2 Your organization has participated, pursued, short-listed, awarded, or studied PPPs in the following regions:**
   *Check all that apply.*

   ☐ Europe
   ☐ North America
   ☐ Asia / Pacific
   ☐ Middle East
   ☐ Latin America
   ☐ Africa

## Section 2: Key factors affecting the design of payment mechanisms

As in the illustration below, to compensate a concessionaire in a PPP project, public agencies may use a payment mechanism that would have several types of payments, e.g. payments based on performance (conforming to specifications - such as availability payments), payments based on demand (usage-based payments - such as highway tolls), and/or based on inputs (milestone payments). A PPP project could have a combination of these payments.

## Payment Types in a Compensation Mechanism



## Section 2(A): The factors affecting the general design of the mechanism structure

3. **2.1 The following factors might affect the design of a payment mechanism. Please indicate your opinion about the likely importance level:**
*Mark only one oval per row.*

| | Not relevant | Less Important | Moderate | Important | Very Important |
|---|---|---|---|---|---|
| Owner goals/objectives in the project | ○ | ○ | ○ | ○ | ○ |
| Availability of the public funding | ○ | ○ | ○ | ○ | ○ |
| Project ability to generate revenues (e.g. sufficient demand) | ○ | ○ | ○ | ○ | ○ |
| Project expected revenue amount | ○ | ○ | ○ | ○ | ○ |
| Project total cost | ○ | ○ | ○ | ○ | ○ |
| Risks to be transferred to the concessionaire | ○ | ○ | ○ | ○ | ○ |
| Bankability/Profitability of the payment mechanism to the concessionaire | ○ | ○ | ○ | ○ | ○ |
| Owner's & Stakeholder's knowledge of the different payment types | ○ | ○ | ○ | ○ | ○ |
| Owner's knowledge of PPP models (e.g. DBF, DBFOM, BOT) | ○ | ○ | ○ | ○ | ○ |
| The simplicity of a payment mechanism (e.g. time & cost needed for payment calculations) | ○ | ○ | ○ | ○ | ○ |
| Owner's ability to monitor project/concessionaire performance | ○ | ○ | ○ | ○ | ○ |
| Ability to design performance measures that reflect owner/project requirements | ○ | ○ | ○ | ○ | ○ |
| Local and general economy | ○ | ○ | ○ | ○ | ○ |
| Availability of permitting law allowing the use of alternative payment types (e.g., performance, usage, etc) | ○ | ○ | ○ | ○ | ○ |

4. **2.2 Would you like to suggest other factor(s) that should be considered for the design of PPP payment mechanism?**

5. **2.3 Having a payment mechanism that has a combination of several types of payments (e.g. availability, usage, etc) would have the following impacts. Please indicate your level of agreement/disagreement.**
*Mark only one oval per row.*

| | Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Add to the cost of the project | ○ | ○ | ○ | ○ | ○ |
| Take significant time and effort in payment determination and calculation | ○ | ○ | ○ | ○ | ○ |
| Increase monitoring and reporting activities in a project | ○ | ○ | ○ | ○ | ○ |
| Increase the chances of disputes in a project | ○ | ○ | ○ | ○ | ○ |
| Achieve the project goals better | ○ | ○ | ○ | ○ | ○ |
| Increase Benefit-Cost Ratio of the project | ○ | ○ | ○ | ○ | ○ |
| Allocate the risk more efficiently | ○ | ○ | ○ | ○ | ○ |
| Having several payment types is not appreciated by concessionaires | ○ | ○ | ○ | ○ | ○ |

6. **2.4 If a payment mechanism is to include only one payment type, I would prefer to use this one:**
*Mark only one oval.*

○ Input-based payments (e.g. capital/milestone)
○ Usage-based payments (e.g. real tolls, shadow tolls)
○ Performance-based payments with deduction (e.g. availability)
○ Other: ____________________

7. **2.5 If several types of payments have to be used in a project, it would be better to limit the following payments to the following levels:**
*Mark only one oval per row.*

| | Minimum | Medium | Maximum | No Preference |
|---|---|---|---|---|
| Usage payments (e.g. toll revenues) | ○ | ○ | ○ | ○ |
| Input payments (e.g. milestone payments) | ○ | ○ | ○ | ○ |
| Availability payments | ○ | ○ | ○ | ○ |
| Other performance payments | ○ | ○ | ○ | ○ |
| Unavailability deductions | ○ | ○ | ○ | ○ |
| Other Performance deductions (e.g. Safety, Environment) | ○ | ○ | ○ | ○ |

## Section 2(B): The factors affecting the selection of particular payment types

8. **2.6 Please indicate an importance level for the following factors that might affect the use of usage-based payments (e.g. tolls)**
*Mark only one oval per row.*

| | Not relevant | Less Important | Moderate | Important | Very Important |
|---|---|---|---|---|---|
| Availability of permitting law | ○ | ○ | ○ | ○ | ○ |
| Government policy on user charges (e.g. toll caps) | ○ | ○ | ○ | ○ | ○ |
| Public opinion on user charges | ○ | ○ | ○ | ○ | ○ |
| User's demand elasticity to the project | ○ | ○ | ○ | ○ | ○ |
| Ability to forecast traffic demand | ○ | ○ | ○ | ○ | ○ |
| Practicality of implementation | ○ | ○ | ○ | ○ | ○ |
| Financial feasibility of using user charges | ○ | ○ | ○ | ○ | ○ |
| Public Agency's goal to transfer demand risk | ○ | ○ | ○ | ○ | ○ |
| Insufficiency of government funds | ○ | ○ | ○ | ○ | ○ |

9. **2.7 Would you like to add other factors affecting usage-based payments.**

## Section 3: Design the appropriate payment mechanism

10. **3.1 A payment mechanism could be designed to achieve various goals. Please check the box(s) that would reflect a good match between a goal and the relevant payment(s).**
*Check all that apply.*

| | Input (milestone) payments | Usage payments | Availability payments | Other specific performance payments | Incentives in addition to the total payment | Performance deduction within the main payment | None in the list |
|---|---|---|---|---|---|---|---|
| Goals related to ensure road availability and improve area mobility | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Goals related to improve project delivery (e.g., expedite delivery, reduce cost overrun) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Goals related to improve project operation efficiency (e.g., reduce O&M cost) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Goals related to improve project characteristics (e.g., safety, demand, environment, etc.) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Goals related to improve project lifecycle quality | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Goals related to improve local economic growth | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

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# Appendix B

# THE ANALYTIC HIERARCHY PROCESS APPROACH FOR DECISION-MAKING

## *B.1 What is the Analytic Hierarchy Process?*

The analytic hierarchy process (AHP) is a decision making support technique and was first proposed by Saaty [81]. It aims to prioritize multiple criteria through pairwise comparisons by assuming that humans are better at making comparative assessments as compared to making absolute assessments [92]. The AHP approach received extensive attention since it was proposed. This is because the approach has a solid mathematical foundation of the approach and it is easy to explain and use [95].

Generally, the process of making decision through the AHP approach consists of five steps, including (1) listing the criteria used as the basis of evaluating available options, (2) structuring such criteria into a hierarchy, (3) using a set of pairwise comparisons to prioritize the relative important of the criteria, (4) further comparing the importance of available options for each criterion in a similar way, and (5) determining the overall importance of each option [103].

## *B.2 The pairwise comparison*

A pairwise comparison allows the decision makers to compare two choices (or criteria) at one time and decide which one they like better and how much they like it in comparison with the other. Saaty ([81] [82]) suggested an nine-point scale can be used to assign pairwise comparisons of all elements in each level of the hierarchy. The definition and meaning of the nine-point scale is summarized in Table B.1.

Table B.1: Scale of relative importance for the pairwise comparison [81]

| Important Level | Definition and Explanation |
|---|---|
| 1 | **Equal importance** (Two elements are equally important) |
| 3 | **Weak importance** (one is slightly preferred than another) |
| 5 | **Strong importance** (one is strongly preferred over another) |
| 7 | **Demonstrated importance** (one is strongly preferred and its dominance demonstrated in practice) |
| 9 | **Absolutely important** |
| 2,4,6,8 | Intermediate values between the two adjacent judgments |
| Reciprocals of above nonzero | If element A has one of the above nonzero value assigned to it when compared with element B, then B has the reciprocal value when compared with A. |

Table B.2: An illustrative example matrix (the upper triangular)

| Objectives | A | B | C |
|---|---|---|---|
| A | $a_{11} = 1$ | $a_{12} = \frac{1}{3}$ | $a_{13} = 5$ |
| B | | $a_{22} = 1$ | $a_{23} = 7$ |
| C | | | $a_{33} = 1$ |

### *B.3 Comparison Matrix*

As an illustrative example, suppose that there are three objectives to be compared (e.g., A, B, and C) in a PPP project. The decision maker needs to make three comparisons on which objective is more important (A vs. B; B vs. C; and A vs. C). A matrix from the three comparisons can be obtained. The diagonal elements of the matrix are always 1. In the upper triangular of the matrix, if the objective in the row is more important than the objective in the column, the actual judgment value is put; otherwise the reciprocal value is put. For example, as shown in Table B.2, comparing A and B, 1/3 is put in row 1 column 2 ($a_{12}$) of the matrix indicates that B is weakly more important than A (Scale: 3). Similar, comparing A and C, the value of 5 (row 1 column 3 or $a_{13}$) indicates that A is strongly more important than C based on the opinion of the decision maker.

To fill the lower triangular matrix, the reciprocal values of the upper diagonal are used. That is $a_{ij} = 1 \ / \ a_{ji}$. A complete comparison matrix of the above example is presented in Table B.3. Noted that, all the elements in the matrix should be positive.

### *B.4 Priority Vectors*

The next is to extract the relative importance from the comparison matrix. That is, how important are the three objectives to a specific PPP project. The first step of computing

Table B.3: An illustrative example matrix (the complete)

| Objectives | A | B | C |
|---|---|---|---|
| A | $a_{11} = 1$ | $a_{12} = \frac{1}{3}$ | $a_{13} = 5$ |
| B | $a_{21} = 3$ | $a_{22} = 1$ | $a_{23} = 7$ |
| C | $a_{31} = \frac{1}{5}$ | $a_{32} = \frac{1}{7}$ | $a_{33} = 1$ |

such relative importance is to normalize each column of the matrix. For example, the 3 by 3 reciprocal matrix in above, we first sum each column of the reciprocal matrix and then divide each element of the matrix with the sum of its column to get the normalized weights (see Table B.4. The normalized principal Eigen-vector, which is called priority vector, can be obtained by averaging across the rows (see the calculation below). Since it is normalized, the sum of all elements in priority vector equals to 1. The priority vector shows relative weights among the objectives that we compare. In the above example, A is 28.28%, B is 64.34% and C is 7.38% after normalization. The most important objective for the project is B followed by A and C.

$$Priority\ Vector = 1/3 \times \begin{bmatrix} 5/21 + 7/31 + 5/13 \\ 15/21 + 21/31 + 7/13 \\ 1/21 + 3/31 + 1/13 \end{bmatrix} = \begin{bmatrix} 0.2828 \\ 0.6434 \\ 0.0738 \end{bmatrix}$$

The AHP approach, in this case, provides us more than just the ranking of each objective. In fact, the relative weight is a ratio scale that we can divide among them. For example, we can say that B is 2.27 (=64.34/28.28) times more important than A and B is so much 8.72 (=64.34/7.38) times more important than C.

Table B.4: Normalize the matrix

| Objectives | A | B | C |
|---|---|---|---|
| A | $a_{11} = 1$ | $a_{12} = \frac{1}{3}$ | $a_{13} = 5$ |
| B | $a_{21} = 3$ | $a_{22} = 1$ | $a_{23} = 7$ |
| C | $a_{31} = \frac{1}{5}$ | $a_{32} = \frac{1}{7}$ | $a_{33} = 1$ |
| Sum | $\frac{21}{5}$ | $\frac{31}{21}$ | 13 |

| Objectives | A | B | C |
|---|---|---|---|
| A | 5/21 | 7/31 | 5/13 |
| B | 15/21 | 21/31 | 7/13 |
| C | 1/21 | 3/31 | 1/13 |
| Sum | 1 | 1 | 1 |

### *B.5 Consistency*

After having the importance of each objective (i.e. the priority vector), the next step is to examine if the decision makers opinion is consistent. For example, in the case above, from the decision makers perspective, B is more important than A ($B > A$); and also A is more important than C ($A > C$). Thus, we would expect that B is more important than C ($B > C$) even without knowing the result of the comparison between B and C. This logic of preference is called transitive property. If the last comparison is transitive (i.e. $B > C$), then we would say the decision is consistent. On the contrary, if the comparison between B and C actually shows that C is more important, then the decision is inconsistent.

The non-consistency of the pairwise comparisons is one of the most practical issues in the AHP approach. If all the comparisons are perfectly consistent, then the following relation should be always true for any combination of comparisons taken from the matrix:

$$a_{ij} = a_{ik} * a_{kj}$$

However, perfect consistency rarely exists in practice. In the AHP, we need to evaluate the consistency of the comparisons based on the consistency ratio (CR). The computation of the CR, shown in Eq. B.1, consists of two elements  the consistency index (CI) and the random consistency index (RCI).

$$CR = \frac{CI}{RCI} \tag{B.1}$$

The CI is calculated as follow (Eq. B.2):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{B.2}$$

Where $\lambda_{max}$ is an approximation of the maximum eigenvalue, which is obtained by adding the columns in the matrix and multiply the resulting vector by the priority vector obtained earlier. In the above example, the $\lambda_{max}$ is calculated in the follow and the corresponding CI is 0.0484 based on Eq. B.2.

Table B.5: RCI values for different n

| n = | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| RCI | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

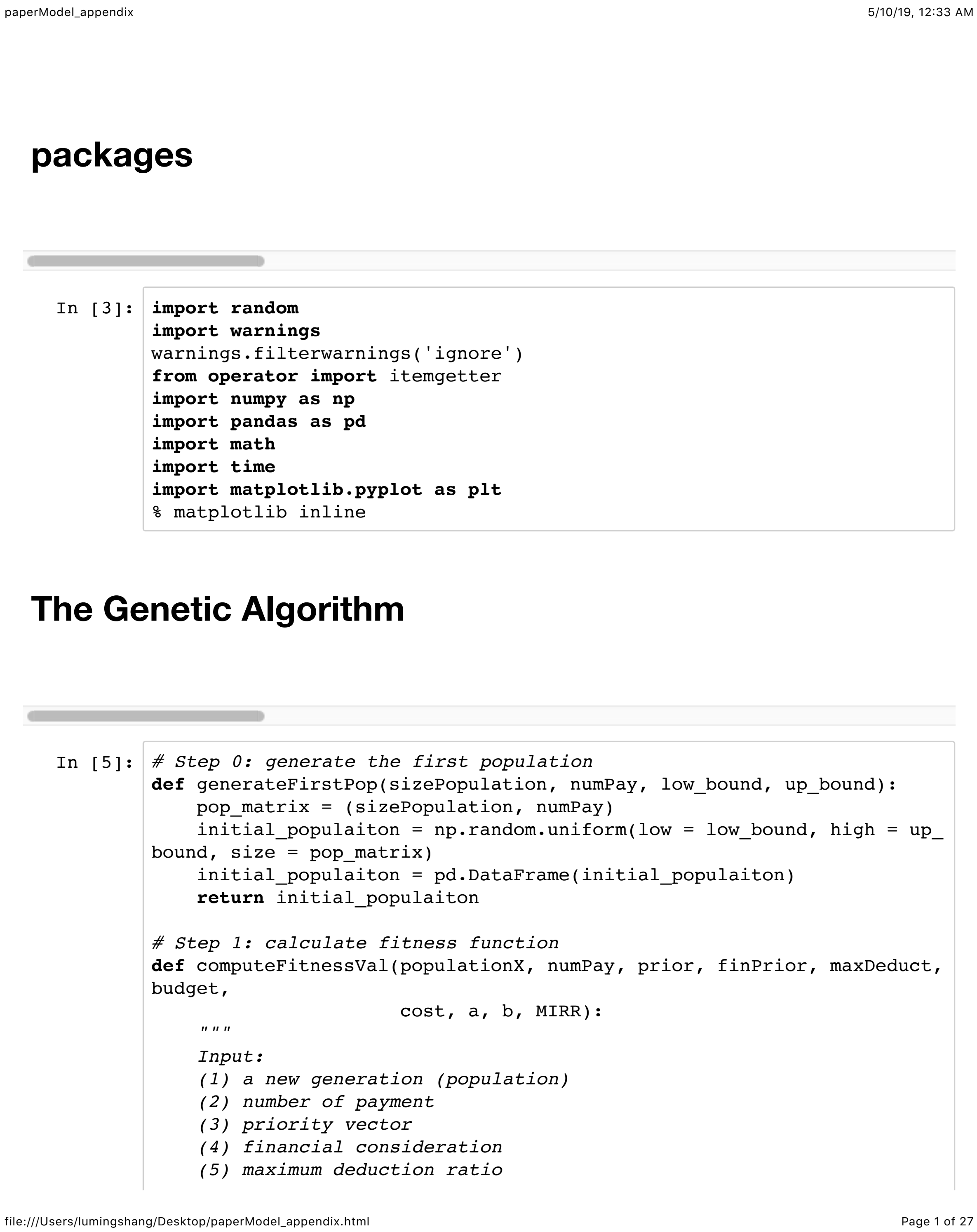
$$\lambda_{max} = \frac{21}{5}(0.2828) + \frac{31}{21}(0.6434) + 13(0.0738) = 3.0967$$

The RCI is obtained by randomly generating a number of reciprocal matrices using scale 1/9, 1/8,  8, 9 and get the mean CI of these randomly generated matrix. For illustration, the mean RCI of sample size 500 matrices is presented in Table B.5.

In the AHP, the consistency of the pairwise comparisons is considered to be acceptable if the corresponding CR is less than 10%. If the CR value is greater than 10%, it implies the decision is not consistent and is better to re-evaluate the pairwise comparisons. For the previous example, the CI is 0.0484 and RCI for n=3 is 0.58, then the CR is 8.3% ($< 10\%$), which indicates that the decision making is consistent.

# Appendix C

# MODEL PROGRAMMING CODE



# packages

In [3]:

```
import random
import warnings
warnings.filterwarnings('ignore')
from operator import itemgetter
import numpy as np
import pandas as pd
import math
import time
import matplotlib.pyplot as plt
% matplotlib inline
```

# The Genetic Algorithm

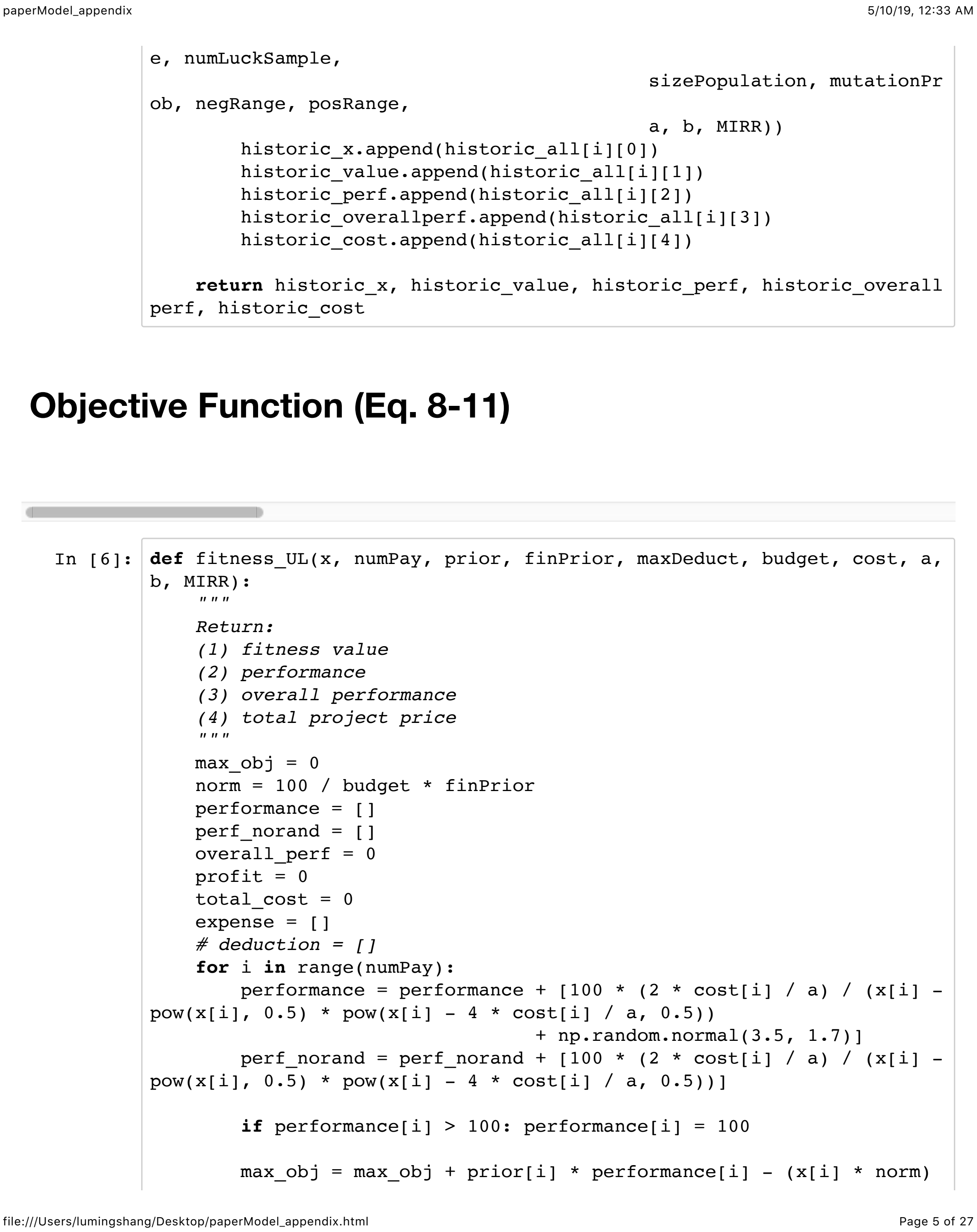
In [5]:

```
# Step 0: generate the first population
def generateFirstPop(sizePopulation, numPay, low_bound, up_bound):
    pop_matrix = (sizePopulation, numPay)
    initial_populaiton = np.random.uniform(low = low_bound, high = up_
bound, size = pop_matrix)
    initial_populaiton = pd.DataFrame(initial_populaiton)
    return initial_populaiton

# Step 1: calculate fitness function
def computeFitnessVal(populationX, numPay, prior, finPrior, maxDeduct,
budget,
                      cost, a, b, MIRR):
    """
    Input:
    (1) a new generation (population)
    (2) number of payment
    (3) priority vector
    (4) financial consideration
    (5) maximum deduction ratio
```

```
    (6) budget
    (7) cost vector
    (8) performance function parameters: a and b
    (9) MIRR

    Return:
    (1) sorted population
    (2) sorted fitness value
    (3) sorted performance
    (4) sorted overall_performance, and
    (5) sorted total cost
    """

    sort_pop = np.empty((populationX.shape[0], populationX.shape[1]))
    fit_pool = {}
    # other_pool = {}
    sort_value = []
    sort_performance = []
    sort_over_perf = []
    sort_cost = []

    for i in range(len(populationX)):
        fit_pool[i] = fitness_UL(populationX.iloc[i,:], numPay, prior,
                                 finPrior, maxDeduct, budget, cost, a,
b, MIRR)
    fit_pool = pd.DataFrame(fit_pool)
    sort_fit = sorted(fit_pool.iloc[0,:].items(), key=itemgetter(1), r
everse = True)

    for j in range(len(populationX)):
        sort_idx = sort_fit[j][0]
        sort_value.append(sort_fit[j][1])
        sort_performance.append(fit_pool.iloc[1, sort_idx])
        sort_over_perf.append(fit_pool.iloc[2, sort_idx])
        sort_cost.append(fit_pool.iloc[3, sort_idx])
        sort_pop[j] = (populationX.iloc[sort_idx,:])
    return sort_pop, sort_value, sort_performance, sort_over_perf, sor
t_cost

# Step 2: the basis of the genetic algorithm functions for generating
next population
# 2.1 select the parents (breeders) from the current population
def selectFromPopulation(populationSorted, numBestSample, numLuckSampl
e):
    """
    (the selection strategy can be modified by other methods)

    Return:
    (1) parents for generating the next population / generation
    """
```

```
    nextParents = []
    for i in range(numBestSample):
        nextParents.append(populationSorted[i][:]) # add a top rank in
dividual; [0] need to be adjusted
    for i in range(numLuckSample):
        nextParents.append(random.choice(populationSorted)[:]) # add a
lucky individual
    random.shuffle(nextParents)
    nextParents = pd.DataFrame(nextParents)
    return nextParents

# 2.2 mating parents (generating children)
def crossover(parents, sizepopulation, numPay):
    offspring = np.empty([sizepopulation, numPay])
    cross_point = np.uint8(numPay / 2) # where to get the combination
(may change by another way)

    for k in range(sizepopulation):
        # index of the first parent to mate
        parent1_idx = k % parents.shape[0]
        # index of the second parent to mate
        parent2_idx = (k + 1) % parents.shape[0]
        parents_array = parents.values
        offspring[k, 0:cross_point] = parents_array[parent1_idx, 0:cro
ss_point]
        offspring[k, cross_point:] = parents_array[parent2_idx, cross_
point:]
    return offspring

# 2.3 mutate the whole populaiton
def mutatePopulation(population, mutationProb, negRange, posRange):
    """
    :return:
    (1) the next generation
    """
    for i in range(population.shape[0]):
            for j in range(population.shape[1]):
                if random.random() * 100 < mutationProb: # possibility
to mutate
                    population[i][j] = population[i][j] + np.random.un
iform(negRange, posRange, 1)
    return population

# Step 3: generate the next payment population (x)
def nextGeneration_UL(preGenerationX, numPay, prior, finPrior, maxDedu
ct, cost,
                      budget, numBestSample, numLuckSample, sizePopula
tion,
                      mutationProb, negRange, posRange, a, b, MIRR):
    """
```

```
    Return:
    (1) the next generation of x (payment)
    (2) Current fitness value
    (3) Current performance
    (4) Current overall performance
    (5) Current cost
    """
    all = computeFitnessVal(preGenerationX, numPay, prior, finPrior, m
axDeduct,
                                   budget, cost, a, b, MIRR)
    popXSorted = all[0]
    currentValue = all[1]
    currentPerf = all[2]
    currentOverallPerf = all[3]
    currentCost = all[4]
    nextBreeders = selectFromPopulation(popXSorted, numBestSample, num
LuckSample) # generate the parents
    nextPopulation = crossover(nextBreeders, sizePopulation, numPay)
    next_generation_x = mutatePopulation(nextPopulation, mutationProb,
negRange, posRange)
    next_generation_x = pd.DataFrame(next_generation_x)
    return next_generation_x, currentValue, currentPerf, currentOveral
lPerf, currentCost

# Step 4: the main interation for the genetic algorithm
def multipleGeneration(number_of_generation, sizePopulation, numPay, l
owBoundPay, upBoundPay,
                       prior, finPrior, cost, maxDeduct, budget, numBe
stSample, numLuckSample,
                       mutationProb, negRange, posRange, a, b, MIRR):
    """
    Return:
    (1) the whole generations of x (payment)
    (2) the whole generations of fitness value
    (3) the whole generations of performance
    (4) the whole generations of overall performance
    (5) the whole generations of cost
    """
    historic_all = []
    historic_x = []
    historic_x.append(generateFirstPop(sizePopulation, numPay, lowBoun
dPay, upBoundPay))
    historic_value = []
    historic_perf = []
    historic_overallperf = []
    historic_cost = []
    for i in range (number_of_generation):
        historic_all.append(nextGeneration_UL(historic_x[i], numPay, p
rior, finPrior, maxDeduct,
                                            cost, budget, numBestSampl
```



```
e, numLuckSample,
                                                sizePopulation, mutationPr
ob, negRange, posRange,
                                                a, b, MIRR))
        historic_x.append(historic_all[i][0])
        historic_value.append(historic_all[i][1])
        historic_perf.append(historic_all[i][2])
        historic_overallperf.append(historic_all[i][3])
        historic_cost.append(historic_all[i][4])

    return historic_x, historic_value, historic_perf, historic_overall
perf, historic_cost
```

# Objective Function (Eq. 8-11)

In [6]:
```
def fitness_UL(x, numPay, prior, finPrior, maxDeduct, budget, cost, a,
b, MIRR):
    """
    Return:
    (1) fitness value
    (2) performance
    (3) overall performance
    (4) total project price
    """
    max_obj = 0
    norm = 100 / budget * finPrior
    performance = []
    perf_norand = []
    overall_perf = 0
    profit = 0
    total_cost = 0
    expense = []
    # deduction = []
    for i in range(numPay):
        performance = performance + [100 * (2 * cost[i] / a) / (x[i] -
pow(x[i], 0.5) * pow(x[i] - 4 * cost[i] / a, 0.5))
                                  + np.random.normal(3.5, 1.7)]
        perf_norand = perf_norand + [100 * (2 * cost[i] / a) / (x[i] -
pow(x[i], 0.5) * pow(x[i] - 4 * cost[i] / a, 0.5))]

        if performance[i] > 100: performance[i] = 100

        max_obj = max_obj + prior[i] * performance[i] - (x[i] * norm)
```

```
        overall_perf = overall_perf + prior[i] * performance[i]

        # constraints
        if performance[i] < 50:
            max_obj = 0.1*max_obj
        if x[i] > budget or \
                x[i] < 0 or \
                x[i] - 4 * cost[i] / (a * maxDeduct) < 0:
                    max_obj = -999

        expense = expense + [(cost[i] * (b - math.log((x[i] - pow(x[i]
, 0.5) * pow(x[i] - 4 * cost[i] / a, 0.5)) / (
                                                     2 * cost[i] / a)
- 1)) / a)]
        profit = profit + (x[i] - ((100 - perf_norand[i]) / 100) * x[i
] - expense[i])
        total_cost = total_cost + (x[i] - ((100 - perf_norand[i]) / 10
0) * x[i])

    if sum(x) > budget or profit < 0: max_obj = -999
    elif profit/sum(expense) < MIRR: max_obj = max_obj - 100 * (1 - (p
rofit/sum(expense))/MIRR)

    fitnessVal = max_obj
    return fitnessVal, performance, overall_perf, total_cost
```

# Visualization

In [7]:

```
# visualization
"1. The value of the overall fitness function" \
"2. The overall performance" \
"3. The total cost" \
"4. The revenue"

# 0) record the best value for each iteration (generation)
def getBestFitnessValueFromPopulationPay (populationX, numPay, prior,
finPrior,
                                          maxDeduct, budget, cost, a,
b):
    return computeFitnessVal(populationX, numPay, prior, finPrior, max
Deduct, budget, cost, a, b)[1][0]
```

```
def getListBestFitvalueFromHistoriquePay (historic_x, numPay, prior, f
inPrior,
                                          maxDeduct, budget, cost, a,
b):
    bestFitness_x = []
    for i in range(len(historic_x)):
        bestFitness_x.append(getBestFitnessValueFromPopulationPay(hist
oric_x[i], numPay, prior, finPrior,
                                                                  maxD
educt, budget, cost, a, b))
    return bestFitness_x

# 1) visualization of each payment amount
def visualPayment(history):
    labels = ['payment 1', 'payment 2', 'payment 3', 'payment 4', 'pay
ment 5']
    all_data = history[0][len(history[1])].T
    fig, axes = plt.subplots(nrows=1, ncols=1, figsize=(8, 4))
    axes.set_title('The Suggested Payment Mechanism')
    bplot1 = axes.boxplot(all_data, vert=True, patch_artist=True, labe
ls=labels)

    colors = ['darkblue', 'darkgreen', 'black', 'darkred', 'purple']

    for patch, color in zip(bplot1['boxes'], colors):
        patch.set_facecolor(color)
    plt.show()

# 2) visualization of the fitness value
def evolutionBestFitness(history):
    plt.axis([0, len(history[1]), -100, 100])
    plt.title("Fitness Value")
    evolutionFitness = []
    for i in range(len(history[1])):
        evolutionFitness.append(history[1][i][0])
    plt.plot(evolutionFitness)
    plt.ylabel('fitness best individual')
    plt.xlabel('generation')
    plt.show()

# 3) visualization of the overall performance
def evolutionBestPerf(history):
    plt.axis([0, len(history[3]), 0, 100])
    plt.title("overall performance")
    evoluaitonPerf = []
    for i in range(len(history[3])):
        evoluaitonPerf.append(history[3][i][0])
    plt.plot(evoluaitonPerf)
    plt.ylabel('overall performance')
    plt.xlabel('generation')
```

```
    plt.show()

# 4) visualization of the government's total cost
def evolutionTotalCost(history, budget):
    plt.axis([0, len(history[4]), 0, budget])
    plt.title("total cost")
    evoluaitonCost = []
    for i in range(len(history[4])):
        evoluaitonCost.append(history[4][i][0])
    plt.plot(evoluaitonCost)
    plt.ylabel('Cost')
    plt.xlabel('generation')
    plt.show()

# 5) visualization of each performance
def getEachPerf(history):
    eachPerf = []
    for i in range(len(history[2])):
        eachPerf.append(history[2][i][0])
    eachPerf = pd.DataFrame(eachPerf)
    return eachPerf

def evolutionPerf(history, eachPerf):
    plt.figure(num=6, figsize=(16, 8))
    # plt.title("Each Performance")
    # performance 1
    plt.subplot(231)
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('Performance 1')
    plt.plot(eachPerf.iloc[:, 0], 'r')
    # performance 2
    plt.subplot(232)
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('Performance 2')
    plt.plot(eachPerf.iloc[:, 1], 'b')
    # performance 3
    plt.subplot(233)
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('Performance 3')
    plt.plot(eachPerf.iloc[:, 2], 'g')
    # performance 4
    plt.subplot(234)
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('Performance 4')
    plt.plot(eachPerf.iloc[:, 3], 'y')
    # performance 5
    plt.subplot(235)
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('Performance 5')
    plt.plot(eachPerf.iloc[:, 4], 'black')
```

```
    plt.show()

    # other way
def evolutionPerf2(history, eachPerf, colorname):
    for i,color in enumerate(colorname):
        plt.subplot(231+i)
        plt.axis([0, len(history[2]), 50, 110])
        plt.title('Performance %d' % (1+i))
        plt.plot(eachPerf.iloc[:, i], color)
    plt.show()

# 6) visualization of the contractor's revenue
def fitness_LL(x, numPay, performance, a, b, cost, maxDeduct):
    total_revenue = 0
    total_expense = 0
    for i in range(numPay):
        total_revenue = total_revenue + (x[i] - ((100-performance[i])/
100)*x[i] - cost[i]*
                                         (b-math.log((x[i] - pow(x[i],
0.5) * pow(x[i] - 4 * cost[i] / a, 0.5)) / (2 * cost[i] / a) - 1))/a)
        total_expense = total_expense + (cost[i] * (b - math.log((x[i]
- pow(x[i], 0.5) * pow(x[i] - 4 * cost[i] / a, 0.5)) / (
                                          2 * cost[i] / a) - 1)) / a)
    return total_revenue, total_expense

def evolutionRevenue(history, numPay, a, b, cost, maxDeduct):
    revenue = []
    for j in range(len(history[2])):
        revenue.append(
            fitness_LL(history[0][j].iloc[0,:], numPay, history[2][j][
0], a, b, cost, maxDeduct)[0]
        )
    plt.axis([0, len(history[2]), -200, 500])
    plt.title('Revenue')
    plt.plot(revenue, 'y')
    plt.ylabel('$')
    plt.xlabel('generation')
    plt.show()

def evolutionExpense(history, numPay, a, b, cost, maxDeduct):
    revenue = []
    for j in range(len(history[2])):
        revenue.append(
            fitness_LL(history[0][j].iloc[0,:], numPay, history[2][j][
0], a, b, cost, maxDeduct)[1]
        )
    plt.axis([0, len(history[2]), 0, 2000])
    plt.title('Expense')
    plt.plot(revenue, 'y')
    plt.ylabel('$')
```

```
    plt.xlabel('generation')
    plt.show()
```

## Advanced Visualization

In [8]:

```
# 1) visualize total payment and overall performance in the same figur
e
def evolutionPriceCost(history, budget):
    evoluaitonPerf = []
    evoluaitonCost = []
    for i in range(len(history[3])):
        evoluaitonPerf.append(history[3][i][0])
        evoluaitonCost.append(history[4][i][0])
    fig, ax1 = plt.subplots()
    plt.title("Project Total Price (Payment) vs. Overall Performance")
    plt.axis([0, len(history[3]), 0, 100])
    ax1.plot(evoluaitonPerf, color = 'blue')
    ax1.set_ylabel(r'Overall Performance', color = 'blue')
    for label in ax1.get_yticklabels():
        label.set_color("blue")
    ax1.annotate('Performance', xy=(200, 92), xytext=(300, 80),
                 arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'b'),
                 color = 'b', horizontalalignment='left',verticalalig
nment='bottom')

    ax2 = ax1.twinx()
    plt.axis([0, len(history[4]), 0, budget])
    ax2.plot(evoluaitonCost, color = 'darkgreen')
    ax2.set_ylabel(r'Project Total Price / Payment', color = 'darkgree
n')
    for label in ax2.get_yticklabels():
        label.set_color("darkgreen")
    ax2.annotate('Total Payment', xy=(500, 1250), xytext=(300, 1000),
                 arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'darkgreen'),
                 color = 'darkgreen', horizontalalignment='left',vert
icalalignment='bottom')

# 2) visualize contractor's revenue and cost in the same figure
def evolutionProfitExpense(history, numPay, a, b, cost, maxDeduct):
    revenue = []
    expense = []
```

```
    for j in range(len(history[2])):
        revenue.append(
            fitness_LL(history[0][j].iloc[0,:], numPay, history[2][j][
0], a, b, cost, maxDeduct)[0]
        )
        expense.append(
            fitness_LL(history[0][j].iloc[0,:], numPay, history[2][j][
0], a, b, cost, maxDeduct)[1]
        )
    fig, ax1 = plt.subplots()
    plt.title("Contractor's Profit vs. Cost")
    plt.axis([0, len(history[2]), 0, 1000])
    ax1.plot(revenue, color = 'darkblue')
    ax1.set_ylabel(r"Contractor's Profit", color = 'darkblue')
    for label in ax1.get_yticklabels():
        label.set_color("darkblue")
    ax1.annotate('Profit', xy=(500, 250), xytext=(300, 100),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'darkblue'),
                  color = 'darkblue', horizontalalignment='left',verti
calalignment='bottom')

    ax2 = ax1.twinx()
    plt.axis([0, len(history[2]), 0, 2000])
    ax2.plot(expense, color = 'darkgreen')
    ax2.set_ylabel(r'Total Expense', color = 'darkgreen')
    for label in ax2.get_yticklabels():
        label.set_color("darkgreen")
    ax2.annotate('Expense', xy=(300, 1100), xytext=(500, 1400),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'darkgreen'),
                  color = 'darkgreen', horizontalalignment='left',vert
icalalignment='bottom')


# 3) visualize the evolution of each payment
def evolutionEachPayment(history):
    payment1 = []
    payment2 = []
    payment3 = []
    payment4 = []
    payment5 = []
    for i in range(len(history[0])):
        payment1.append(history[0][i].iloc[0,0])
        payment2.append(history[0][i].iloc[0,1])
        payment3.append(history[0][i].iloc[0,2])
        payment4.append(history[0][i].iloc[0,3])
        payment5.append(history[0][i].iloc[0,4])

    fig, ax1 = plt.subplots()
```

```
    plt.title("The Evolution of Each Payment")
    plt.xlabel('Generation')
    plt.axis([0, len(history[0]), 0, 1000])

    ax1.plot(payment1, color = 'darkblue')
    ax1.set_ylabel(r"Payment ($M)")
    ax2 = ax1.twinx()
    ax2.plot(payment2, color = 'darkgreen')
    ax2.get_yaxis().set_visible(False)
    ax3 = ax1.twinx()
    ax3.plot(payment3, color='black')
    ax3.get_yaxis().set_visible(False)
    ax4 = ax1.twinx()
    ax4.plot(payment4, color='darkred')
    ax4.get_yaxis().set_visible(False)
    ax5 = ax1.twinx()
    ax5.plot(payment5, color='purple')
    ax5.get_yaxis().set_visible(False)
```

In [9]:

```
# 4) performance and each payment
def evolutionEachPerfPay(history, eachPerf):
    payment1 = []
    payment2 = []
    payment3 = []
    payment4 = []
    payment5 = []
    for i in range(len(history[0])):
        payment1.append(history[0][i].iloc[0,0])
        payment2.append(history[0][i].iloc[0,1])
        payment3.append(history[0][i].iloc[0,2])
        payment4.append(history[0][i].iloc[0,3])
        payment5.append(history[0][i].iloc[0,4])

    plt.figure(num=6, figsize=(8, 4))
    # plt.title("Each Performance")
    # performance 1
    # plt.subplot(231)
    fig, ax1 = plt.subplots()
    plt.axis([0, len(history[2]), 50, 110])
    plt.xlabel('Generation')
    plt.title('(a) Goal 1')
    ax1.plot(eachPerf.iloc[:, 0], 'r')
    ax1.set_ylabel(r'Performance', color = 'r')
    for label in ax1.get_yticklabels():
        label.set_color("r")
    ax1.annotate('Performance', xy=(150, 98), xytext=(200, 105),
                 arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'r'),
                 color = 'r', horizontalalignment='left',verticalalig
```

```
nment='bottom')

    ax2 = ax1.twinx()
    plt.axis([0, len(history[0]), 0, 1000])
    ax2.plot(payment1, color='b')
    ax2.set_ylabel(r'Payment ($M)', color='b')
    for label in ax2.get_yticklabels():
        label.set_color("b")
    ax2.annotate('Payment', xy=(150, 600), xytext=(250, 450),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'b'),
                  color = 'b', horizontalalignment='left',verticalalig
nment='bottom')

    # performance 2
    # plt.subplot(232)
    fig, ax3 = plt.subplots()
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('(b) Goal 2')
    plt.xlabel('Generation')
    plt.plot(eachPerf.iloc[:, 1], 'r')
    ax3.set_ylabel(r'Performance', color = 'r')
    for label in ax3.get_yticklabels():
        label.set_color("r")
    ax3.annotate('Performance', xy=(150, 95), xytext=(200, 80),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'r'),
                  color = 'r', horizontalalignment='left',verticalalig
nment='bottom')

    ax4 = ax3.twinx()
    plt.axis([0, len(history[0]), 0, 1000])
    ax4.plot(payment2, color='b')
    ax4.set_ylabel(r'Payment ($M)', color='b')
    for label in ax4.get_yticklabels():
        label.set_color("b")
    ax4.annotate('Payment', xy=(150, 280), xytext=(200, 80),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'b'),
                  color = 'b', horizontalalignment='left',verticalalig
nment='bottom')

    # performance 3
    # plt.subplot(233)
    fig, ax5 = plt.subplots()
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('(c) Goal 3')
    plt.xlabel('Generation')
    plt.plot(eachPerf.iloc[:, 2], 'r')
    ax5.set_ylabel(r'Performance', color = 'r')
```

```
    for label in ax5.get_yticklabels():
        label.set_color("r")
    ax5.annotate('Performance', xy=(150, 90), xytext=(200, 80),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'r'),
                  color = 'r', horizontalalignment='left',verticalalig
nment='bottom')

    ax6 = ax5.twinx()
    plt.axis([0, len(history[0]), 0, 1000])
    ax6.plot(payment3, color='b')
    ax6.set_ylabel(r'Payment ($M)', color='b')
    for label in ax6.get_yticklabels():
        label.set_color("b")
    ax6.annotate('Payment', xy=(200, 250), xytext=(250, 400),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'b'),
                  color = 'b', horizontalalignment='left',verticalalig
nment='bottom')

    # performance 4
    # plt.subplot(234)
    fig, ax7 = plt.subplots()
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('(d) Goal 4')
    plt.xlabel('Generation')
    plt.plot(eachPerf.iloc[:, 3], 'r')
    ax7.set_ylabel(r'Performance', color = 'r')
    for label in ax7.get_yticklabels():
        label.set_color("r")
    ax7.annotate('Performance', xy=(150, 100), xytext=(250, 90),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'r'),
                  color = 'r', horizontalalignment='left',verticalalig
nment='bottom')

    ax8 = ax7.twinx()
    plt.axis([0, len(history[0]), 0, 1000])
    ax8.plot(payment4, color='b')
    ax8.set_ylabel(r'Payment ($M)', color='b')
    for label in ax8.get_yticklabels():
        label.set_color("b")
    ax8.annotate('Payment', xy=(400, 50), xytext=(500, 300),
                  arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'b'),
                  color = 'b', horizontalalignment='left',verticalalig
nment='bottom')

    # performance 5
    # plt.subplot(235)
```

```
    fig, ax9 = plt.subplots()
    plt.axis([0, len(history[2]), 50, 110])
    plt.title('(e) Goal 5')
    plt.xlabel('Generation')
    plt.plot(eachPerf.iloc[:, 4], 'r')
    ax9.set_ylabel(r'Performance', color = 'r')
    for label in ax9.get_yticklabels():
        label.set_color("r")
    ax9.annotate('Performance', xy=(150, 80), xytext=(300, 75),
                 arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'r'),
                 color = 'r', horizontalalignment='left',verticalalig
nment='bottom')

    ax10 = ax9.twinx()
    plt.axis([0, len(history[0]), 0, 1000])
    ax10.plot(payment5, color='b')
    ax10.set_ylabel(r'Payment ($M)', color='b')
    for label in ax10.get_yticklabels():
        label.set_color("b")
    ax10.annotate('Payment', xy=(150, 180), xytext=(200, 300),
                 arrowprops=dict(facecolor='black', shrink=0.05, widt
h = 1, headwidth = 5, color = 'b'),
                 color = 'b', horizontalalignment='left',verticalalig
nment='bottom')
    plt.show()
```

# Other Plots (model concept visualization)

In [10]:

```
# Model Concept Visualization
# 1) performance function
def visualPerfFunc(a, b):
    x = np.linspace(0, 120, 1000)
    y = []
    for num in x:
        y.append(100/(1+math.exp(b - a*num)))
    plt.plot(x, y, color = 'black')
    plt.title('Visualization of Performance Function')
    plt.xlabel("The Contractor's DOM Strategy (y)")
    plt.ylabel('The Performance (P(y))')
    plt.text(0, 90, 'a = 0.1; b = 6.5')
```

```
    plt.show()

# 2) LL function plot
def visualLLFunc(pay, a, b, maxDeduct, cost):
    x = np.linspace(0, 120, 1000)
    y = []
    for num in x:
        y.append(pay - ((100-100/(1+math.exp(b-a*num)))/100) * pay * m
axDeduct - cost * num)
    plt.axis([0, 101, -40, 40])
    plt.plot(x, y, color = 'black')
    plt.axhline(y=0, color = 'b', linestyle='--')
    plt.title('(a) Visualization of LL Function')
    plt.xlabel("The Contractor's DOM Strategy (y)")
    plt.ylabel("The Value of LL Function (the Contractor's Profit ($M)
")
    plt.text(5,20, 'a = 0.1; \nb = 6.5; \ncost = 1 M/unit; \npayment =
120 M')
    plt.show()


# 3) UL function plot
def visualULFunc(a, maxDeduct, cost, pri1, pri2):
    x = np.linspace(39, 200, 1000)
    UL = []
    for num in x:
        if num < 4*cost/(a*maxDeduct):
            UL.append(None)
            print('no feasible solution')
        else:
            UL.append(((100*2*cost/(a*maxDeduct))
                      /(num-math.sqrt(num)*math.sqrt(num-4*cost/(a*max
Deduct))))*pri1 -
                      pri2*num)
#     plt.axis([40, 200, 0, 100])
    plt.plot(x, UL, color = 'black')
    plt.axhline(y=69.4, color = 'b', linestyle='--')
    plt.title('(b) Visualization of UL Function')
    plt.xlabel("The Payment Assigned to the Project Goal ($M) (x)")
    plt.ylabel("The Value of UL Function")
    plt.text(120,50, 'a = 0.1; b = 6.5; \ncost = 1 M / unit; \nPriorit
y Of Saving Money = 20%',
            horizontalalignment='left', verticalalignment='top')
    plt.show()
```

# Case Input

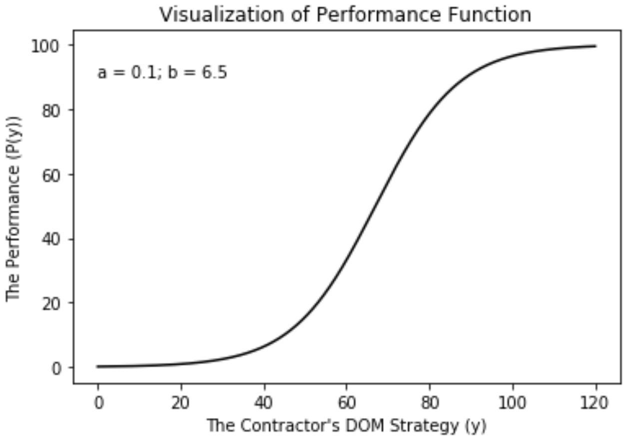
```
In [19]: # Project Parameters
         prior = [0.55, 0.25, 0.1, 0.05, 0.05] # objective priority
         numPay = len(prior) # number of payment types
         budget = 1834 # project budget
         maxDeduct = 1 # the maximum deduction percentage in the total payment
         finPrior = 0.2 # the priority of monetary consideration (beta)
         lowBoundPay = 0 # the minimum payment
         upBoundPay = budget # the maximum payment
         cost = [6.76, 2.38, 1.82, 0.002, 1.41] # union cost to achieve each pr
         oject objective (num of cost = num of project goals)
         MIRR = 0.10
         if len(cost) != numPay: print("the inputs are not correct")
```

```
In [12]: # GA Parameters
         generation = 800
         sizePopulation = 150 # the number of individuals in each population
         numBestSample = 40 # the number of top performance individuals selecte
         d from each population
         numLuckSample = 10 # the number of randomly selected individuals (to i
         ncrease the diversity)
         mutationProb = 35 # the probability of mutation
         negRange = -10 # the mutation lower range
         posRange = 10 # the mutation upper range
         a = 0.1 # performance function parameter 1
         b = 6.7 # performance function parameter 2
```

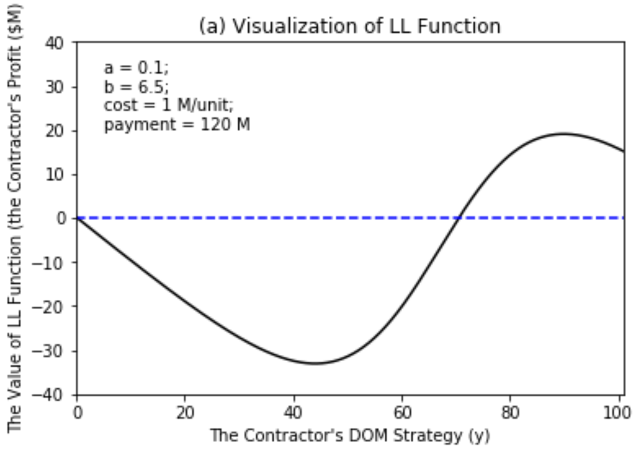
# Model Result:

# Model Shape

```
In [13]: visualPerfFunc(a, b)
```



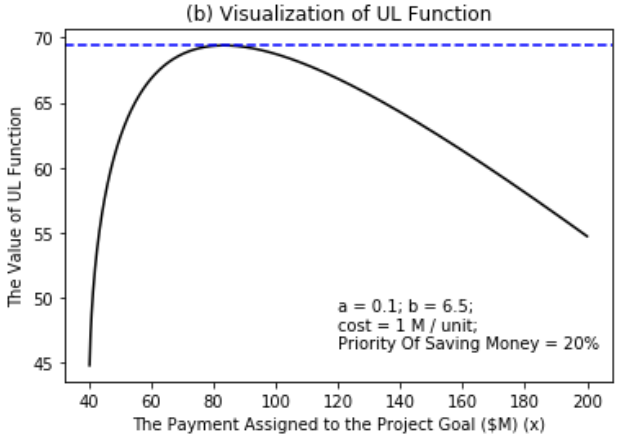
```
In [14]: visualLLFunc(120, a, b, 1, 1)
```



In [15]:

```
visualULFunc(0.1, 1, 1, 1, 0.2)
```

```
no feasible solution
no feasible solution
no feasible solution
no feasible solution
no feasible solution
no feasible solution
no feasible solution
```



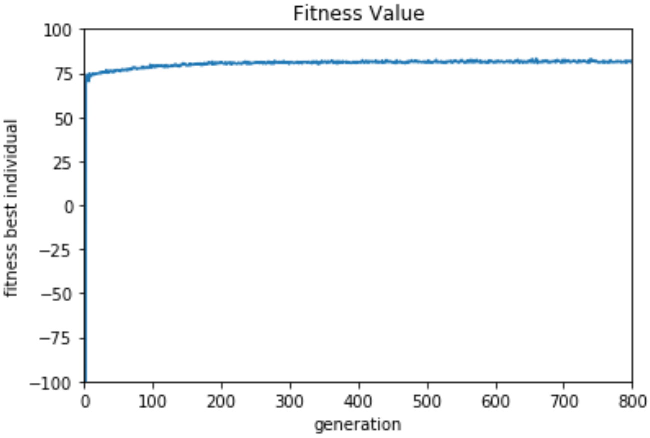
## Results from the case input

In [20]:

```
# function to calculate the result
result = multipleGeneration(generation, sizePopulation, numPay, lowBou
ndPay, upBoundPay,
                            prior, finPrior, cost, maxDeduct, budget, numBe
stSample, numLuckSample,
                            mutationProb, negRange, posRange, a, b, MIRR)
```

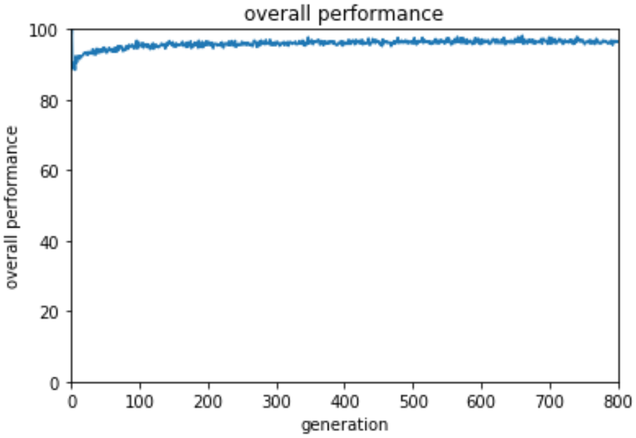
In [21]:

```
# fitness value
evolutionBestFitness(result)
```

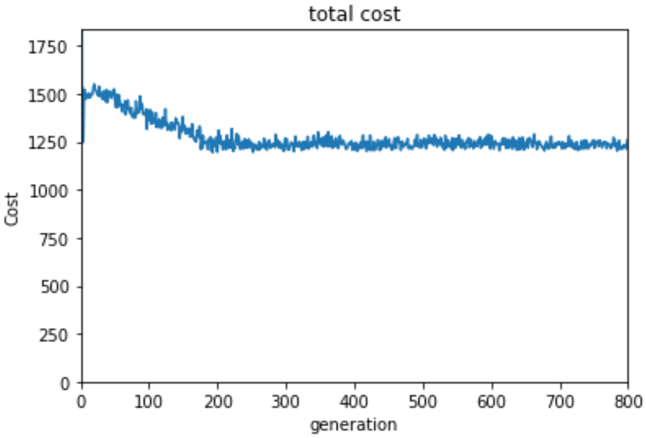


In [22]:

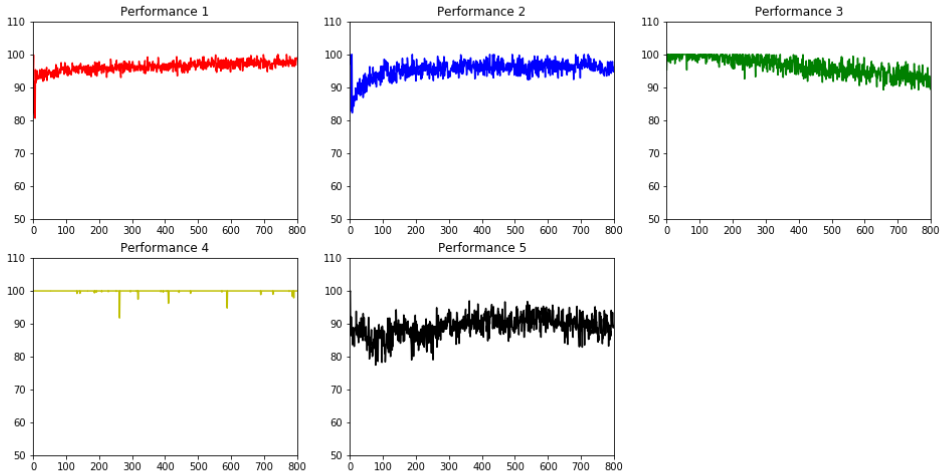
```
# overall performance
evolutionBestPerf(result)
```



```
In [23]: # total project payment
         evolutionTotalCost(result, budget)
```

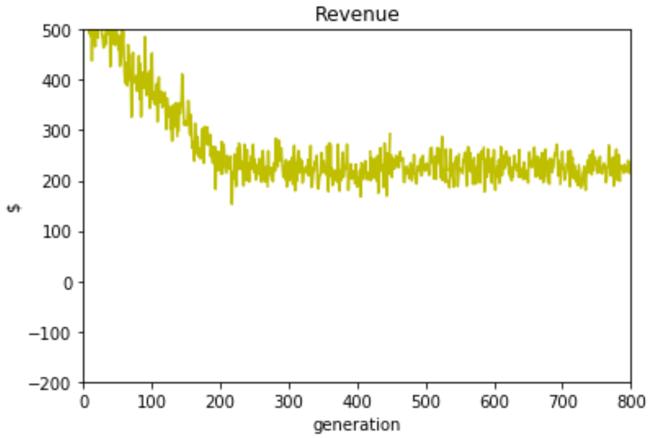


```
In [24]: # each performance
         eachPerf = getEachPerf(result)
         evolutionPerf(result, eachPerf)
```



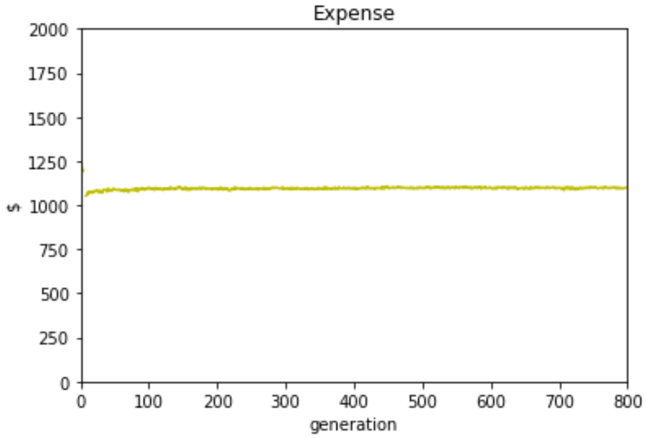
In [25]:

```
# contractor's revenue
evolutionRevenue(result, numPay, a, b, cost, maxDeduct)
```



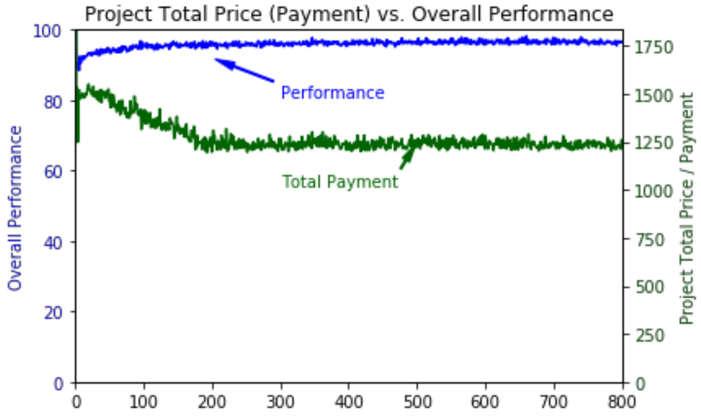
In [26]:

```
# contractor's expense
evolutionExpense(result, numPay, a, b, cost, maxDeduct)
```



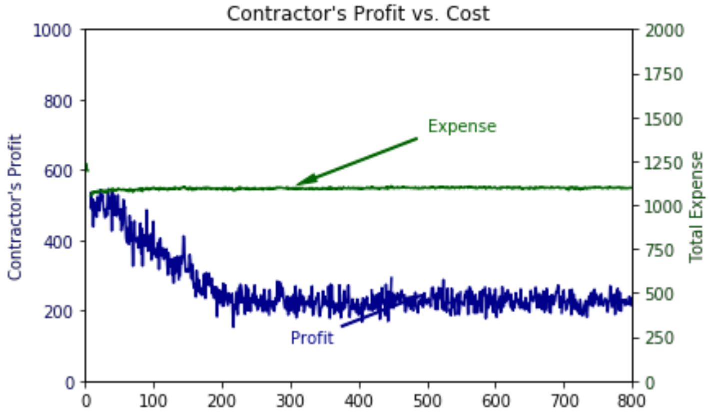
In [27]:

```
# Project total payment vs. overall performance
evolutionPriceCost(result, budget)
```



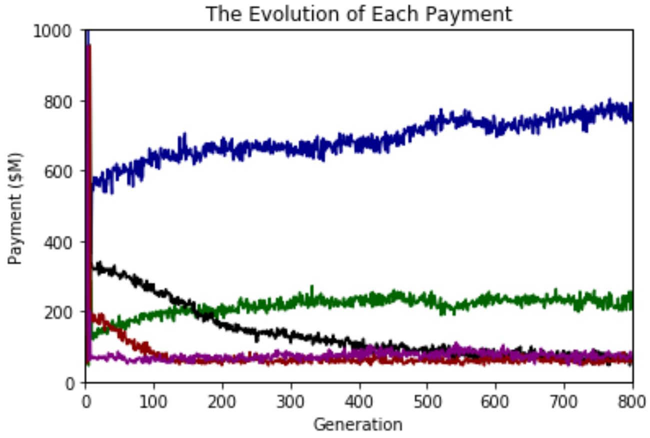
In [28]:

```
# Contractor's overall profit vs. cost
evolutionProfitExpense(result, numPay, a, b, cost, maxDeduct)
```



In [29]:

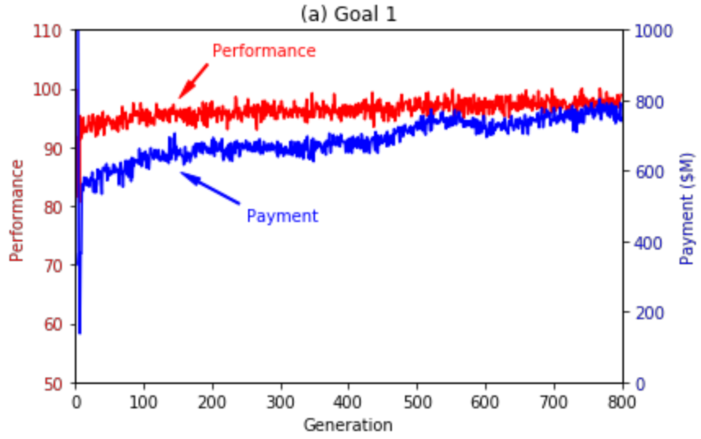
```
# Evolution of each payment
evolutionEachPayment(result)
```

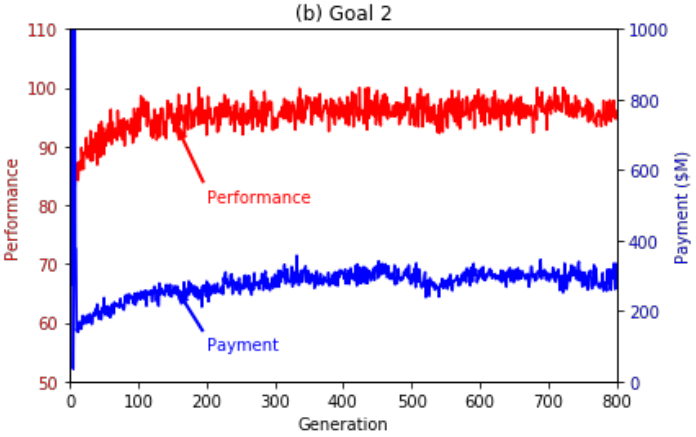


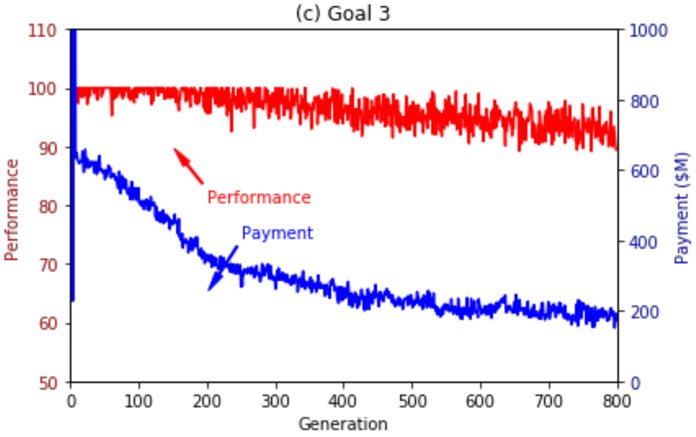
In [30]:

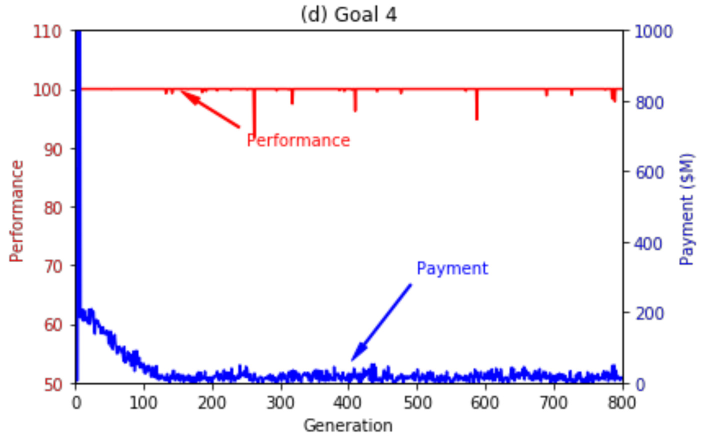
```
# Payment vs. Performance for each project goal
eachPerf = getEachPerf(result)
evolutionEachPerfPay(result, eachPerf)
```

```
<Figure size 576x288 with 0 Axes>
```

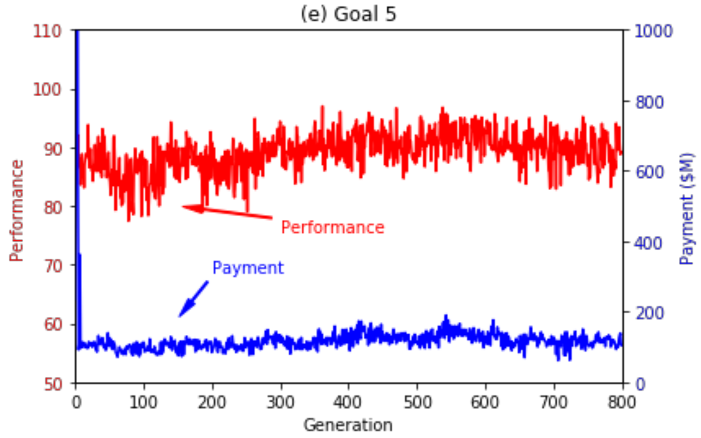



(b) Goal 2
Performance
Payment
Performance
Payment ($M)
Generation
110
100
90
80
70
60
50
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
800


(c) Goal 3
Performance
Payment
Performance
Payment ($M)
Generation
110
100
90
80
70
60
50
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
800



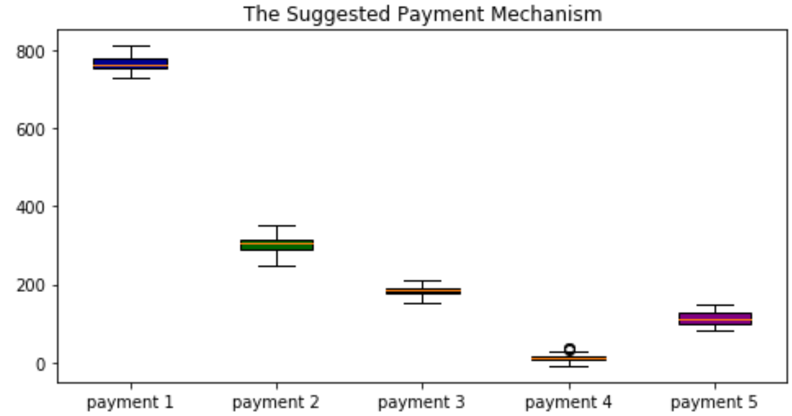
(d) Goal 4



(e) Goal 5

In [31]:

```
# The suggested payment mechanism
visualPayment(result)
```



# VITA

Luming Shang was born in Jinan, Shandong, China. He completed the high school education at Shandong Experimental High School in June 2008. He continued his undergraduate education at the University of Jinan with a specialization in mathematics and civil engineering, and graduated in June 2012 with a Bachelor of Science degree in civil engineering. Three months later, he went to New York for his graduate study at Columbia University and graduated in May 2014 with a Master of Science degree in Construction Engineering. Three months later, he joined the doctoral program in the College of Built Environment at the University of Washington, Seattle.