International Journal of Construction Management

ISSN: 1562-3599 (Print) 2331-2327 (Online) Journal homepage: https://www.tandfonline.com/loi/tjcm20

An exact optimization approach to the principal-agent problem in infrastructure projects via PPPs

Camilo Gomez, Diego Castiblanco, Jorge M. Lozano & Camilo Daza

INTERNATIONAL JOURNAL OF CONSTRUCTION MANAGEMENT
https://doi.org/10.1080/15623599.2020.1757572

Taylor & Francis
Taylor & Francis Group

An exact optimization approach to the principal-agent problem in infrastructure projects via PPPs

Camilo Gomez[a], Diego Castiblanco[a], Jorge M. Lozano[b] and Camilo Daza[a]

[a]Departamento de Ingeniería Industrial, Centro para la Optimización y Probabilidad Aplicada (COPA), Universidad de los Andes, Bogotá, Colombia; [b]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

ABSTRACT

PPPs are a compelling mechanism for infrastructure procurement but are vulnerable to the principal-agent problem due to the divergence in the parties' utility functions. This research considers PPPs in infrastructure maintenance problems, in which the *principal* pursues high performance levels, whereas the *agent* pursues cost-efficiency. This paper proposes an optimization model that describes infrastructure performance as a result of deterioration and maintenance processes, and computes the associated benefits and costs for the principal and the agent, combining game theoretical notions with life-cycle analysis. Illustrative examples show how the organizational conditions surrounding PPPs shape the parties' decisions and outcomes by running the model under different scenarios. For instance, the model can anticipate the agent's optimal reaction to specific contractual conditions; i.e., what maintenance plan can be expected from a contractor depending on whether certain performance-related constraints or incentives are in place. Finally, the model can find the optimal maintenance plan for one party conditioned on respecting the other party's optimum within a specified tolerance. This allows to explore a variety of middle-ground solutions and choose an alternative in which one party's gain exceeds the other's loss, providing evidence for incentive design. This research provides a quantitative tool to support decisions and policy on PPPs by integrating physical, financial, and organizational aspects of infrastructure management.

KEYWORDS

Infrastructure maintenance; exact optimization; public-private partnerships; principal-agent problem

Introduction

Public Private Partnerships (PPPs) have been widely discussed and implemented worldwide as a means to leverage the development of public projects with the participation of private companies, with infrastructure projects being a typical case in which PPPs show interesting potential. PPPs, however, have been criticized, among other issues, because of the potential conflicts of interest that may arise when business-oriented actors get involved in the public realm. For instance, while the highest system performance is desirable from a public perspective, financial pressure may drive private companies in a different direction, which is of particular concern in contexts where institutions are weak, and corporations have disproportionate influence on policy and regulation (Percoco 2014; Liu et al. 2016). There is, thus, a challenge in developing analysis tools that help determine the conditions under which PPPs may be adequate, relying on comprehensive technical evidence, and aside from ideological controversies.

Infrastructure management problems are complex, as they integrate a variety of phenomena and fields of knowledge. Broadly, these include the behavior of physical components (e.g., roads, bridges, buildings); the analysis of societal costs and benefits associated to infrastructure systems; and the analysis of coupled decision-making processes between involved actors, considering the influence of the legal and organizational framework (e.g., through regulation and/or incentives). The analysis of complex infrastructure management problems should, thus, respond to a thorough yet tractable integration of these aspects, which poses a challenging problem in mathematical and computational modeling.

This research proposes a methodological framework that integrates technical, financial, and organizational aspects of PPPs into exact optimization models that allow to analyze the interactions and decision strategies of governments and companies in the context of infrastructure management projects. We analyze decisions for involved actors adopting the notion of agency problem, in which a principal (in this case the government) hires an agent (in this case a private company) to perform a task. The problem arises as the agent may take advantage of information asymmetries to pursue its individual benefit to the detriment of the task. The proposed methodology integrates these key aspects of infrastructure management into a model that enables quantitative analysis of PPPs.

Figure 1 provides an overview of the optimization model that supports the proposed methodology. Its purpose is to describe a system's physical performance through its life cycle as a function of deterioration and maintenance, which in turn determine outcomes for the parties in a PPP. The left-hand side of the figure describes the model in terms of its objective function (maximization of utility from the perspective of either the principal or the agent) and four blocks of constraints. The first block of constraints models the system's performance using deterioration functions as an input parameter. The second block translates the performance (often related to continuous physical variables) to a set of discrete service levels, which

CONTACT Camilo Gomez gomez.ch@uniandes.edu.co

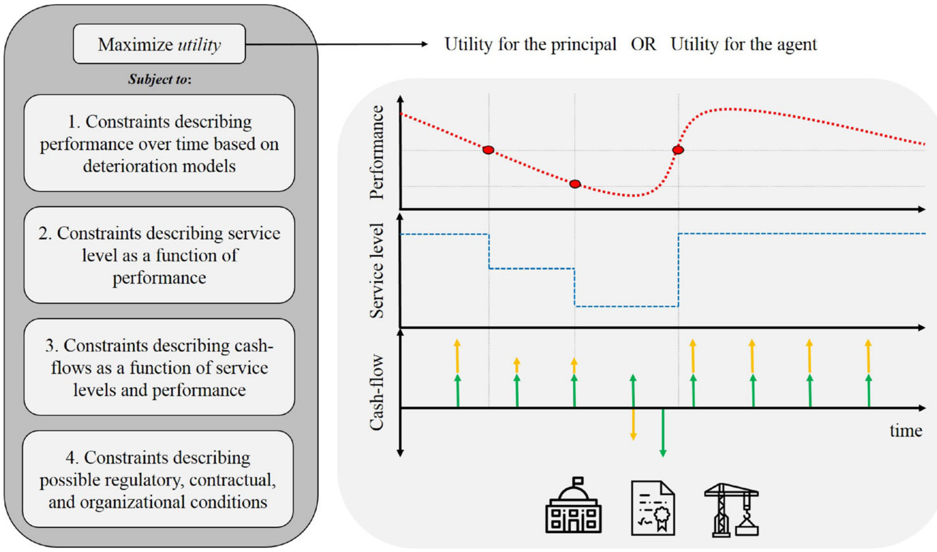

Figure 1. Overall description of the proposed optimization model as blocks of constraints that keep track of the performance, service levels, cash-flows, and contractual aspects throughout an infrastructure's life cycle.

represent different categories of quality that can be mapped to different levels of economic benefit derived from the system. The third block keeps track of financial aspects, including the costs of, and payments of, maintenance actions, and potentially other earnings and expenditures (e.g., credit). The fourth block includes conditions related to the organizational context (e.g., minimum mandatory performance levels, incentives, etc.).

The integration of technical, financial, and organizational aspects into a computationally tractable optimization model allows to perform *what-if* analyses by comparing how optimal decisions change under different input conditions, echoing the essence of optimization-based simulation. Given a set of rules (e.g., a PPP contract), the proposed methodology can help governments anticipate the strategies that companies might adopt as rational decision-makers, providing evidence on whether the stated rules produce the intended effect. As a result, discussions on policy and regulation can be informed by comparing how different sets of rules shape the behavior of the involved parties. This research, thus, opens avenues towards a quantitative methodology to test and refine practices around PPPs in the context of infrastructure management. Most engineering fields rely on simulations before incurring the expenses and risks of project execution. Similarly, mathematical and computational tools have the potential to inform the analysis and design of the conditions that shape decisions in major infrastructure projects. The main contribution of this work is an optimization-based methodology that allows to analyze advantages and drawbacks of PPPs by integrating diverse aspects of infrastructure management into computational experiments, thus, paving the way for research on mechanisms to potentiate such advantages and overcome drawbacks.

This paper is organized as follows: Section "**Literature review**" offers a departure point for devising analysis methodologies for PPPs in the context of infrastructure management, relying on tools from operations research. Because the literature on PPPs aggregates contributions from diverse disciplines, Section "**Literature review**" explores the general overview of research on PPPs, on life-cycle analysis for infrastructure management, and on contributions to infrastructure engineering from operations research. Section "**Methodology**" provides a detailed definition of the problem of interest, followed by the formulation of the corresponding mathematical model, and the presentation of a methodological framework for analysis. Section "**Illustrative example**" demonstrates the use of the proposed methodology considering the maintenance of a road via PPPs. Section "**Conclusions**" provides a discussion about the proposed methodology and results.

Literature review

Infrastructure systems such as road networks and water supply systems can be seen as complex systems in which relevant outcomes depend on the physical behavior of their components, on factors from the external environment, and on their organizational context (e.g., legal and socio-economic conditions). Therefore, the design of methodologies that support the planning and management of such systems requires the integration of diverse frameworks and techniques. This section provides a brief account of literature on PPPs and infrastructure management, highlighting the variety of communities doing research on this problem and the need for contributions that integrate them. Section "**Non-physical aspects of infrastructure projects**" addresses organizational and socio-economic issues, focusing on the interactions between involved parties, particularly regarding the principal-agent (PA) problem. Section "**Life-cycle analysis of infrastructure systems**" addresses a standard framework in structural engineering and infrastructure management, and highlights the potential of adopting tools from operations research in infrastructure-related problems. Section "**Computational modeling in infrastructure management**" addresses research efforts seeking to merge the physical deterioration of infrastructure systems with the broader aspects of PPP projects. The section concludes by highlighting the need for methodologies that exploit the potential of quantitative analysis while dealing with aspects beyond physical performance.

Non-physical aspects of infrastructure projects

The infrastructure engineering community has progressively moved beyond disciplinary frontiers to incorporate societal aspects into the analysis of infrastructure systems. In this paper, we are concerned with research addressing the effects of organizational interactions; i.e., of the relationships between the parties involved in a project. For instance, Thomas et al. (2019) "examine the dynamic relationships between human resilience and the resilience of complex, socio-technical critical infrastructure systems". Similarly, Roos et al. (2004) claim that "next generation infrastructure development requires a holistic perspective which includes organizational and contextual factors in addition to technical factors as an integral part of the design process".

Ellingwood and Lee (2016) discuss inter-generational aspects for risk-informed life-cycle analysis of infrastructure systems, while Corotis (2009) discusses the issues of adopting life-cycle concepts for infrastructure systems within the political context (i.e., conflicting political interests and time horizons). Sanford Bernhardt and McNeil (2008) discuss the adoption of agent-based models to improve the decision-making and management of infrastructure systems. Mostafavi et al. (2014) propose a hybrid agent-based and system dynamics approach to incorporate the behavior of stakeholders in the analysis of policies related to infrastructure problems. Furthermore, Gómez et al. (2014) propose a framework in which agents with diverse preferences make decisions for different sub-systems in an infrastructure network, accounting for potential misalignment of interests at the organizational level of infrastructure management. Finally, Zhang et al. (2005) incorporate a game theoretical approach to model interdependent infrastructure systems (as multiple layers).

The research on PPPs has focused on managerial issues, contract analysis and best practices, as well as economic and incentive analyses. For example, Zou and Zhang (2009) present a review of risk management in construction projects throughout their life cycle, not incorporating structural factors, but analyzing key risks on the different stages of the project. Moreover, Antoniou and Aretoulis (2019) use a multi-criteria decision-making system to select the best contractor for a highway construction project. Osei-Kyei and Chan (2015) discuss the Critical Success Factors (CSF) for PPPs, including strong private consortium and transparent procurement. Likewise, several authors present best practices and CSF in PPPs around the world, such as Ling et al. (2011) in Singapore, Osei-Kyei and Chan (2017) in Ghana, Debela (2019) in Ethiopia, or Li et al. (2005) in the UK. These studies are vital to understand critical decisions in infrastructure contracts. Besides, they provide insight on the main variables for an optimization model that includes different actors' decisions in this type of projects. Nonetheless, recent studies have proven that PPPs are also failing in certain types of projects (Jienan et al. 2017), such as water infrastructure in developing countries (Tariq et al. 2019) and the rail system in Korea (Hong 2016). This evidences the need for research that improves decision-making in PPPs to prevent cases of bad risk management.

Previous research has considered game theory as a means to model PPPs. Scharle (2002) highlights the importance of game theory to clearly define the players' actions in uncertain ecosystems, such as PPPs. Furthermore, some authors have dealt with the problem of renegotiation in PPPs. High rates of renegotiation have been identified in PPP contracts, especially in developing countries, which demonstrates the lack of viability of decision making between multiple entities in these contracts (Guasch et al. 2008). Therefore, understanding the relationship between the principal (i.e., the government) and the agent (i.e., the private contractor) is paramount, as this interaction determines payoffs for both players and, more importantly, the performance of the infrastructure project over time. Within the realm of game theory, the principal-agent (PA) model is a natural choice to analyze PPPs. This model has been widely used to establish the set of decisions for both parties that converge to an equilibrium of their interests. For instance, Leruth (2012) and De Palma et al. (2012) proposed PA frameworks to conceptualize the relationship between the government and the private firm in PPPs. In fact, Shrestha and Martek (2015) highlight the need to address the problems in PPPs using the PA problem as a tool to model the behavior of each entity. Moreover, modeling PPPs with the PA problem (as a non-cooperative game) shows the inefficiency of the parties to arrive to an equilibrium state, causing society to pay huge costs (Miao et al. 2010). Some authors have also used non-linear programming to solve PA problems (Cecchini et al. (2013); Renner and Schmedders (2015)); however, there is no incorporation of life-cycle within the actor's decisions, which disregards the deterioration of the system throughout a planning horizon.

Life-cycle analysis of infrastructure systems

Decision theory and life-cycle performance assessment have been combined and established as a suitable framework to address infrastructure-related problems, as they provide a comprehensive, yet macroscopic, tool to analyze complex projects by relating the performance of physical structures with their associated costs and benefits over long planning horizons Furuta et al. 2014; Frangopol and Furuta 2001; Faber and Stewart 2003. The key elements in the life-cycle framework are: the definition of models that describe the evolution of the system over time, including progressive deterioration and shocks (e.g., Riascos-Ochoa et al. (2016); van Noortwijk and Frangopol (2004)), according to a specified performance metric (e.g., reliability); and the estimation of costs and effects of interventions (e.g., maintenance, repair, replacement), as well as of the benefits that can be derived from the system (at different performance levels). This can be represented by a cash-flow, such that different intervention policies can be assessed, for instance, in terms of their (expected) net present value; hence, the estimation of parameters such as deterioration and discount rates, as well as of expected societal benefits derived from the system, deserve special attention. We adopt this framework instead of, e.g., project management frameworks, because we are interested in the connection with structural aspects of the problem. A comprehensive review of life-cycle related literature in the context of infrastructure systems is beyond the scope of this paper. However, Frangopol et al. (2004) offer a review of probabilistic methods to address life-cycle performance of deteriorating structures, while Frangopol (2011) reviews issues of management and optimization of structural systems under uncertainty, and Frangopol and Soliman (2016) and Biondini and Frangopol (2018) provide more recent reviews of life-cycle oriented works in structural systems.

While optimization is certainly not new in infrastructure problems, there has been an increasing interest from the Operations Research (OR) community in contributing with methods that have proven to be helpful to address complex infrastructure problems. A few examples include the optimal recovery of interdependent networks (González et al. 2016), the use of stochastic programming approaches to evaluate retrofit actions in transportation networks (Liu et al. 2009; Gomez and Baker 2019), and the analysis of risk and resilience in complex systems (Barker and Haimes 2009; Gama Dessavre et al. 2016). Other works include the use of modeling, simulation and optimization techniques in the context of critical infrastructures (Ouyang 2014; Ouyang and Fang 2017). OR methods have, thus, proven to be adequate when dealing with combinatorial decision alternatives and large sets of scenarios, as is the case of infrastructure operation via PPPs.

Computational modeling in infrastructure management

The recognition of the contract as a crucial element that governs PPP interactions (Klijn and Koppenjan 2016; Lozano and Sánchez-Silva 2019) is our motivation to analyze the conditions under which a PPP can be feasible for both parties, and the arrangements under which favorable trade-offs can be obtained. From this perspective, the principal's landscape is not entirely negative, since it has the discretion to adopt a PPP scheme (or not), and to specify contract terms, risk-sharing mechanisms, liability conditions, and other incentives that can drive the agent to favorable behaviors (Buxbaum and Ortiz 2009; Medda 2007).

A common tool to model the behavior of autonomous entities in a dynamic problem is the agent-based modeling (ABM) framework, which provides a way to find emergent strategies in a system with incomplete information. In the case of infrastructure contracts, Mostafavi et al. (2016) created a set of financing scenarios to model the response of PPPs in the USA. Castiblanco (2011) used a game theoretical approach to model a PPP interaction and Castiblanco et al. (2012) further explored organizational issues in the context of infrastructure management. Later, Paez-Perez and Sanchez-Silva (2016) conceptualized the agency problem of PPPs in a dynamic PA model that included maintenance decision and dynamic deterioration of the roads using ABM. Then, Lozano and Sánchez-Silva (2019) defined the contract parameters that improved both the principal and the agent's utility in maintenance policies of PPPs. Furthermore, regarding the use of optimization models, Ng et al. (2007) developed a model to find the optimal concession period in PPPs, while Wu et al. (2011) formulated a mixed integer program to find the optimal build-operate-transfer project within a set of different finance scenarios.

Research gap

Researchers have highlighted the need for a formal, systematic, and operational way to evaluate the performance of PPPs (Cui et al. 2018), recognizing the need to address prominent challenges faced by PPPs, such as the complexity of risk management, the inadequate consideration of life-cycle aspects, and the presence of moral hazard (Jayasuriya et al. 2019). As a response to this need, the remainder of this paper discusses a unified model based on exact optimization, in which the life-cycle analysis framework is adopted to describe key physical, financial, and organizational aspects that affect infrastructure management projects via PPPs. To the best of our knowledge, this is a novel approach that offers an analysis tool that enriches the discussion on advantages and drawbacks of PPPs.

Methodology

The proposed methodology addresses the principal-agent problem in infrastructure management projects via PPPs by means of exact optimization models considering a life-cycle performance framework. Section "**Problem definition**" narrows the focus of the proposed methodology to road maintenance problems. Then, Section "**Mathematical formulation of the optimization model**" presents the technical details of the proposed model. Section "**Methodological steps to use the model for analysis**" describes the proposed framework to analyze decisions and tradeoffs for the public and private parties involved in the problem, while Section "**Assumptions and limitations**" provides a closure for the methodological section.

Problem definition

Suppose a private contractor is in charge of the maintenance of a public infrastructure system through a PPP. The system is subject to a deterioration function that describes the degradation of a given performance metric. Although physical deterioration may be described as a continuous process, the performance of the system at any given time can be mapped to a discrete set of categories. For instance, roads are often classified into discrete service levels (e.g., depending on their flows and speeds), which can be associated with different levels of economic benefit. The private contractor (the *agent* hereinafter) must define a maintenance plan to control the deterioration process. Depending on the maintenance plan, the system may experience different service levels over time. The government (the *principal* hereinafter) pursues the economic benefit derived from the system throughout its life cycle, whereas the agent pursues the cost-effectiveness of the maintenance plan. Such divergence may lead to significantly different maintenance plans depending on whose objective is being considered. PPP contracts can address this issue by imposing a minimum performance constraint that guarantees high service levels. However, monitoring and enforcing such constraints may have technical, budgetary, and organizational limitations in practice. Alternatively, contracts may include performance-dependent payments to the agent as incentives to maintain high service levels, even in the absence of monitoring. The specific design of such constraints and incentives is challenging as their success depends on understanding the integrated effect of physical and financial processes, observed through the rationality of the involved parties. Computational tools can significantly contribute to understanding and designing such mechanisms by allowing trial-and-error experimentation *in silico* rather than in actual high-stakes projects.

We propose a mathematical model that describes the stated situation in a comprehensive yet tractable way, as a first step towards an analysis framework for complex infrastructure management problems. We focus on maintenance actions as an essential part of a system's life-cycle, but ongoing research is devoted to modeling broader forms of PPPs (e.g., those that include build, operate, and transfer activities). The central decision in the model is the definition of a maintenance plan, based on information such as the fixed and variable costs of maintenance actions, a quantification of the economic benefit obtained from the system at each service-level, and the magnitudes of payments and possible penalties/rewards from the principal to the agent. The model keeps track of the performance of the system at any time as a function of maintenance actions, given a deterioration function, which can be non-linear (as it is modeled as a parameter rather than a variable) and may be stochastic (under minor modifications of the model); we focus on the deterministic case for simplicity in exposition. The service level and economic benefit for the system, as well as associated cash flows for the principal and the agent, can be derived from the performance and maintenance actions over time.

Table 1. Summary of sets, parameters and variables in the mathematical model.

Category	Mathematical notation	Description
Sets	$\mathcal{T}$:	set of periods in planning horizon
	$\mathcal{L}$:	set of discrete service-levels
	$\mathcal{Q}$:	set of periods in a renewal cycle
Parameters	γ_τ :	performance obtained after τ periods without restoration
	$\bar{\gamma}$:	$\max(\gamma_t)$
	$c^{(f)}$:	fix cost for restoration action
	$c^{(u)}$:	unit cost to restore a performance unit
	a:	fixed income from the principal to the agent
	g_l:	economic benefit obtained from the system at service-level $l \in \mathcal{L}$
	g^* :	target benefit
	ϵ :	target return rate for the agent
	$\check{\xi}_l$:	lower bound for service level $l \in \mathcal{L}$
	$\hat{\xi}_l$:	upper bound for service level $l \in \mathcal{L}$
Variables	x_t:	whether a maintenance action is applied at period $t \in \mathcal{T}$
	y_t:	number of periods elapsed after last restoration
	$b_{t,\tau}$:	whether $y_t = \tau$ for $\tau \in \mathcal{Q}$
	$z_{t,l}$:	whether system is at service level $l \in L$ at period $t \in \mathcal{T}$
	v_t:	performance at period $t \in \mathcal{T}$
	p_t:	earnings at period $t \in \mathcal{T}$
	q_t:	expenditures at period $t \in \mathcal{T}$
	κ_t:	available budget at period $t \in \mathcal{T}$
	w_t:	linearization of $y_{t-1}x_t$
	u_t:	linearization for $v_t x_t$

Mathematical formulation of the optimization model

This section presents the mathematical formulation for the optimization model illustrated in Figure 1, which responds to the problem defined in Section "**Problem definition**". Table 1 summarizes the sets, parameters, and variables of the problem. The model considers a set of periods in the planning horizon ($\mathcal{T}$), a set of service levels ($\mathcal{L}$), and an auxiliary set, $\mathcal{Q}$, to count the periods elapsed since the last maintenance action.

Parameter γ_τ is crucial for the proposed model as it indicates the performance that would be observed after τ periods without applying maintenance actions under a given deterioration function (e.g., $\gamma_5 = 87\%$ means that when the system is left without intervention for 5 periods, the performance drops from 100% to 87%). This parameter can be pre-computed based on case-specific deterioration models, such as those described in Section "**Literature review**" (e.g., Riascos-Ochoa et al. (2016)). The latter describes a deterministic deterioration process, but can be extended to a stochastic version by re-defining the parameter as $\gamma_{\tau,\xi}$, where ξ denotes different realizations of the deterioration process within a set Ξ of scenarios. Parameters $c^{(f)}, c^{(u)}$, a, d_l, f_t, g_l, and g^* (detailed in Table 1) correspond to crucial economic magnitudes in the problem (costs, benefits, payments), which must be carefully estimated on a case-by-case basis, as they determine the outcomes for the involved parties. The remaining parameters in Table 1 are instrumental to construct the model but do not have crucial interpretations.

The core variables of the model are x_t, which models maintenance actions, and y_t, $b_{t,\tau}$, v_t and $z_{t,l}$, which jointly keep track of maintenance actions, as well as system performance and associated service-levels. Variables p_t, q_t, and κ_t model the financial aspects of the problem, keeping track of earnings, expenditures, and overall budget. The remaining variables in Table 1 are auxiliary for the linearization of products between other variables in the model, which are discussed later.

The proposed mathematical model is expressed in Equations (3) through (22). Equation (3) states a generic objective function, which can be tailored for the principal or the agent, as shown in Equations (1) and (2), respectively.

$$Utility_{principal} = \sum_{t\in\mathcal{T}}\sum_{l\in\mathcal{L}} g_l z_{l,t} - \sum_{t\in\mathcal{T}}\left(a + \sum_{l\in\mathcal{L}} k_l z_{l,t}\right) \tag{1}$$

$$Utility_{agent} = \sum_{t\in\mathcal{T}} (p_t - q_t) \tag{2}$$

The model's constraints can be grouped into the four blocks presented in Figure 1:

- *Performance*: Equations (4) and (5) keep track of the number of periods since the previous maintenance action. Equations (6) and (7) transform the integer number of periods since the previous maintenance (y_t) into a binary representation ($b_{t,\tau}$) stating whether, at time t, τ periods have passed since the previous maintenance. Equation (8) quantifies the performance level v_t as a function of the number of periods elapsed since the previous maintenance by means of parameter γ_t.
- *Service levels*: Equations (9) and (10) compute which of the discrete service levels can be associated to the continuous performance level, v_t, at the current period (i.e., compute $z_{t,l}$); this will be useful to associate such service level to its corresponding societal benefit.
- *Finance*: Equations (11) and (12) describe the costs and earnings associated to the operation of the infrastructure system, while Equations (13) and (14) model the budget based on such cash-flow. Equation (15) guarantees that the available budget is not exceeded.
- *Organizational aspects*: Equation (16) sets a minimum target profit for the agent (ϵ), while Equation (17) sets a minimum target performance for the principal (k). Setting ϵ or k to zero can disable each of these constraints, respectively, if necessary for a specific analysis. Other constraints related to contractual and regulatory conditions may be included. For this research, however, the focus is on the tradeoff between performance and cost-efficiency.

Finally, Equations (18) through (22) define the domain of the variables.

$$\max Utility \tag{3}$$

Subject to:

$$y_1 = 0 \tag{4}$$
$$y_t = (y_{t-1} + 1)(1 - x_t), \qquad \forall t \in \mathcal{T} | t > 1 \tag{5}$$
$$y_t = \sum_{\tau \in \mathcal{Q}} t(b_{t,\tau}), \qquad \forall t \in \mathcal{T} \tag{6}$$
$$\sum_{\tau \in \mathcal{Q}} b_{t,\tau} = 1, \qquad \forall t \in \mathcal{T} \tag{7}$$
$$v_t = \sum_{\tau \in \mathcal{Q}} \gamma_\tau b_{t,\tau}, \qquad \forall t \in \mathcal{T} \tag{8}$$
$$\check{\xi}_l z_{t,l} \le v_t \le \hat{\xi}_l z_{t,l} \qquad \forall t \in \mathcal{T}, l \in \mathcal{L} \tag{9}$$
$$\sum_{l \in \mathcal{L}} z_{t,l} = 1, \qquad \forall t \in \mathcal{T} \tag{10}$$
$$q_t = \left[c^{(f)} + c^{(v)}(\bar{\gamma} - v_t)\right] x_t, \qquad \forall t \in \mathcal{T} \tag{11}$$
$$p_t = a + f_t + \sum_{l \in \mathcal{L}} (d_l + k_l) z_{l,t}, \qquad \forall t \in \mathcal{T} \tag{12}$$
$$\kappa_1 = p_1 - q_1 \tag{13}$$
$$\kappa_t = \kappa_{t-1} + p_t - q_t, \qquad \forall t \in \mathcal{T} | t > 1 \tag{14}$$
$$q_t \le \kappa_t, \qquad \forall t \in \mathcal{T} \tag{15}$$
$$\sum_{t \in \mathcal{T}} p_t = (1 + \epsilon) \sum_{t \in \mathcal{T}} q_t \tag{16}$$
$$v_t \ge k \qquad \forall t \in \mathcal{T} \tag{17}$$
$$x_t \in \{0, 1\}, \qquad \forall t \in \mathcal{T} \tag{18}$$
$$b_{t,\tau} \in \{0, 1\}, \qquad \forall t \in \mathcal{T}, \tau \in \mathcal{Q} \tag{19}$$
$$z_{t,l} \in \{0, 1\}, \qquad \forall t \in \mathcal{T}, l \in \mathcal{L} \tag{20}$$
$$y_t, w_t \in \mathbb{Z}, \qquad \forall t \in \mathcal{T} \tag{21}$$
$$v_t, u_t, p_t, q_t, \kappa_t \in \mathbb{R} \qquad \forall t \in \mathcal{T} \tag{22}$$

Some constraints in the model have nonlinear terms. In Equation (5), we apply the linearization $w_t = y_{t-1}x_t$ as follows:

$$w_1 = 0 \tag{23}$$
$$w_t \le y_{t-1}, \forall t \in \mathcal{T} | t > 1 \tag{24}$$
$$w_t \ge y_{t-1} - |Q|(1 - x_t), \forall t \in \mathcal{T} | t > 1 \tag{25}$$
$$w_t \le |Q| x_t, \forall t \in \mathcal{T} | t > 1 \tag{26}$$

where $|Q|$ works as an upper bound for y_{t-1}. Similarly, in Equation (11), we apply the linearization $u_t = v_t x_t$ as follows:

$$u_1 = 0 \tag{27}$$
$$u_t \le v_t, \forall t \in \mathcal{T} | t > 1 \tag{28}$$
$$u_t \ge v_t - \bar{\gamma}(1 - x_t), \forall t \in \mathcal{T} | t > 1 \tag{29}$$
$$u_t \le \bar{\gamma} x_t, \forall t \in \mathcal{T} | t > 1 \tag{30}$$

where $\bar{\gamma}$ works as an upper bound for v_t. These linearizations are applied to Equations (5) and (11) in the computational implementation of the model.

Methodological steps to use the model for analysis

The proposed model returns the best maintenance plan that can be obtained (for either the principal or the agent) given a set of input parameters (which may specify constraints and incentives). Hence, it can be used in a way similar to optimization-based simulation, which performs repeated runs of an optimization model that describes a situation of interest in order to understand the effect of different input parameters. Consequently, the proposed optimization model can be used as a means to understand how changes in the conditions surrounding PPPs (e.g., contractual or regulatory) may produce different maintenance plans and, hence, different societal benefit. Three analyses are proposed in this direction, as described below.

First, a sensitivity analysis is performed on parameters ϵ and k to assess the joint feasible region for the principal and the agent (i.e., discard cases in which a certain target profit is not feasible under a given performance constraint, and vice versa). This sets the bounds for negotiation as it helps define walk-away point for both parties. This experiment is performed by iteratively running the model from the perspective of the principal and the agent, considering a set of target performance levels and target profits of interest. An illustration of this analysis is shown in Section "**Exploring the joint feasibility space**".

Second, the following questions are addressed: to what extent does the agent's optimal maintenance plan differ from the principal's? How does the agent respond to incentives to pursue higher service levels if not forced to via constraints (e.g., under weak or no supervision)? This experiment is performed by finding the optimal maintenance plan from the perspective of the principal and comparing it with the optimal maintenance plan from the perspective of the agent, considering four cases, depending on whether the agent is forced to comply with a performance level, k, via constraints, and whether there are economic incentives associated to higher service levels. This yields the following cases: performance constraint and economic incentive; performance constraint and no incentive; no performance constraint and incentive; and no performance constraint and no incentive. An illustration of this analysis is shown in Section "**Assessing the impact of diverging objectives**"

Third, we address the following question: how can the principal define win-win incentives to drive the agent towards solutions that yield higher service levels? This experiment is achieved by running a so-called lexicographic optimization process. The process starts by finding the best unilateral solution for both the principal and the agent. Then, the model is solved for one party (say, the principal) incorporating a constraint stating that the other party's objective function (i.e., the agent's) cannot deviate from its unilateral optimum by β percent. The new objective function for both parties can be obtained and compared to their unilateral optima. If the gain of one party (say, the principal) outweighs the loss of the other, there is an opportunity to generate a compensation that moves the agent towards a solution that is better-performing for the principal. By repeating this exercise for a range of values of β, it is possible to find the compensation that produces the largest benefit cost ratio. Figure 2 summarizes this procedure. It is worth noting that, although the mathematical model produces an exact solution each time it is run, the procedure to find good compensations is heuristic as it does not consider the coupled decisions of the involved parties, and considers a finite set of values for β. An illustration of this analysis is shown in Section "**Searching for win-win compensation schemes**".

Assumptions and limitations

The proposed model includes the following assumptions. Maintenance actions take place immediately and make the system as good as new. Monetary parameters are defined as time-indexed arrays to reflect the effect of discount rates, which can

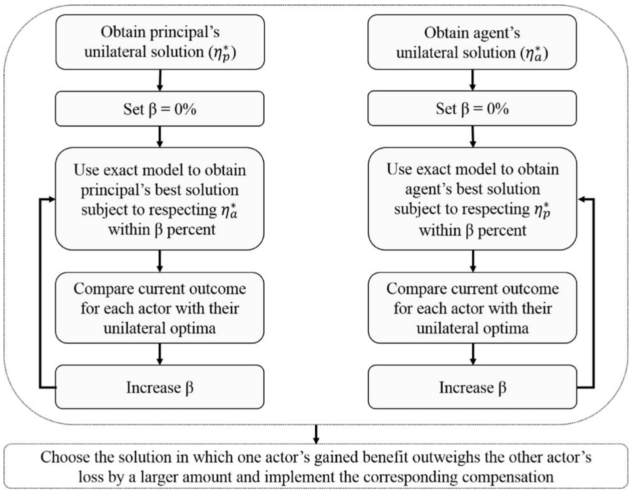

Figure 2. Heuristic procedure based on the exact optimization model to estimate win-win compensations to reconcile diverging objectives.

be different for the principal and the agent. The principal and the agent cannot associate in a corrupt way. The agent is allowed to obtain unbounded positive profits. Progressive deterioration is accounted for without considering the effects of extreme events. Every contractual constraint must be fulfilled unless stated otherwise for a specific experiment.

The proposed methodology has two limitations that are being addressed as part of ongoing research. First, game theoretical problems often rely on bi-level optimization models to capture the fact that involved parties pursue strategies that maximize their own utility while considering the opposite party's best possible decision within their optimization process. Bi-level optimization problems are relatively easy to solve when variables are continuous. For integer problems, however, it is necessary to apply specialized solution methods that exceed the scope of this paper. The proposed approach, although more limited than bi-level optimization, does not compromise the proposed analysis. Second, the deterioration functions in the illustrative example do not incorporate stochasticity. This limitation can be easily overcome by including multiple realizations of the deterioration process, but was not explored in order to test and exploit the features of the core methodology, allowing for streamlined analyses and adjustments before further complicating the model.

Finally, the constraints in the model are limited to establishing logical relationships between variables so that the maintenance process is captured properly. For instance, if a maintenance action is applied, performance and service levels should be restored accordingly, and expenses recorded. Hence, as there are no theoretical hypotheses in the model, its validation can be performed visually (i.e., there are no inconsistencies in how maintenance decisions affect performance and cash-flows). The accuracy of the model to describe real situations, however, depends strictly on its input information; i.e., on the parameters that describe deterioration, costs, benefits, etc., which may be thoroughly estimated for realistic case studies. Conditions related to minimum performance and profit threshold can drastically affect solutions, but that responds to the purpose of the proposed methodology: being able to estimate the impact of such conditions *in silico*, prior to the implementation of large-scale projects. The construction of a case study with emphasis on parameter estimation is currently being carried out, applying data analysis on public databases in Colombia.

Illustrative example

This section presents a simple yet general example of a PPP between the government (i.e., the principal) and a private contractor (i.e., the agent) to maintain a road for 30 years. The purpose of the example is to illustrate the potential of the proposed methodology to produce relevant analyses for projects and policy on PPPs. The proposed model has the potential to provide concrete numerical results (which may vary significantly on a case-by-case basis), but their relevance depends on the accuracy and completeness of the input parameters. Most parameters in this illustrative example are informed from available documentation regarding large infrastructure projects via PPPs for the so-called fourth generation (4 G) of concessions in Colombia (CONPES 2013), while others are estimated using sensitivity analysis as part of the proposed academic exercise. Therefore, the focus of this section, rather than pursuing a numerical result, is on how the optimization model can be used in multiple ways to analyze how the conditions surrounding PPPs shape the decisions of both parties, and how these, in turn, have an effect on the system's performance and associated economic outcomes.

Cash-flows for the principal and the agent are at the core of the problem (as this drives their utility function and decisions) along with deterioration (which drives maintenance policies). The example assumes that the agent agrees on a fixed income with the principal, and may obtain additional income due to the usufruct of the road (e.g., via tolls), or funding from financial institutions (as is the case in Colombian 4 G sample contract payment structures); discount rates are based on literature analysis. The costs incurred by the agent due to maintenance actions are project-specific and not available in public data. In this example, these values were set as a ratio with respect to the income. Road deterioration is highly dependent on design, construction technologies, and environmental conditions, for which precise estimations exceed the scope of this paper. Hence, exponential deterioration functions are used to illustrate the model's capabilities. After setting initial parameters based on literature Villarreal (2005), and expert-opinion, sensitivity analysis were performed, yielding intuitive variations (e.g., infeasibility when maintenance costs are too high; infrequent maintenance for mild deterioration), but no significant impact on the general logic of the model which may affect the proposed analyses. With all parameters set to values that reflect a normal maintenance process, we proceed to perform analyses that address the effect of the minimum performance threshold, k, the minimum profit threshold, ϵ, and the potential performance related incentives.

Exploring the joint feasibility space

The minimum performance threshold, k, and the minimum profit threshold, ϵ, are crucial parameters in defining trade-offs between the principal and the agent, thus, being critical in the negotiation of contractual conditions. A sensitivity analysis is performed on these parameters by running the optimization model from the perspective of the principal and the agent in order to construct a joint feasibility space; i.e., the ranges of k and ϵ where agreements are possible. Table 2 presents a summary of such analysis, showing that the agent is able to achieve all of the considered return targets up to a performance threshold of 0.6; beyond this value, the problem becomes infeasible for the agent. Analyses of this kind can help governments and companies make informed decisions when embarking on PPPs (e.g., by fine-tuning requirements such that benefit for society can be pursued while still making projects attractive for companies).

Assessing the impact of diverging objectives

The divergence in the objective functions of the principal and the agent can cause optimal maintenance plans to be significantly different when solving from each party's perspective. Analyzing how far these solutions are from each other, and their associated economic impact, is of interest for two reasons. First, even if a minimum desirable performance can be theoretically imposed to the agent via model constraints, it is expensive to monitor and enforce such constraint in practice, thus, opening the possibility for violations of the threshold (most critically in institutionally weak contexts). Second, even if the agent converges to a solution that complies with the minimum performance, it is often possible to find solutions that yield a better objective for the principal without affecting the agent, or affecting it to a lesser extent (allowing win-win compensation schemes). The proposed methodology can be used to assess the impact of diverging objectives on the optimal maintenance plan, as well as its effect on the outcomes of the principal and the agent. Figure 3 shows the performance of the road when solving from the perspective of both actors for four different cases:

1. The minimum performance constraint is not imposed and the agent's income does not depend on performance. In this case, the agent chooses not to apply maintenance actions, while the principal regularly does so (more intensively in later years due to the discount rate).
2. The minimum performance constraint is imposed and the agent's income does not depend on performance. In this case, the agent strictly satisfies the constraint.
3. The minimum performance constraint is not imposed, but the agent's income depends on performance. This is the most interesting case, as this drives the agent towards a solution similar to the principal's without incurring the effort it would take to enforce the constraint in practice.

Table 2. Analysis of the joint feasibility space for the principal (regarding its performance threshold k) and the agent (regarding its target profit ϵ). The tuples in each cell indicate the objective function obtained for the principal and the agent in monetary units, while the cases that lead to infeasibility are denoted with *Inf*.

ϵ / k	0.35	0.45	0.55	0.6	0.65
0.2	(424, 66)	(424, 66)	(424, 66)	(424, 66)	Inf
0.4	(424, 114)	(424, 114)	(424, 114)	(424, 113)	Inf
0.6	(416, 149)	(416, 149)	(416, 149)	(416, 148)	Inf
0.8	(396, 176)	(396, 176)	(412, 176)	(408, 173)	Inf
1	(380, 197)	(380, 197)	(396, 197)	(408, 173)	Inf
1.4	(328, 229)	(372, 228)	(380, 218)	(408, 173)	Inf
1.6	Inf	Inf	Inf	Inf	Inf

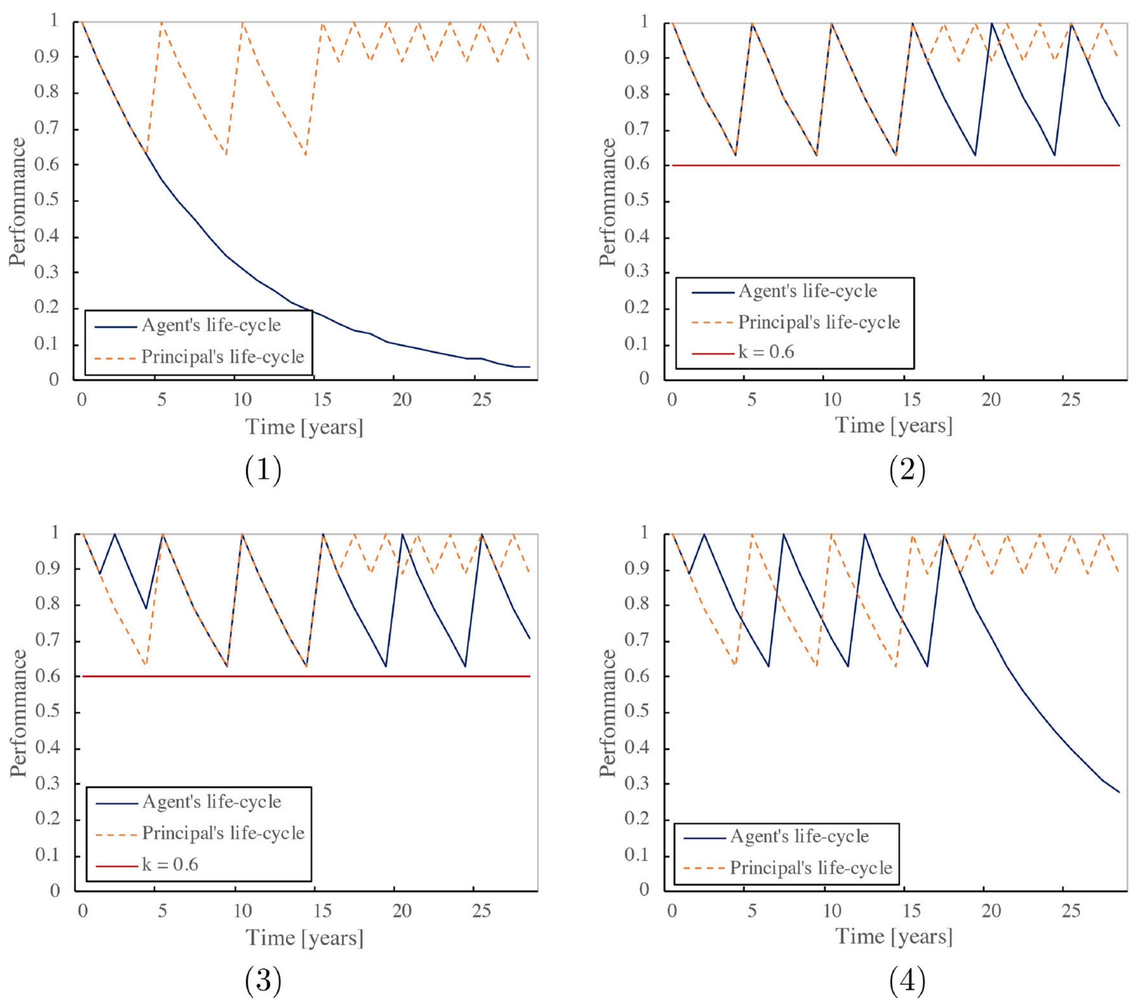

Figure 3. Life cycle of the road from the perspective of the principal and the agent for four cases: (1) no performance constraint and no incentives; (2) performance constraint and no incentives; (3) no performance constraint and incentives; (4) performance constraint and incentives.

4. The minimum performance constraint is imposed and the agent's income depends on performance. In this case, the agent sticks to the constraint and occasionally engages in slightly superior performance.

As shown in Figure 3, different maintenance plans can be obtained depending on whose utility function is prioritized, leading to different economic outcomes for the involved parties. Table 3 shows the objective function that the principal and the agent would obtain under the implementation of their own and each other's maintenance plan (considering the case in which the performance constraint is imposed and there are no performance-related incentives). The results show that the principal would lose 180 units in its utility function if the agent's maintenance plan is implemented, whereas the agent would lose 297 units if the principal's maintenance plan is implemented. In both cases, adopting the opposite party's solution causes a significant impact, which makes those solutions unattractive for negotiation. Therefore, it is important to explore middle-ground solutions that may offer more attractive alternatives, which is the purpose of Section "**Searching for win-win compensation schemes**".

Searching for win-win compensation schemes

Section "**Assessing the impact of diverging objectives**" showed how optimal maintenance plans change in the absence of a minimum performance threshold (or under the failure to monitor and enforce such constraint in practice), and how performance-related incentives may be effective at pushing agent's optimal solutions towards higher service levels. The natural subsequent question is: are such incentives viable for implementation (i.e., can the principal afford them), and how can they be calculated towards win-win arrangements? This section illustrates the heuristic procedure presented in Section "**Methodological steps to use the model for analysis**" (Figure 4), which performs repeated runs of the proposed optimization model imposing concessions of different magnitudes from both the principal and the agent (i.e., progressively allow larger sacrifices in their objective functions). From the resulting set of "middle-ground solutions", it is possible to find alternatives in which the gain for one party outweighs the loss of the other and choose the one that does so to a larger extent.

Table 3. Outcomes for the principal and the agent under the optimal maintenance plan obtained from the perspective of each.

	Outcome for principal	Outcome for agent
Principal's best maintenance plan	456	22
Agent's best maintenance plan	276	319

Figure 4 shows the magnitude of gains and losses for the principal and the agent with respect to their unilateral optima for different values of β (i.e., concessions of different magnitude). The main insight from the figure is that there is no shortage of solutions in which gains for one party exceed the losses of the other, and that, in some cases, large improvements for the principal can be achieved with little detriment to the agent. This occurs because the benefit derived from high-performing infrastructure includes long-term macro-economic factors and externalities; hence, under pessimistic valuations of such economic benefits, the investments towards higher-performing infrastructure could not be justified as easily. A key takeaway, however, is that the PPP relationship is not a zero-sum game, thus, opening opportunities for creating shared value. These results clearly depend on input parameters and, therefore, are not meant to be generalizations. Instead, they show how the proposed quantitative models may help discover alternatives that improve the state of affairs. In this case, the maintenance plan that results when the agent allows to sacrifice a 60% (short blue bar at 60%) of its objective function is largely out-weighted by the additional benefit obtained by the principal (tall orange bar at 60%).

The presented analyses provide simple illustrations of the potential of the proposed model to enrich design and implementation processes of PPPs in the context of infrastructure management, mainly, by allowing the principal to estimate how the agent would react to policy, regulation, and contractual conditions (although similar analyses can be made from the perspective of the agent). All models are Mixed Integer Programs and were implemented in Python, using Gurobi as a solver (which proved convergence to optimality for all runs). In computational terms, the most complex experiment is the third one, which

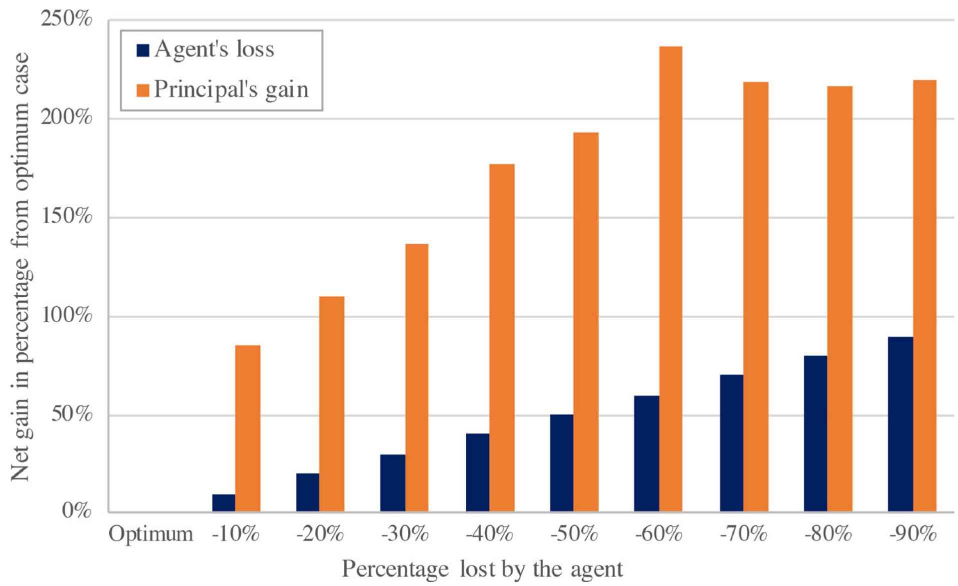

Figure 4. Net gains (positive or negative) for the principal and the agent for different middle-ground solutions (i.e., best agent solutions that respect best principal's solutions within β percent).

demands multiple runs of the exact model (one for each value of β). Each run takes about 20 seconds in a personal computer (Intel Core i7 @ 3 GHz; 16GB RAM), although runs differ in execution time. This means that even this demanding experiment can be run within minutes, which is reasonable for the long-term nature of the decisions it seeks to support. Computational complexity is sensitive to the number of discrete service levels and the periods in the planning horizon. In this example, these values were set to 5 levels and 30 years, which is arguably representative of the size expected for a realistic case. Computational complexity, thus, does not seem to be prohibitive or challenging at this scale.

Conclusions

We proposed an optimization-based methodology to model and analyze Public-Private-Partnerships (PPPs) in the context of infrastructure management, adopting a life-cycle performance framework, and considering the potential principal-agent problems that may arise due to divergent objectives of the public and private parties. The core of the methodology is an exact optimization model that describes the performance of a system of interest as function of a deterioration process and maintenance actions that are applied seeking to maximize a utility function from the perspective of either the public or private parties. Contractual or regulatory conditions (e.g., minimum performance thresholds, or performance-dependent incentives) can be included in the model, allowing to obtain different optimal maintenance plans, as these conditions change. As a result, it is possible to identify the strategies and economic outcomes for each party under a variety of technical, financial and organizational conditions. An illustrative example was presented in which parametric and scenario-based analysis are applied to evaluate the effect of key parameters and rules within a PPP. Additionally, a heuristic procedure was proposed to estimate win-win compensations for parties to agree on middle-ground solutions.

This research responds to the trans-disciplinary nature of infrastructure related problems, which demands an integrative understanding of the combined effects of natural, physical, and social phenomena. The proposed methodology captures the physical deterioration process of a system of interest, along with the costs and benefits associated to it throughout its life-cycle, and the surrounding organizational context (e.g., contracts, regulation), into an exact optimization model that opens avenues for innovative quantitative analyses for problems that, like PPPs, are an intricate blend of these diverse aspects. The incorporation of the principal-agent problem in PPPs within a comprehensive but simple quantitative model enables analyses that range from assisting either of the parties in the planning and negotiation of PPP contracts, to assisting the design and evaluation of policy related to infrastructure management via PPPs. The fundamental questions addressed by the proposed methodology are: how does an optimal maintenance plan look like from the perspective of either the public or private parties given some performance requirements and payment structures? How much does one party's benefit decrease if the other's optimal maintenance plan is adopted, given some contractual conditions? These analyses are useful to estimate the extent of the conflict of interest that may arise between the parties, and whether surrounding conditions (e.g., contractual) may lessen or magnify that conflict, thus, providing evidence for contract or policy design. Furthermore, by running the model repeatedly, it is possible to estimate adequate values for parameters or to explore win-win alternatives in public-private negotiations. For instance, running the model for different performance thresholds can help determine which value better satisfies both parties. Similarly, the model can obtain the best solution for one party, subject to respecting the other party's optimum within a specified tolerance. Hence, by running for different tolerances, it is possible to choose the middle-ground solution in which the loss of one party can be compensated by the other's gain, thus, providing evidence for incentive design. For governments and companies, the proposed methodology enables a variety of *what-if* analyses that can inform contract design and negotiation, as well as strategic planning for project implementation. Finally, this methodology opens opportunities to further develop the model with more specific aspects regarding, for example, deterioration processes, financial instruments (such as credit), regulatory contexts, etc.

The proposed methodology opens future work in the analysis of PPPs and infrastructure management by providing an optimization model that can be used as a simulation engine, i.e., as a black box in which repeated runs can enable experimentation with deterioration, payment structures, or contractual conditions, and evaluating their effect on the parties' strategies and outcomes. Ongoing research is devoted to tackling the main limitations of the current model, namely: applying strategies to solve integer bi-level problems in order to simultaneously model the coupled decisions of both parties; extend the model to a stochastic version and include analyses of the effect of uncertainty on performance and outcomes; and construct a case study with a realistic parameter estimation based on data analysis of publicly available information of PPP contracts.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Antoniou F, Aretoulis G. 2019. A multi-criteria decision-making support system for choice of method of compensation for highway construction contractors in Greece. Int J Constr Manage. 19(6):492–417.

Barker K, Haimes YY. 2009. Assessing uncertainty in extreme events: Applications to risk-based decision making in interdependent infrastructure sectors. Reliab Eng Syst Saf. 94(4):819–829.

Biondini F, Frangopol DM. 2018. Life-cycle performance of civil structure and infrastructure systems: Survey. J Struct Eng. 144(1):06017008.

Buxbaum JN, Ortiz IN. 2009. Public sector decision making for public-private partnerships. Vol. 391. Washington, D.C.: Transportation Research Board.

Castiblanco D. 2011. Managing infrastructure through incentives. Bogotá: Universidad de los Andes.

Castiblanco D, Gómez C, Faber M, Sánchez-Silva M, Dueñas-Osorio L. 2012. Organizational issues on decision-making for temporary activities in the context of infrastructure management. In: International Forum on Engineering Decision Making; 6th IFED Forum January 26-29, 2012 ; Lake Louise, Canada.

Cecchini M, Ecker J, Kupferschmid M, Leitch R. 2013. Solving nonlinear principal-agent problems using bilevel programming. Eur J Oper Res. 230(2): 364–373. http://www.sciencedirect.com/science/article/pii/S0377221713003123.

CONPES. 2013. Proyectos Viales bajo el esquema de asociaciones público privadas: Cuarta generación de concesiones viajes (Documento Conpes 3760). Consejo Nacional de Política Económica y Social - Departamento Nacional de Planeación - República de Colombia.

Corotis RB. 2009. Societal issues in adopting life-cycle concepts within the political system. Struct Infrastruct Eng. 5(1):59–65. https://doi.org/10.1080/15732470701322867.

Cui C, Liu Y, Hope A, Wang J. 2018. Review of studies on the public–private partnerships (ppp) for infrastructure projects. Int J Project Manage. 36(5): 773–794.

De Palma A, Leruth L, Prunier G. 2012. Towards a principal-agent based typology of risks in public-private partnerships. Reflets et Perspectives de la Vie Economique. LI(2):57–73.
Debela GY. 2019. Critical success factors (CSFs) of public–private partnership (PPP) road projects in ethiopia. Int J Constr Manage. 1–12. https://doi.org/10.1080/15623599.2019.1634667.
Gama Dessavre D, Ramirez-Marquez JE, Barker K. 2016. Multidimensional approach to complex system resilience analysis. Reliab Eng Syst Saf. 149: 34–43. http://www.sciencedirect.com/science/article/pii/S0951832015003610.
Thomas JE, Eisenberg DA, Seager TP, Fisher E. 2019. A resilience engineering approach to integrating human and socio-technical system capacities and processes for national infrastructure resilience. J Homeland Secur Emergency Manage. 16(2):1–17.
Ellingwood BR, Lee JY. 2016. Life cycle performance goals for civil infrastructure: intergenerational risk-informed decisions. Struct Infrastruct Eng. 12(7):822–829. .
Faber MH, Stewart MG. 2003. Risk assessment for civil engineering facilities: critical overview and discussion. Reliab Eng Syst Saf. 80(2):173–184. https://www.sciencedirect.com/science/article/pii/S0951832003000279.
Frangopol DM. 2011. Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges. Struct Infrastruct Eng. 7(6):389–413.
Frangopol DM, Furuta H. 2001. Life-cycle cost analysis and design of civil infrastructure systems. Reston, VA, USA: American Society of Civil Engineers. https://ascelibrary.org/doi/abs/10.1061/9780784405710.
Frangopol DM, Kallen M-J, Noortwijk J. M v. 2004. Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. Prog Struct Engng Mater. 6(4):197–212. https://onlinelibrary.wiley.com/doi/abs/10.1002/pse.180.
Frangopol DM, Soliman M. 2016. Life-cycle of structural systems: recent achievements and future directions. Struct Infrastruct Eng. 12(1):1–20.
Furuta H, Frangopol DM, Akiyama M. 2014. Life-cycle of structural systems: design, assessment, maintenance and management. London: CRC Press.
Gomez C, Baker JW. 2019. An optimization-based decision support framework for coupled pre- and post-earthquake infrastructure risk management. Struct Saf. 77:1–9.
Gómez C, Sánchez-Silva M, Dueñas-Osorio L. 2014. An applied complex systems framework for risk-based decision-making in infrastructure engineering. Struct Saf. 50:66–77.
González AD, Dueñas-Osorio L, Sánchez-Silva M, Medaglia AL. 2016. The interdependent network design problem for optimal infrastructure system restoration. Comput-Aided Civ Infrastruct Eng. 31(5):334–350. http://dx.doi.org/10.1111/mice.12171.
Guasch JL, Laffont J-J, Straub S. 2008. Renegotiation of concession contracts in latin america: evidence from the water and transport sectors. Int J Ind Organ. 26(2):421–442.
Hong S. 2016. When does a public–private partnership (ppp) lead to inefficient cost management? evidence from South Korea's urban rail system. Publ Money Manage. 36(6):447–454.
Jayasuriya S, Zhang G, Jing Yang R. 2019. Challenges in public private partnerships in construction industry: a review and further research directions. Built Env Proj Ass Manage. 9(2):172–185.
Jienan G, Shengyue H, Xu R. 2017. Influencing factors of the early contract termination under the public-private partnerships mode. In Forum on science and technology in China. Beijing: Editorial Department of China Science and Technology Forum. p. 16–17.
Klijn EH, Koppenjan J. 2016. The impact of contract characteristics on the performance of public–private partnerships (ppps). Publ Money Manage. 36(6):455–462.
Leruth LE. 2012. Public-private cooperation in infrastructure development: a principal-agent story of contingent liabilities, fiscal risks, and other (un) pleasant surprises. Netw Spat Econ. 12(2):223–237.
Li B, Akintoye A, Edwards PJ, Hardcastle C. 2005. Critical success factors for ppp/pfi projects in the uk construction industry. Constr Manage Econ. 23(5):459–471.
Ling FYY, Kumaraswamy MM, Dulaimi MF, Khalfan M. 2011. Public private partnerships: overcoming pre-contract problems faced by public clients and private providers in infrastructure projects in singapore. Int J Constr Manage. 11(1):63–77.
Liu C, Fan Y, Ordóñez F. 2009. A two-stage stochastic programming model for transportation network protection. Comput Oper Res. 36(5):1582–1590. http://www.sciencedirect.com/science/article/pii/S030505480800052X.
Liu J, Gao R, Cheah CYJ, Luo J. 2016. Incentive mechanism for inhibiting investors' opportunistic behavior in ppp projects. Int J Project Manage. 34(7):1102–1111.
Lozano J-M, Sánchez-Silva M. 2019. Improving decision-making in maintenance policies and contract specifications for infrastructure projects. Struct Infrastruct Eng. 15(8):1087–1102.
Medda F. 2007. A game theory approach for the allocation of risks in transport public private partnerships. Int J Project Manage. 25(3):213–218.
Miao X, Yu B, Xi B, Tang Y-h. 2010. Modeling of bilevel games and incentives for sustainable critical infrastructure system. Technol Econ Develop Econ. 16(3):365–379.
Mostafavi A, Abraham D, DeLaurentis D. 2014. Ex-ante policy analysis in civil infrastructure systems. J Comput Civ Eng. 28(5):A4014006.
Mostafavi A, Abraham D, DeLaurentis D, Sinfield J, Kandil A, Queiroz C. 2016. Agent-based simulation model for assessment of financing scenarios in highway transportation infrastructure systems. J Comput Civ Eng. 30(2):04015012.
Ng ST, Xie J, Cheung YK, Jefferies M. 2007. A simulation model for optimizing the concession period of public–private partnerships schemes. Int J Project Manage. 25(8):791–798.
Osei-Kyei R, Chan APC. 2015. Review of studies on the critical success factors for public–private partnership (ppp) projects from 1990 to 2013. Int J Project Manage. 33(6):1335–1346.
Osei-Kyei R, Chan APC. 2017. Implementing public–private partnership (ppp) policy for public construction projects in ghana: critical success factors and policy implications. I J Constr Manage. 17(2):113–123.
Ouyang M. 2014. Review on modeling and simulation of interdependent critical infrastructure systems. Reliab Eng Syst Saf. 121:43–60. https://www.sciencedirect.com/science/article/pii/S0951832013002056.
Ouyang M, Fang Y. 2017. A mathematical framework to optimize critical infrastructure resilience against intentional attacks. Comput-Aided Civ Infrastruct Eng. 32(11):909–929. http://doi.wiley.com/10.1111/mice.12252.
Paez-Perez D, Sanchez-Silva M. 2016. A dynamic principal-agent framework for modeling the performance of infrastructure. Eur J Oper Res. 254(2): 576–594.
Percoco M. 2014. Quality of institutions and private participation in transport infrastructure investment: evidence from developing countries. Transp Res Part A: Policy Pract. 70:50–58.
Renner P, Schmedders K. 2015. A polynomial optimization approach to principal–agent problems. Econometrica. 83(2):729–769.
Riascos-Ochoa J, Sánchez-Silva M, Klutke G-A. 2016. Modeling and reliability analysis of systems subject to multiple sources of degradation based on Lévy processes. Probab Eng Mech. 45:164–176. https://www.sciencedirect.com/science/article/pii/S0266892016300704.
Roos D, de Neufville R, Moavenzadeh F, Connors S. 2004. The design and development of next generation infrastructure systems. Systems, Man and Cybernetics, 2004 IEEE International Conference on; vol. 5. p. 4662–4666.
Sanford Bernhardt KL, McNeil S. 2008. Agent-based modeling: approach for improving infrastructure management. J Infrastruct Syst. 14(3):253–261.
Scharle P. 2002. Public-private partnership (ppp) as a social game. Innovation: The European J Social Sci Res. 15(3):227–252.
Shrestha A, Martek I. 2015. Principal agent problems evident in chinese ppp infrastructure projects. Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate; Springer. p. 759–770.
Tariq S, Zhang X, Leung RHM. 2019. An analytical review of failed water public–private partnerships in developing countries. Proc Inst Civil Eng-Manage, Procurement and Law. 172(2):60–69.
van Noortwijk JM, Frangopol DM. 2004. Two probabilistic life-cycle maintenance models for deteriorating civil infrastructures. Probab Eng Mech. 19(4):345–359. https://www.sciencedirect.com/science/article/pii/S0266892004000347.
Villarreal J. 2005. The cost of capital in projects of basic civil infrastructure (IB). A practical example: the WACC for an airport concession. Revista de Ingeniería. 21:19–29.
Wu D, Yin Y, Lawphongpanich S. 2011. Optimal selection of build–operate-transfer projects on transportation networks. Transp Res Part B: Methodol. 45(10):1699–1709.
Zhang P, Peeta S, Friesz T. 2005. Dynamic game theoretic model of multi-layer infrastructure networks. Netw Spat Econ. 5(2):147–178.
Zou PXW, Zhang G. 2009. Managing risks in construction projects: life cycle and stakeholder perspectives. Int J Constr Manage. 9(1):61–77.