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OPTIMIZATION OF PUBLIC-PRIVATE PARTNERSHIP CONTRACTS THROUGH A DYNAMIC PRINCIPAL-AGENT MODEL

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The construction of infrastructure often requires high experience on the development of massive projects, thus the government subcontracts a private firm to construct and operate infrastructure. This type of agreement is called Public-Private Partnership (PPP), a common way to construct infrastructure in the late years. However, both entities make bad decisions (i.e., maintenance rates and inspection times), since they do not understand well enough the deterioration of the facility and the uncertainty associated to it. Besides, the information asymmetry between them and the existence of uncertainty linked to natural processes increase the complexity of the problem. We analyze the interaction between each entity and the effects of nature in the system to improve decision-making in PPPs. Then, we propose the optimal strategies each entity should perform in order to maximize their utility, through a dynamic model that takes into account the deterioration process of infrastructure, the entities' decisions embedded into the problem, and the time value of the cost of operating the system. Through a sensitivity analysis of the contract parameters, we demonstrate the importance of dynamic models in infrastructure development and show how the evolution of the system through time is important to understand the behavior of each decision maker. Additionally, a contractual procedure is constructed to help the government to ensure the best contract of the project, because it will take into account the variability of natural processes and the financial incentives of the private sector.

Keywords: Infrastructure systems, public-private partnership, decision-making, system dynamics, Agent-based modeling

1 Introduction

Infrastructure development is the driving force of modern economies; in particular, many studies have shown that access to infrastructure is essential for economic growth and reducing inequality. Nonetheless, the complexity of infrastructure development requires an active participation of a specialized private third party. Out of the different financial mechanisms to involve the private sector, the so-called Public-Private-Partnership (PPP) (Levy 2008, Kwak et al. 2009), has attracted a lot of interest recently being widely adopted in many countries around the world. However, there are still problems that need to be addressed to make these mechanisms more efficient. For example, poor administration of resources and understanding of the uncertainties are some of the causes for major cost overruns in infrastructure projects. Besides, in a study of major projects in 20 countries, nine out of ten had cost overruns (Flyvbjerg et al. 2002). Also, another study showed that cost overruns and benefit shortfalls of 50% are common; and in many cases they may reach values above 100% (Flyvbjerg et al., 2009). Typically, this underperformance can be attributed to uncertainties in numerous aspects such as project complexity, technology, and unexpected geological features (Flyvbjerg 2004).

The objective of this paper is to find the optimal strategies to maximize the utilities of the parties involved. We will accomplish it by modeling the deterioration of a road facility, and taking into account the incentives that drive each individual to perform certain decisions regarding the operation of infrastructure. To understand how these decisions can improve PPPs, Section 2 will show the simulation model and the structure of the game we are going to analyze. Next, the optimization process is presented in Section 3. Then, in Section 4, the optimal strategies for the agent are displayed. Following this section, a sensitivity analysis of the contract parameters is performed in Section 5. Finally, in Section 6 we construct the contract procedure, followed by the conclusions in Section 7.

2 System identification

In PPPs, the Principal-Agent problem is used to represent the interactions between entities in economy (Fudenberg 1991), where the principal is the public entity (treated as a female), and the agent is the private firm (treated as a male) (Laffont and Martimort 2009). The Principal-Agent problem is a good representation of the interaction between the players, but it is not sufficient for the representation of the embedded system (Páez-Pérez and Sánchez-Silva 2016). A system comprises the delegation, from the government to a private firm, of the construction of an infrastructure (e.g., a highway). The private oversees the construction costs *cc* and maintenance to prevent the failure of the system. To make sure the infrastructure performance $V(t)$ is operating as required, the public entity makes inspections and checks the performance at certain times. In case the performance is below an established value k, the principal charges a penalty fee P and causes the agent to perform a mandatory maintenance. These actions occur under an uncertain process, thus there are several possible outcomes for the monetary balance of each player. Figure 1 shows one possible realization of this system.

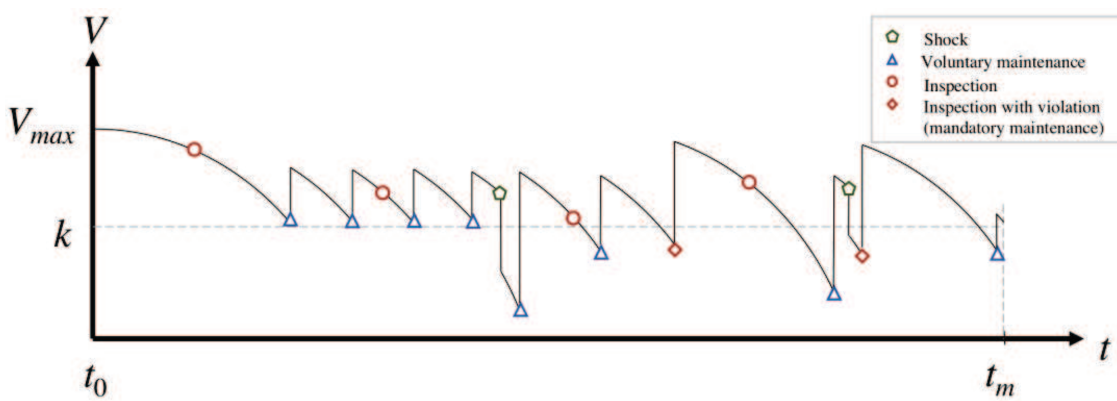

Figure 1. One realization of the system, showing the infrastructure performance V in time.

As a result, the game starts when the principal defines the parameters of the contract at t_0, such as: the duration of the partnership t_m, the schedule of payments made by the principal to the agent h, the performance threshold k that ensures the infrastructure operates as required, and the penalty fee P, which is the amount of money charged to the agent if the principal finds out the infrastructure is below the performance threshold. For the inspections, she has to construct an inspection strategy s_i, to optimize the number and frequency of inspections. For the agent, there are two main decisions to make. The first involves the voluntary maintenance, where he decides the time and the level of performance he is going to perform at each intervention. The second is the mandatory maintenance, where the agent increases the level of performance after the principal detects the performance level is below the threshold. Finally, an entity called "nature" is included to describe external discrete (e.g., earthquakes affecting building performance), and continuous (e.g., weather conditions like rain, humidity, and heat) conditions that affect the performance of infrastructure.

The combinations of these actors' decisions may lead to many possible scenarios during the length of the contract's duration (See Figure 1). This system was first implemented by Páez-Pérez and Sánchez-Silva in 2016, with an Object-Oriented-Program in MATLAB. Then, in 2018, Lozano-Ramírez and Sánchez-Silva developed the optimal strategies for this system, taking into account the same structure of delegation.

3 Optimization process

The model describes the interaction between the principal who will choose the contract parameters to maximize her utility, and the agent that will maximize his utility from the parameters chosen by the principal. This results in a bi-level optimization problem, where two players want to optimize their conflicting utilities; and where one is embedded into the other (Bard 2013). Hence, we optimize the agent utility first, by proposing the best strategies that adapt to any type of contract given by the principal (see Section 4). From there, the principal will know how the agent will optimize his utility and then, she can construct the best contract that maximize her utility, but still gives a cost-effective project to the private firm (see Section 6). Sometimes, a bi-level optimization problem requires performing several iterations of the problem in order to found the optimal utilities of both players (Colson 2007). To eliminate this problem, we carry out a sensitivity analysis with the contract parameters. Following this procedure, we can set the terms of how the principal should formulate her contract in order to maximize her utility.

4 Agent's Strategies

4.1 *Voluntary maintenance*

The optimal size of maintenance if there are no inspections is calculated as:

$$V_{OP_1} = \underset{k \le V_f \le V_{\max}}{\arg\min} \sum_{i=1}^{m} \frac{\psi(V_f, k)}{(1+r)^{m_t(i)}}, \tag{1}$$

where Ψ is the maintenance cost function, that depends on the current performance $V(t)$ and final performance V_f. Moreover, r is the agent's discount rate, m is the number of interventions, and $m_t(i)$ is the time of each maintenance throughout the project. This strategy will ensure the highest utility for the agent, because it considers the cost of every intervention and the discount effect by the rate r. Maintenance is carried out when the current performance reaches the threshold k.

It was assumed that before the third inspection arrives, the agent will maintain the facility at $V=V_{OP1}$ every time the performance reaches the threshold k. After three inspections, the agent will estimate the frequency of inspections by calculating the mean inspection time t_e. As time passes, the agent's estimation improves and it is more likely to be correct, since he acquires more information. Nevertheless, this action generates a chance that performance will go below k and the agent will be at risk of receiving a penalty. To reduce this risk, the agent will increase the size of maintenance from V_{OP1} to equal the discounted average value of the penalty. It can be observed in Figure 2 that after the third inspection, the agent estimates the mean value of inspection times t_e and performs an intervention with a performance higher than V_{OP1} (Lozano-Ramírez and Sánchez-Silva 2018).

4.2 *Mandatory maintenance*

When the system performance is below the admissible threshold and it is detected in an inspection, the agent needs to decide the extent of the maintenance. At first sight, the agent should maintain the infrastructure at the lowest level, because he does not want to spend capital in unnecessary maintenance. However, small interventions would increase the risk to be penalized again for being below the threshold. Therefore, after optimization, it was found that mandatory interventions should have the same size of the optimal level found before the third inspection (V_{OP1}).

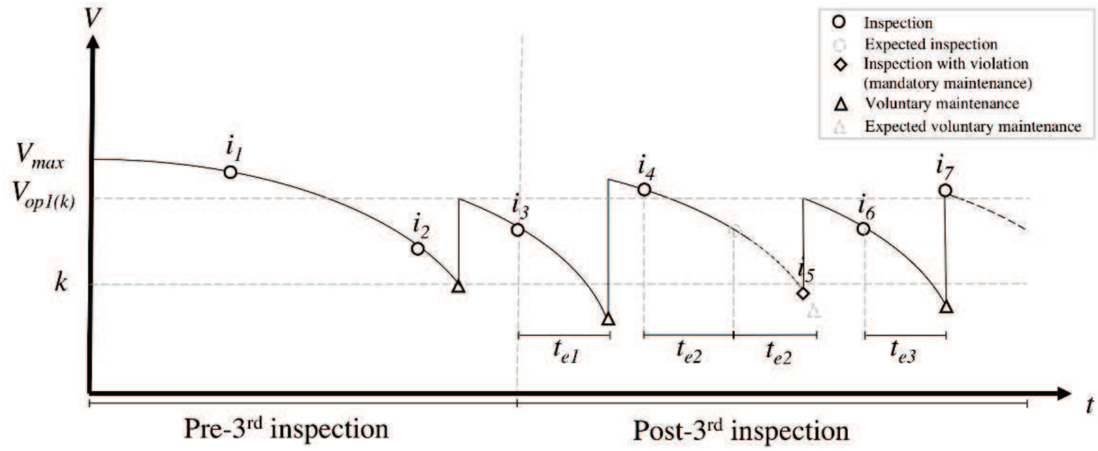

Figure 2. One possible realization of the Agent's strategy, showing the infrastructure performance V vs. t.

5 Sensitivity Analysis

A good way to understand the contract dependency on the main variables is to perform a sensitivity analysis on the performance threshold k, mean time of inspection μ_{in}, and penalty fee P). The results from this analysis are shown in Table 1. In the table, a check-mark means that if a change on any of the contract's parameter results in a significant change on the value of the variable's mean (i.e., > 5%).

Table 1. Variables dependency to the contract parameters

ϕ	k	μ_{in}	P
U_A	✓	✓	✓
U_P	✓	✓	✗
b_P	✓	✓	✓
$\bar{V}$	✓	✗	✗
$\hat{V}$	✓	✗	✗
I_v	✓	✓	✗

Besides, the sensitivity of the players' utility in terms of the contract parameters is plotted (See Figure 3). This graph required running 500 iterations per contract. Therefore, each point corresponds to the mean value of utility for certain contract parameters (i.e., k, μ_{in}, P). The values presented on Figure 3 represent the behavior of the agent against the principal's contract decisions. For example, in terms of the mean time of inspection, the agent earns more capital if the mean time of inspection μ_{in} is big, because the principal is not performing regular inspections, so he can estimate large inspections reducing the total maintenance costs.

Regarding the performance threshold k, the agent has to spend greater amount of money on maintenance costs, if the principal increases the threshold. At the same time, the utility of the principal increases because the infrastructure performance level is higher. This shows that a participation constraint from the agent has to be present, because he will not accept a contract where the principal asks him to maintain an infrastructure with a very high level of performance.

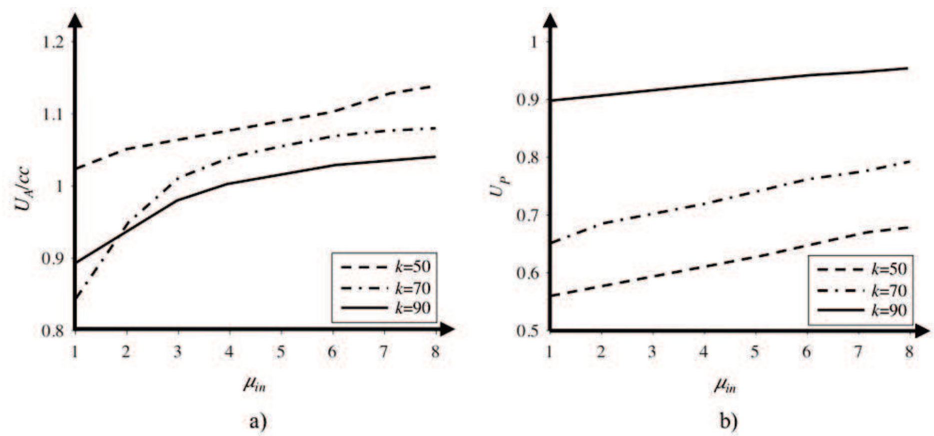

Figure 3. Sensitivity of players' utility for different contract parameters. a) Agent's utility standardized by construction cost b) Principal's utility

6 Contract Procedure

The purpose of developing a contract procedure is to improve decision-making in PPP projects, reducing information asymmetry and increasing the Principal's control over the project. Using the results presented on Table 1, we can conclude that the performance threshold is the parameter with the higher dependency on the players' utility. Therefore, we iterate different contracts until it satisfies certain restrictions. First, it needs to satisfy the agent's participation constraint that ensures the agent's utility is above some utility value so he is willing to perform the project. Also, there is the principal's budget, because if there are not enough monetary resources to pay the agent, the contract is invalid.

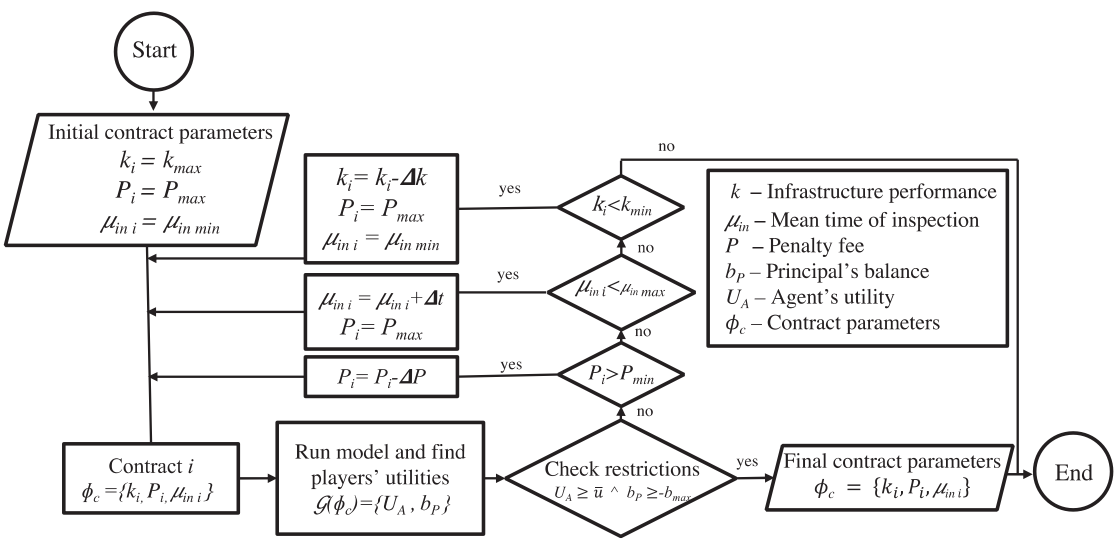

Figure 4. Contract procedure

The diagram shown in Figure 4 is a process where the model finds the mean value of utility from each player (using the MATLAB program), considering some contract ϕ_c with certain parameters. Then the program checks that the restrictions are satisfied. If not, the model changes one of the parameters of the program, calculates the utilities again, and checks the restrictions until it finds the contract with the highest utilities for the players (Lozano-Ramírez and Sánchez-Silva 2018).

7 Conclusions

This paper explores the importance of using dynamic models in infrastructure development and operation. The advantage of these types of models, is that they help to understand how the system evolves through time, according to the decisions made in the infrastructure operation, and the environmental forces affecting the system.

The strategies proposed for the agent, capture the uncertainty in decision-making, because decisions should depend on the state of the system at each time, rather than anticipating actions from the start of the project. The voluntary maintenance strategy shows how the agent adapts to the inspection frequency, taking into account the deterioration of the system and the parameters of the contract previously agreed.

With the sensitivity analysis performed in Section 5, the principal can understand which is the optimal contract offer, because she can construct the contract taking into account the decisions made by the agent, and the performance level she wants to achieve. However, the principal has to foresee the participation constraint of the agent, because she cannot offer a contract that will be too expensive to the agent.

The contract procedure is an important tool for the Principal because it helps her to make better decisions. This procedure considers the effect of uncertainty in both natural processes and decision-making, creating a comprehensive tool to make PPPs. It is important to note that the system's stochasticity remains linked to the outcome of the contractual procedure, thus it cannot be guaranteed that the use of these strategies will always produce a satisfactory profit for each player. Nonetheless, in the long term, this procedure does deliver the highest expected utility for the players, considering the restrictions that apply to it, such as the participation from the agent and the Principal's balance.

References

Bard, J.F., *Practical bilevel optimization: algorithms and applications*, Springer Science & Business Media, 2013.

Colson, B., Marcotte, P., and Savard, G., An overview of bilevel optimization. *Annals of operations research, Springer,* 153(1):235–256, 2007.

Flyvbjerg, B., Holm, M.S., and Buhl S., Underestimating Costs in Public Works Projects: Error or Lie?, *Journal of the American Planning Association*, 68(3) 279–295, 2002.

Flyvbjerg, B., Holm, M., and Buhl S., What causes cost overrun in transport infrastructure projects?, *Transport reviews*, 24(1):3–18, 2004.

Flyvbjerg, B., Garbuio, M., and Lovallo, D., Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster. *California management review.* SAGE Publications Sage CA: Los Angeles, CA, 51(2) 170–194,2009.

Fudenberg, D., and Tirole J., *Game theory. Technical report*, The MIT press, 1991.

Kwak, Y.H., Chih Y., and Ibbs C., Towards a comprehensive understanding of public private partnerships for infrastructure development, *California management review*, 51(2):51–78, 2009.

Laffont, J.J., and Martimort D., *The theory of incentives: the principal-agent model*. Princeton university press, 2009.

Levy, S.M., Public-private partnerships in infrastructure, *Leadership and Management in Engineering*, 8(4):217–230, 2008.

Lozano-Ramírez, J.M. and Sánchez-Silva, M., Improving decision-making in public-private-partnership projects through a dynamic principal-agent problem. Paper under review, 2018.

Páez-Pérez, D., and Sánchez-Silva, M., A dynamic principal-agent framework for modeling the performance of infrastructure, *European Journal of Operational Research*, 254(2):576–594, 2016.