Innovation and tariff-adjustment options in public-private partnerships

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1. Introduction

There are numerous instruments that the public sector uses to indirectly boost innovation such as offering tax credits, setting regulations and standards that incentivise new ways of doing certain things, and creating markets for innovative ideas. Even more indirectly, public sector can also support education and training and can enhance capacities for knowledge exchange. But the public sector also takes direct measures to spur innovation, for example by funding R&D for specific projects. In addition, public agencies may demand new products for its own use or for the use of third parties. This is what is known today as public procurement for innovation (PPI) (and previously as public technology procurement (PTP), Edquist *et al*. 2000). PPI occurs when a public organization places an order for the fulfillment of certain functions within a reasonable period of time through a new product. There is consensus in the importance of public procurement not only for achieving greater efficiency in public sector spending but also as a vehicle for innovation and economic development. It has been repeatedly stated that PPI is an important policy instrument (Rothwell and Zegveld, 1981, Geroski, 1990, Dalpé, 1994, Edler and Georghiou, 2007, Edquist, 2011, Brammer and Walker, 2011, Tsipouri, 2015 or Uyarra *et al*., 2020) and that the rationale for using public procurement lies in the overall importance of demand-side activities to support innovation (Lundvall 1988; Gregersen 1992; Edquist 2005, Timmermans and Zabala-Iturriagagoitia, 2013).

In recent times there has been a re-emergence of mission-oriented innovation policies for tackling "grand societal challenges" such as climate change and aging societies (Fagerberg *et al*, 2016, Chicot and Matt, 2018), while the concept of innovation is being refocused from a purely technological field to a more open definition (Weber and Rohracher, 2012 and Kattel and Mazzucato, 2018). In this context, innovation in public-private partnerships (PPPs) is becoming of central interest in discussions about social welfare and productivity growth.

On the one hand, a PPP can be broadly defined as an arrangement that brings public and private sectors together in long-term partnerships for mutual benefit (HM Treasury, 2000). A hallmark of procurement through PPPs is the bundling of functions in construction and operation of infrastructure assets. The integration of the life cycle of activities around an asset relating to its design, construction, financing, operation and maintenance may encourage the private consortium to develop innovative thinking to exploit synergies and positive externalities. This is why public-private partnerships can achieve value for money in public spending.

On the other hand, innovation is not a very precise term. Just as many other aspects in management and life, it means different things to different people (Von Stamm, 2003). Among many definitions, one of the most common is from The Oslo Manual, which defines innovation as the implementation of a new or significantly improved product (good or service), or a process, new marketing method, or a new organisational method in business practices, workplace organisation or external relations. Successful innovation results in significant improvements in outcomes efficiency, effectiveness or quality (Albury, 2005).

In binomial innovation/public-private partnerships (PPPs) there are two issues that deserve attention from the economic literature. Firstly, how can PPP schemes be used to exploit R&D projects? A number of papers focus on this approach (e.g. Tawiah and Russell, 2008; Lember *et al.*, 2014, 2015; Scherrer *et al*., 2016). Secondly, what are the factors that promote or inhibit the introduction of innovations in the construction of public infrastructures and in the provision of public services through PPPs? In the same vein, how are grantor governments affected by innovation in PPPs? This paper addresses the second type of questions. In particular, an attempt is made to assess whether the introduction of options for adjusting fees paid by the public sector can increase the likelihood of available innovations being implemented and reduce opportunity costs for grantor governments

Many public management reforms and programmes identify innovation as their primary goal (Considine and Lewis, 2007). The use of PPPs to build and operate infrastructure aims to incorporate not only the private sector's capital, expertise and risk management, but also its creativity and efficiency. The increasing weight of the public-private partnership as a method of infrastructure delivery in many countries helps explain the growing interest in encouraging the introduction of innovation in PPPs projects.

Uncertainty about the frequency of the emergence of innovations and the magnitude of their impact in long-term concessions is usually high. Innovations may alter the risks assumed by the partners in a PPP. If a solution is not implemented, emerging technologies that impact on revenues or costs may lead to an over-or-under transfer of benefits to the private partner. As a result, initial bidding prices may be sub-optimal and if the concession's contract does not adequately address risk allocation, innovations that would otherwise have been applied may not be implemented. Figure 1 shows the possible impact of risks arising from the emergence of innovations in the absence of tariff-adjustment options.

Figure 1: Risks arising from the emergence of innovations in PPP value for money

Positive and negative effects on revenues and costs of concessionaires resulting from the adoption of technological changes are varied. Table 1 shows some examples for four industries: transport, energy, education and healthcare.

Table 1. Examples of how technological changes impact on concessionary firms' profitability

In PPP projects, contracts are usually long-term and uncertainty about the evolution of certain economic variables affecting income and expenditure can be high. As a result, competition from private partners in tenders may be low. In such cases, governments may grant concessionaires the right to extend or shorten the concession term in certain circumstances or, alternatively, provide them with a minimum income guarantee. On the contrary, when innovations may alter the evolution of operating costs, governments may face significant opportunity costs. To the extent that concessionaires may benefit from large productivity gains, grantor governments would like to reserve the option of early termination of concession contracts or to adjust governmental payments in certain circumstances.

This paper explores the question of whether the inclusion in PPP contracts of options to adjust economic conditions in the face of technological changes may help the adoption of such innovations while reducing the opportunity cost for governments. In particular, the type of option envisaged offers the grantor government the right to cut its payments to the concessionaire when the latter implement technological innovations with a reducing effect on operating costs. The paper addresses the existing gap in the literature regarding the analysis of uncertainty associated with the adoption of innovations in PPPs and the role that options may have in this context. This framework is not exclusive of PPP contracts and can be extended to management contracts as the innovation is not considered to affect the construction stage, but the operation of the infrastructure. We consider a project in which the government pays an annual fee to the private partner to provide a given service to citizens. If a technological innovation that significantly reduces the operating costs of a project occurs, the grantor government is in a better position if it has the option to shorten the concession period and re-tender the project or, alternatively, if it has the right to adjust the economic terms of the concession. Tariff adjustment options can be more efficient than early termination options as they avoid the costs of re-bidding. In addition, tariff-adjustment options may avoid renegotiation processes that involve negotiation costs, may raise doubts about the validity of the concession model and may indicate excessively opportunistic behaviour on the part of governments, with a consequent impact on reputation (Guasch, 2004, Guasch *et al*., 2006 and 2007). Moreover, the likelihood of renegotiation failure may not be small if the enforcement mechanism is not very effective (Laffont, 2003).

Taking a pragmatic approach, it is assumed that innovation occurs outside the scope of PPP projects and concessionaries have to decide whether or not to implement new technologies becoming available on the market. In the proposed model, innovations occur over time stochastically and their impact on operating costs is also stochastic in nature. As technological innovations take place, tariffs paid by the government are adjusted downwards, so that the concessionaire benefits partially from productivity improvements.

The paper is of interest given that digital transformation and *robotization* can generate relevant productivity improvements in areas where a significant part of the public budget is spent, such as health and education services. Moreover, the topic is relevant since every year new social services in these areas are provided under PPP agreements. The model considers discrete time, as in practice contracts for early termination and economic rebalancing options are exercisable at specific points in time, usually on an annual basis.

One may think that a major limitation of the paper consists of ignoring that private operators may have hidden information about operating costs. The issue of asymmetric information has been profusely treated in the literature on public procurement. However, in the context of the analysis, private partners in a PPP do not have hidden information or influence on the circumstances that give rise to technological developments (e.g. new developments in the Internet of Things, virtual and augmented reality, developments in artificial intelligence, new devices for online communication, etc.). It is assumed that innovation events occur at the margin of both the grantor government and the private partner, so that once a new technology reaches the market its applications and its cost of integration are in the public domain.

This paper delves into the issue of the inherent uncertainty in PPPs in connection to the question of innovation. The paper adds to the existing literature in a number of ways. To our knowledge, no other study exists that quantifies the impact of introducing tariff-adjustment options in PPPs where the concessionaire may decide to implement technological innovations. Research on the application of real option theory to PPP arrangements when operating costs "jump" over time is scarce. This study contributes to the body of knowledge by making novel use of the Poisson probability distribution in this context.

The remainder of the paper is organized as follows. In Section 2 we position this work within the literature. In section 3 we present the model. In section 4 some theoretical results are derived. In Section 5 we provide some numerical simulations to illustrate the merit of the proposed model. The paper concludes in Section 6 with some final comments.

2. Related literature

This paper can be positioned at the intersection of several strands of the literature.

Strictly speaking, it does not integrate with any of the three main lines of the literature on PPI that Obwegeser and Müller (2018) has categorized: i) public procurement for innovation (PPfI); ii) public procurement of innovations (PPoI); and iii) innovative public procurement (IPP). However, as highlighted below, this paper has some common features with this literature.

A variety of PPI taxonomies have been developed (Edler, 2009; Hommen and Rolfstam, 2009; Uyarra and Flanagan, 2010). Traditionally, procurement has been classified in two types: normal vs. innovative. In *regular procurement*, public agencies buy products or services in which no innovation is involved, such that only the price and the quality are taken into account when selecting the supplier. In contrast, in a PPI the development of new products or the dissemination of innovations is an integral part of the programme from the very start of the procurement process. Uyarra and Flanagan, 2010 consider, however, that we should be cautious in dividing up procurement into these two mutually exclusive categories. Our article is a good example of this, as it investigates how a regular PPP, whose contract includes certain options, could incentivise the adoption of innovations.

In connection with pure IPPs, a distinction has been made between those focusing on the missions or needs of the procuring agency and those aimed at supporting innovation across the economy. Our article is closer to the latter as it proposes to introduce certain clauses in PPP contracts to ensure that private partners incorporate innovations that occur in the market, without determining what kind of innovations should be adapted.

On an alternative taxonomy where the relevant dimension refers to whom the user of the resulting product good, service or system is, procurements can be categorized as direct or catalytic (Edquist y Zabala-Iturriagagoitia, 2012). Arguably, by introducing certain clauses as we propose in our paper a PPP may become a catalytic IPP, as the public agency acts to catalyse the development of innovations for wider public use.

According to a second dimension that refers to the character of the result of the procurement process, three types of PPI categories have been identified (Edquist y Zabala-Iturriagagoitia, 2012): i) pre-commercial procurement (PCP) that refers to the procurement of expected research results and is a matter of direct public R&D investments; ii) developmental or creation oriented PPI that aims radical innovation and iii) adaptive or diffusion oriented PPI. The proposal included in this paper would be in the spirit of the latter type.

In addition, according to Cave and Frinkin's, 2003 terminology, our proposal drives *indirect demand-pull impacts*, where innovation is a by-product of government procurement. And according to Cabral *et al*'s (2006) classification of the types *of indirect influence* of public procurement on innovation, our proposal would refer to those that facilitate the adoption of new standards.

Our paper is also in line with the consideration that public procurement may responds to a multi-objective policy, the main objective of which is to ensure the quality of public services and the use of products and services for the public sector, but where innovation can be an explicit secondary objective in certain instances. As Uyarra and Flanigan, 2010 have highlighted it is clear then that procuring 'goods and services that do not exist' is not always a necessary condition and is by no means a sufficient one to generate systemic impacts. We argue in favour of a broader interpretation that recognises that public procurement serves specific public needs and that innovation should be encouraged, where possible, as a 'by-product' of the procurement process.

Edler and Georghiou (2007) also distinguishes between the *general procurement* practice and the *strategic procurement*. In the first, government procurement is organised such that innovation becomes an essential criterion in the election of suppliers. In the second, the demand for certain technologies, products or services is encouraged in order to stimulate the market. The proposal included in this paper would be in the spirit of the *strategic procurement.*

Finally, Lembert *et al.* (2014) point out that there is a need to take into account wider strategic factors through which governments create capacity to undertake PPI and they envision four strategies for the future: i) PPI as experimental innovation policy; ii) from fiscal policy under austerity to PPI; iii) mission-oriented PPI and iv) shifts in administrative culture towards PPI. Our work would be proposing a fifth strategy aimed at managing regular PPPs with the consideration of fostering innovation.

The number of studies on effects and possible solutions when there is uncertainty in PPP projects is far from scarce in the economic literature. One solution explored in this context has been the explicit introduction of options in PPP contracts. This paper is in the line of the already extensive research using real option valuation applied to PPPs.

The mechanism analysed in this paper also falls within the scope of the debate between the price cap and the rate of return regulation. On the one hand, the price cap regulation limits the highest price the concessionaire could possibly charge in each year of the concession for the services it provides at the minimum required standards. Some incentive schemes have incorporated profit sharing into price caps. This incentive regulation aims to ensure that, at least in some circumstances, shareholders and/or managers of the regulated firm are better off if production costs are reduced. On the other hand, the rate of return regulation, determined in part based on the cost of capital to the industry to which the project belongs, considers the ‘necessary’ costs to set the required level of revenues. The price is regulated to ensure that the resultant revenues are just sufficient to cover the costs incurred. If the revenues are less than the required amount, the price will be increased and/or the excessive revenues in previous years are used to compensate for the revenue shortage in the current year, and to ensure adequate revenues for future years. Conversely, revenues in excess of the required amount are reverted to the public sector and/or prices are frozen or even reduced for the following years. Since there are both advantages and drawbacks to both systems, in practice, hybrid regulation schemes are often adopted. See Laffont and Tirole (1993), Ergas and Small (2001), Cowan, 2002, Carbonara *et al.* (2016) and many others.

Finally, the topic of this paper is related to the literature investigating the existence and the consequences of innovation when the PPP method is used in the provision of social services. Innovations that can be implemented in a PPP project include a wide range of creative ideas, from minor incremental improvements (Bugge and Bloch, 2016 and Fuglsang, 2010) to disruptive or transformative innovations that completely alter or replace processes or services (Osborne and Brown, 2011). In particular, these innovations basically concern new or improved services, new ways to deliver services, new processes, and changes in administrative and organizational systems. One of the key arguments in favor of PPPs is that new technologies tend to be earlier applied into infrastructures and social service projects when the manager is a private partner. On the contrary, it has been argued that in the traditional procurement method, the adoption of new technologies may be delayed. Table 2 shows a summary of findings by papers that focus on the factors that encourage and restrain the adoption of innovations in PPP projects. Some scholars find that private partners are able to provide better and more innovative solutions to deliver infrastructure and services but other conclude that it does not always happen.

Table 2. Some studies on the implementation of innovations in PPP projects

In contrast to our paper, none of the mentioned studies in Table 1 make use of a probability distribution relative to innovation events nor apply an option pricing method.

3. Model description

We consider a public procurement model with two players: a concessionaire firm and a governmental agency that tenders a PPP project for the provision of a social service (e.g. schooling). The provision of this service involves the construction of an infrastructure asset (e.g. a school building) by the concessionaire with a cost of C. At the end of the concession period, the asset reverts free of charge to the public sector. For simplicity's sake, we suppose that the construction can be instantaneously carried out. The expected return on equity by concessionaire shareholders to incur this cost must be at least r. In order to finance the construction cost, concessionaire shareholders provide equity E and borrow a bullet debt for the amount of L, such that $C = E + L$. The expected return r on the equity provided by concessionaire's shareholders equals the yield i of the concessionaire debt plus a required risk premium r, such that $r = i + z$. We assume that the temporal structure of interest rates is flat and stable; that shareholders of any new concessionaire have the same risk premium z over time, being this independent of the concession's term. In a low interest rate regime, such as the current one, these assumptions do not alter the results of the model. To simplify, the return on equity is calculated with a single final dividend that is the result of capitalizing cash flows at the risk-free rate. The credit spread of the debt issued by the concession firm is assumed to be nil. These assumptions significantly simplify the analysis, without altering the results of the model.

The evolution of the demand for educational services in the concession period is given by:

$$S = S_1 = S_2 = \cdots = S_n \qquad [1]$$

It is assumed that the school operates each year at the limit of its capacity and therefore, the annual number S of students is constant over time. This is an assumption that fits reality.

The concessionaire provides the service free of charge to the students and receives a certain amount α_t per pupil in year *t* from the government.

3.1. A scenario without technological innovations

In a scenario without technological innovation, the annual payment per student by the government can be written as

$$\alpha_t = \left(1 + \pi_{g,t}\right) \alpha_{t-1} \quad [2]$$

where the linear stationary process $\pi_{g,t}$ is assumed to be Gaussian. We make the additional assumption of $\pi_{g,t}$ being Markovian, with intercept and parameters, μ_g and ϕ_g respectively (see Contreras and Angulo, 2017).

The rationale for this public expense is that schooling provides a social utility per student β_t, such that

$$\beta_t = \left(1 + \pi_{g,t}\right) \beta_{t-1} = \beta_0 \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \quad [3]$$

and

$$E[\beta_t] = \beta_0 \left(1 + \mu_g\right)^t \quad [4]$$

It is assumed that β_t reflects the sum of individual utilities for those who benefit from education and the positive externality for society.

The utility of the government in annual period *t* can be expressed as

$$G_t = S\left(\beta_t - \alpha_t\right) \quad [5]$$

Therefore, the value of the concession for the government is given by

$$G = \sum_{t=1}^{n} G_t \left(1 + i\right)^{-t} \quad [6]$$

Note that for simplicity purposes, we ignore the tax collection arising from the net income of the concessionaire's firm, which is the same as assuming that the corporate tax rate $\tau = 0$. This assumption significantly simplifies the analysis, while the results are only marginally impacted.

In a context without innovations, the cash flow of the concessionaire in period t, B_t, is given by

$$B_t = S\,(\alpha_t - \gamma_t) - iL \quad [7]$$

for $1 \leq t < n$, where γ_t is the operating cost per student faced by the concessionaire in time t . This unit cost includes salaries of teachers, administrators and staff, as well as the cost of maintenance and renewal of equipment, such that

$$\gamma_t = \left(1 + \pi_{r,t}\right) \gamma_{t-1} \quad [8]$$

where $\pi_{r,t}$ denotes the specific inflation of the inputs used in the productive process of the relevant industry. Note that the concessionaire firm faces the risk of an adverse deviation between the expected values of the stochastic rate of change of the tariffs paid by the government $\pi_{g,t}$ and of its operating costs $\pi_{r,t}$. The linear Gaussian stationary process $\pi_{r,t}$ behaves according to an evolution with intercept $\mu_r \neq \mu_g$ (normally $\mu_r > \mu_g$). From now on, for simplicity, and without loss of validity, we assume that $\phi_g = \phi_r = 0$.

For period n, the concessionaire's cash flow will be given by

$$B_n = S\,(\alpha_n - \gamma_n\,) - (1 + i)L \quad [9]$$

Therefore, the value of the concession for the private partner is given by

$$B = -L + \sum_{t=1}^{n} B_t\,(1 + i)^{-t} \quad [10]$$

Note that in period n, the bullet loan is amortized.

3.2 Option type I: concessionaire's remuneration is reduced by a fixed proportion of the expected impact of technological innovations on costs.

In this section we consider a PPP contract that includes a clause according to which government payments are reduced by a fixed proportion of the expected impact of technological innovations on costs. This scheme is in the spirit of price caps regulation, but the private concessionaire may have an upside in profits if the impact of innovations on operating costs exceeds what was initially expected. The scheme requires an informational-weak condition since in order to apply a cut on the payments made to the concessionaire firm, the grantor government just needs to observe whether an innovation event (in particular, the implementation of an innovation) has occurred. Note that according to the concession contract, the concessionaire is not obliged to implement any innovation available on the market.

For the purpose of introducing the impact of technological innovations on costs, we assume the existence of a second component of costs. Non-recurring cost $\gamma_{a,t}$ starts with a zero initial value and adopts average negative values when technological improvements take place. We assume that the stochastic process of the occurrence of innovation events behaves according to a discrete Poisson stochastic function of λ parameter, appropriate for modeling the stochastic behavior of *rare events*. It is assumed that $\gamma_{a,t} = -\lambda \, c_t$ where c_t represents the expected average value of the economic impact of an innovation in period t. The starting value c_0 (for $t = 0$) can be expressed as $c_0 = \Omega_0 \, \gamma_0$ being γ_0 the starting value of the operating costs. Evidently, the proportionality Ω_t between c_t and γ_t does not remain constant over time. Although c_t is a random variable, which could be well described under a Gaussian density (with both positive and negative values possible), for the sake of simplicity, we consider here that it takes positive average values.

It is assumed that the impact on costs occurs in the same year that the technological innovations are implemented, and that the introduction of a new technology reduces the operating costs net of the expenses derived from its implementation. Therefore, if payments made by the government were not adjusted, there would be , an increase in the operating margin of the concessionaire firm. Our model considers however that the government has the right to reduce annual fees paid, in a proportion *x*, each time a technological innovation takes place. For each pair of values for λ and Ω_0, there is a value x^0 below which concession's managers have the incentive to implement new technologies when available. Above this value, the innovation will not be adopted in the relevant PPP project.

In a scenario with innovation the government annual payment per student will be given by

$$\alpha_t = \left(1 + \pi_{g,t}\right)(1 - x)^{w_{t-1}}\,\alpha_{t-1} \qquad [11]$$

As it seems reasonable, it is assumed that both relevant inflation rates, $\pi_{g,t}$ and $\pi_{r,t}$, are not correlated with Poisson's stochastic process. The non-negative integer number w_t describes the stochastic behavior of innovations and represents the number of such events occurring in period t, such that the probability $P_{k,t} = P[w_t = k_t]$ is given by

$$P_{k,t} = e^{-\lambda}\frac{\lambda^{k_t}}{k_t!} \qquad [12]$$

being λ a parameter representing the average number of innovations that occur annually. Therefore, $P_{0,t} = P[w_t = 0] \simeq 1 - \lambda$, $P_{1,t} = P[w_t = 1] \simeq \lambda$, when λ is small enough, and

$$\alpha_t = \alpha_0 \,(1-x)^{\sum_{l=1}^{t} w_l} \prod_{j=1}^{t} \left(1+\pi_{g,j}\right) \qquad [13]$$

Therefore, it may be deduced that

$$E[\alpha_t] = \alpha_0 \left\{e^{-\lambda x}\left(1+\mu_g\right)\right\}^t \qquad [14]$$

Denoting γ_t as the total operating costs per student and $\gamma_{a,t}$ as atypical costs due to innovations. Regarding cost savings arising from technological innovations, we can express

$$\gamma_{a,t} = -c_0 \; w_t \; \prod_{j=1}^{t}\left(1+\pi_{g,j}\right) \qquad [15]$$

The parameter c_0 represents the initial unitary economic impact of an innovation in time 0, and it is revalued every year with the inflation rate. Therefore, it is possible to rewrite [15], in terms of expected value, as

$$E\left[\gamma_{a,t}\right] = -\; \Omega_0 \,\gamma_0 \,\lambda \left(1+\mu_g\right)^t \qquad [16]$$

So, we can write

$$\gamma_t = \left(1+\pi_{r,t}\right)\gamma_{t-1} + \gamma_{a,t} \qquad [17]$$

And

$$E[\gamma_t] = \left\{\gamma_0 - c_0 \,\lambda \prod_{j=1}^{t} \left(\frac{1+\mu_g}{1+\mu_r}\right)^j\right\} (1+\mu_r)^t \qquad [18]$$

Since μ_g and μ_r are small amounts of the same order of magnitude and therefore the difference $\mu_{g-}\mu_r$ is small enough, we can propose the approximated expression

$$E[\gamma_t] = \{\gamma_0 - c_0 \,\lambda \, t\,\}\,(1+\mu_r)^t \qquad [19]$$

and, if $c_0 \,\lambda\, t \ll \gamma_0$ is met, it is possible to use the approximation

$$E[\gamma_t] = \gamma_0 \{e^{-\lambda\Omega_0}\ (1+\mu_r)\}^t \qquad [20]$$

It is interesting to compare equations [14] and [20] based on the (α_0, γ_0), (x, Ω_0), and (μ_g, μ_r) value pairs.

In this scenario, we denote the government utility as G_1, so that the expected net present value of G_1 is given by

$$E[G_1] = E\left[\sum_{t=1}^{n} G_{1,t}(1+i)^{-t}\right] = E\left[\sum_{t=1}^{n} S\ (\beta_t - \alpha_t)\ (1+i)^{-t}\right] \qquad [21]$$

It is assumed that innovations do not produce an increase in service quality, so that β_t is not affected.

Taking into account [4] and [13] we get

$$E[G_1] = S\ (\beta_0 f_g - \alpha_0 f_{g,x}) \qquad [22]$$

where

$$f_g = \sum_{t=1}^{n} \{(1+\mu_g)(1+i)^{-1}\}^t\ = \sum_{t=1}^{n} h_g^t \qquad [23]$$

$$f_{g,x} = \sum_{t=1}^{n} \{e^{-\lambda x}(1+\mu_g)(1+i)^{-1}\}^t\ =\ \sum_{t=1}^{n} h_{g,x}^t \qquad [24]$$

being h_g and $h_{g,x}$ two discounted growth factors. Therefore, $h_{g,x} = e^{-\lambda x} h_g \leq h_g$. As it is observable, f_g and $f_{g,x}$ are two finite geometric series that obviously verify $f_{g,x} \leq f_g$. Although, as is known, the sum of the terms of a finite geometric series can be expressed explicitly easily, we use the above expressions for convenience of notation.

A particularly interesting scenario is one in which innovation events occur but they do not lead to changes in the concessionaire's remuneration, such that $x = 0$. In this case, if we denote the governmental utility as G_1^0, we can obtain from [23] that

$$E[G_1^0] = S\, f_g(\beta_0 - \alpha_0) \qquad [25]$$

By calling ΔG_1^x the increase in the utility of the government based on the x compensation, such that $\Delta G_1^x = E\,[G_1] - E\,[G_1^0]$, we get

$$\Delta G_1^x = S\,\alpha_0\big(f_g - f_{g,x}\big) \qquad [26]$$

The cash flow $B_{1,t}$ received by the concessionaire throughout the concession period can be expressed as

$$B_{1,t} = S\,(\alpha_t - \gamma_t) - iL \qquad [27]$$

for $1 \leq t < n$, and

$$B_{1,n} = S\,(\alpha_n - \gamma_n\,) - (1+i)L \qquad [28]$$

Therefore, the expected net present value of the concession value B_1 is given by

$$E[B_1] = E\left[\sum_{t=1}^{n} B_{1,t}(1+i)^{-t}\right] = -L + E\left[\sum_{t=1}^{n} S\,(\alpha_t - \gamma_t)\,(1+i)^{-t}\right] \qquad [29]$$

That is,

$$E[B_1] = -L + S\sum_{t=1}^{n}\left\{\alpha_0 e^{-\lambda x t}\big(1+\mu_g\big)^t - \gamma_0 e^{-\lambda \Omega_0 t}\,(1+\mu_r)^t\right\}(1+i)^{-t} \qquad [30]$$

or, equivalently,

$$E[B_1] = -L + S\big\{\alpha_0 f_{g,x} - \gamma_0 f_{r,\Omega}\big\} \qquad [31]$$

where

$$f_{r,\Omega} = \sum_{t=1}^{n} \left\{ e^{-\lambda \Omega_0 t} \ (1+\mu_r)(1+i)^{-1} \right\}^t \ = \sum_{t=1}^{n} h_{r,\Omega}^t \qquad [32]$$

being $h_{r,\Omega}$ a discounted growth factor such that $h_{r,\Omega} = e^{-\lambda \Omega_0 t} \ (1+\mu_r)(1+i)^{-1}$. We call f_r the gamma value of $f_{r,\Omega}$ when $\lambda = 0$, because, in this case, Ω_0 has no impact.

3.3 Option type II: concessionaire's remuneration is reduced by a proportion of actual impacts of technological innovations on costs.

Innovations, depending on their more or less disruptive nature, affect production costs to a different extent. A priori, it is not possible to know when innovations with more or less intense effects on costs will occur. This section considers a different clause for the PPP contract, according to which the government has the option to reduce the concessionaire's remuneration in proportion to the actual impact of each innovation event on operating costs. It brings the scheme closer to the rate of return regulation approach. The informational condition in this scenario is stronger, since the government has to know not only when an innovation is adopted in the project, but also its impact on operating costs.

We start from equations [13] y [15], which now adopt the form

$$\alpha_t = \alpha_0 \left(1 - \frac{x}{c_0} c_t\right)^{\sum_{l=1}^{t} w_l} \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [33]$$

$$\gamma_{a,t} = - \ c_t \, w_t \ \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [34]$$

where c_t is a random Gaussian variable with mean c_0 and standard deviation σ_c. The ratio between c_0 and σ_c will ensure that the probability of obtaining negative values for c_t is virtually zero. In the previous section we worked with expected values. Now, taking a step further, we will consider that α_t and $\gamma_{a,t}$ are random variables resulting from the joint effect of random variables innovation w_t, impact c_t and inflation $\pi_{g,t}$. Since it does not alter the results related to the question under analysis, it is assumed that inflation behaves in a deterministic way. We assume the scenario in which the two variables are mutually independent.

In addition, since the x quantity is considered small enough, we will use the following approximation, for α_t,

$$\alpha_t = \alpha_0 \left(1+\mu_g\right)^t \left(1 - \frac{x}{c_0} \sum_{l=1}^{t} c_i w_l\right) \qquad [35]$$

assuming that α_t does not come close to negative values.

Calling $\sigma(\alpha_t)$ to the volatility of α_t, we get

$$\sigma(\alpha_t) = \alpha_0 \; x \; q \; \sqrt{\lambda t} \; \left(1+\mu_g\right)^t \qquad [36]$$

where the q factor is given by the expression:

$$q = \left\{1 + (1+\lambda)\frac{\sigma_c^2}{c_0^2}\right\}^{\frac{1}{2}} \qquad [37]$$

We denote the volatility of the governmental utility G_2 as $\sigma(G_2)$. In order to estimate that volatility, it is necessary to know $\rho\left(G_{2,t}, G_{2,s}\right)$, that is, the correlation between $G_{1,t}$ and $G_{s,t}$ (for $s, t = 1, n$). This correlation is given by

$$\rho\left(G_{2,t}, G_{2,s}\right) = \frac{Min(t,s)}{\sqrt{t}\sqrt{s}} \qquad [38]$$

Consequently, we get

$$\sigma(G_2) = S \; \alpha_0 \; x \; q \; \sqrt{\lambda} \; \left\{\sum_{t,s=1}^{n} h_g^{t+s} \; Min(t,s) \; \right\}^{\frac{1}{2}} \qquad [39]$$

or, equivalently,

$$\sigma(G_2) = S\ \alpha_0\ x\ q\ \sqrt{\lambda}\ \left\{\sum_{t=1}^{n} t h_g^t \sum_{s=t}^{n} h_g^s\right\}^{\frac{1}{2}} \quad [40]$$

We already have two measures, $E\ [G_2]$ and $\sigma(G_2)$, which characterize a Gaussian distribution. Although G_2 is not, it could be handled as an acceptable approximation of a Gaussian distribution.

Additionally, the expression of the volatility $\sigma(\gamma_t)$ of γ_t, is given, analogously, by

$$\sigma(\gamma_t) = \gamma_0\ \Omega_0\ q\ \sqrt{\lambda t}\ \ (1+\mu_r)^t \quad [41]$$

so that we can estimate

$$\sigma(\alpha_t - \gamma_t) = \sigma(\alpha_t) - \sigma(\gamma_t) = (\alpha_0 x - \ c_0)\ q\ \sqrt{\lambda t}\ \left(1+\mu_g\right)^t \quad [42]$$

These expressions are achieved under several assumptions as discussed below. It is assumed that values $\mu_g$and μ_r are similar enough, allowing $\left(1+\mu_g\right)^t$ to be used as a common factor. It has also been assumed that the correlation between α_t and γ_t is high enough to consider it almost equal to 1. Finally, since $\sigma(\alpha_t - \gamma_t)$ must be non-negative, they are considered values of *x* such that $x \geq \ \alpha_0^{-1} c_0$.

Moreover, the volatility of B_2 (defined for this case from expressions [7] and [8]) is denoted by $\sigma(B_2\ )$. Its estimation is necessary to know the correlation between $B_{2,t}$ and $B_{2,s}$ (for $s, t\ = 1, n$), be it $\rho\left(B_{2,t}, B_{2,s}\right)$. For all of the above, we can also write

$$\rho\left(B_{2,t}, B_{2,s}\right) = \frac{Min(t,s)}{\sqrt{t}\sqrt{s}} \quad [43]$$

The volatility $\sigma(B)$ of the value B of the concession takes the expression

$$\sigma(B_2) = \mathrm{S}(\alpha_0 x - \ \gamma_0 \Omega_0)\ q\sqrt{\lambda}\left\{\sum_{t=1}^{n} t h_g^t \sum_{s=t}^{n} h_g^s\right\}^{\frac{1}{2}} \quad [44]$$

Therefore, we have the rough probabilistic distribution B_2, on which the same considerations previously made with regard to the distribution of G_2 can be made.

Table 3 provides a comparison of features and effects of the two types of adjustment options on the fees paid by the government to the concessionaire in the presence of innovation events.

Table 3

From the government's perspective, the fact that it is not mandatory to implement innovations ensures sufficient private competition in tenders in both cases, but option II is more protective in the presence of a strong cost reduction impact.

From the perspective of the concessionaire, protection occurs in both cases. In contracts involving option I, the private partner will not implement those innovations whose cost impact is lower than the revenue reduction, but when the magnitude of the impact is high, there is a relevant potential upside in profits. In the case of option II, an improvement in margins is always guaranteed and innovations are more likely to be adopted, but the upside is lower.

4. Theoretical results

In this section we offer a number of theoretical outcomes. We start with those involving the model of Section 3.2, where the government has the option to reduce the concessionaire's remuneration by a fixed proportion when innovations occur.

First, for any strictly positive value of x, the expected utility of the grantor government is positively affected by increases in the frequency of innovation events, such that $\frac{\partial E[G_1]}{\partial \lambda} \geq 0$.

Second, as is obvious, the expected government utility increases with the proportion by which annual fees paid are reduced when an innovation event occur $\frac{\partial E[G_1]}{\partial x} \geq 0.$.

Third, we investigate the critical value that ensures innovations are implemented. In other words, the $1 - x$ value above which the concessionaire benefits from the implementation of a new technology. Let us now call B_1^0 the value of the concession when $\lambda = 0$, that is, when innovations do not take place, and, therefore, $x = 0$. Then, it is evident that

$$E[B_1^0] = -L + S\{\alpha_0 f_g - \gamma_0 f_r\} \qquad [45]$$

Since λ is exogenous and x is a value to be determined by the government when designing the tender specifications, there is a critical value of the reduction in payments applied for each innovation that we denote x^0. For a given value of λ, we have $E[B_1] = E[B_1^0]$. Then, the following condition is only satisfied when $x = x^0$.

$$\sum_{t=1}^{n} \left\{\alpha_0 e^{-\lambda x^0 t}\left(1+\mu_g\right)^t - \gamma_0 e^{-\lambda \Omega_0 t}(1+\mu_r)^t\right\}(1+i)^{-t} = \alpha_0 f_g - \gamma_0 f_r \qquad [46]$$

or, equivalently,

$$f_{g,x^0} = f_g + \frac{\gamma_0}{\alpha_0}\left(f_r - f_{r,\Omega}\right) \qquad [47]$$

being f_{g,x^0} the discounted growth factor for revenue when the innovation reduction coefficient is x^0. That is, $f_{g,x^0} = \sum_{t=1}^{n} h_{g,x^0}^t$ where $h_{g,x^0} = e^{-\lambda x^0}\left(1+\mu_g\right)(1+i)^{-1}$.

For any technological innovation that may occur, if $\lambda > 0$, any value of $x > 0$ benefits the government. However, the concessionaire only benefits when $x < x^0$.

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Fourth, we focus on valuing the option of the government to reduce its payment when innovations are implemented. To that end, let us define the amount G_1^0, which represents the utility for the government in a context where innovations do not occur. We can reasonably propose that the non-negative value V_g of the option for the government is given, from [26], by

$$V_g = S\,\alpha_0\left(f_g - f_{g,x}\right) \qquad [48]$$

Regarding the V_c value of the option from the perspective of the concessionaire, we propose the following expression $V_c = E\,[B_1] - E\,[B_1^0]$, from [31] and [45]. Therefore,

$$V_c = S\left\{\alpha_0\left(f_{g,x} - f_g\right) - \gamma_0\left(f_{r,\Omega} - f_r\right)\right\} \qquad [49]$$

Now, it can be verified that the asymmetric relationship [50] is met.

$$V_c = -V_g - S\gamma_0\left(f_{r,\Omega} - f_r\right) \qquad [50]$$

Finally, we analyze the role of the return on the equity r, obtained by concessionaire's shareholders, such that

$$r = -1 + (1+i)\left\{\frac{E[B]}{E}\right\}^{\frac{1}{n}} \qquad [51]$$

where $E[B]$ is given by [14]. So, the risk premium z is given by

$$z = (1+i)\left[-1 + \left\{\frac{E[B]}{E}\right\}^{\frac{1}{n}}\right] \qquad [52]$$

Further results from the comparative analysis of the two types of options are presented below. In both cases, the assessment of the government's utility is based on paths describing its expected value. However, in the second scenario, this trajectory is representative of a multiplicity of possible trajectories, depending on the behavior of random factors associated with the possible innovations. In this context, the introduction of a type II option ensures that any available innovation will be implemented while reduces the opportunity cost of the grantor government.

Assuming a Gaussian behavior of g, it could be affirmed that, with a probability of 50%, the value $G_2^M$of G_2 would be above $E[G_2]$. Therefore, a value representing all the trajectories of this set could be estimated by

$$G_2^M = E[G_2] + \sqrt{2\pi^{-1}}\,\sigma(G_2) = E[G_2] + 0.80\,\sigma(G_2) \qquad [53]$$

In general, given a α confidence level (such that $\alpha = P\left[\frac{G_2 - E[G_2]}{\sigma(G_2)} > \lambda_\alpha\right]$, the average G_2^α of all government utility values that fall within that confidence level can be estimated by the following expression

$$G_2^\alpha = E[G_2] + \bar{\lambda}_\alpha\,\sigma(G_2) \qquad [54]$$

where $\bar{\lambda}_\alpha = e^{-\frac{\lambda_\alpha^2}{2}} / \{\sqrt{2\pi} N(-\lambda_\alpha)\}$, being $N(\bullet)$ the cumulative standard Gaussian distribution.

Similarly, expressions could be obtained for confidence levels between any lower λ_{α_m} and higher λ_{α_M} values, which allow a number of optionality analysis.

5 Numerical simulations

5.1. Base case

In this section we apply the previous theoretical framework by considering a school concession project with the representative values listed in Table 4. It is worth mentioning that the base case data correspond to a hypothetical project, but the values are plausible according to the empirical experience of the sector – see Gwang-Hee *et al.*, 2013 and Public School Review, 2019. One of the technological implementation projects with the greatest economic impact on school management is that of virtual campuses (Turoff, 1997, Cartelli, *et al.*, 2008, Stansfield *et al.*, 2009 among others).

Table 4. Base case scenario

5.2. Results

We start by discussing the evolution of government payments per student. Among the infinite number of possible scenarios, Figure 2 shows seven hypothetical scenarios of the evolution of the per-student payment that, ex-post, would have to be made by the government. The scenarios differ, on the one hand, in that innovations do not take place or occur every three, four or five years and, on the other hand, in the type of choice in favour of the government. In this regard, in one of the scenarios, the government has no option to adjust its payments, in three other scenarios it has the option to reduce its payments by a fixed proportion each time there is an innovation event (option type I), and in the last three scenarios, government payments are reduced by a percentage of the actual reduction in operating costs caused by the innovation (option type II). As can be seen, for the same percentage of reduction x, if the government has the option to reprice , the greater the frequency of innovations, the lower the growth rate of payment per student. Moreover, in the case of the option type II, this rate is lower than in the case of option type I, because the impact on costs has been considered to be above the expected average.

Figure 2. Comparative annual payments per pupil.

Secondly, we discuss how innovation and contractual clauses affect the utility of the government. In the presence of innovations, the government is obviously more protected when it has the option to renegotiate its payments than when it does not. In addition, the option type II protects it more than the option type I, when the impact of innovations on costs is high enough. And above all, option type II, unlike option type I, ensures that all innovations are adopted in the projects. For x levels between 2.50% and

3.00%, the government's utility in terms of the amounts paid when there is no option to adjust fees is 1.2%. In the case of option type I, this rate is in the range between 8.0% and 9.4%. In the case of option type II, since the volatility of the impact of the innovations on operating costs is transferred to the government's utility, it can range from 3.4%-3.9% to 12.5%-14.9%. See Figure 3.

Figure 2. Utility of the government in terms of total cost

Third, we discuss to what extent the value of the government option to reduce its payments positively depends on the expected frequency of innovation events. For one innovation event expected every four years (λ= 0.25) and the values of the rest of the parameters being those of the base case, the value of the option represents a significant percentage of 6.8 % of the aggregate amount paid by the grantor government during the concession period. For a range of λ between 0.10 (an expected average innovation every ten years) and 0.50 (an expected average innovation every two years), this value ranges between 2.7% and 13.8%. See Table 5.

Table 5. Sensitivity of the value for the government of the option type I to changes in λ and x

Next, we carry out a simulation exercise to evaluate to what extent the value of the option depends on the percentage reduction in the annual government payment when a technological innovation is implemented.. The estimates indicate that the value of the option in terms of the total amount of government payments during the concession period ranges from 5.4 % to 7.6 % for a range of values of x between 2.0% and 2.8%. See Table 5.

Another simulation is carried out to determine the sensitivity of the equilibrium values corresponding to the percentage reduction of government payments x^0 for different levels of cost savings implied by technological innovations in terms of the initial recurrent operating cost, Ω. The simulation results indicate that the value of x^0 ranges from 0.64% % to 3.00% % for a range of Ω values from 0.5% to 4.5%. See Table 6.

Table 6. Sensitivity of the value for the government of the option type I to changes in Ω

Finally, we discuss the impact of expectations regarding the innovation process in the design of PPP contracts. If the concessionaire considers that the frequency of innovation events will be high enough, it will accept a higher percentage of revenue reduction. For example, if the concessionaire needs a minimum return of 7.78% and expects innovations every 5 years ($\lambda = 0.20$), then it would accept a value for x of 2.50%. However, if the concessionaire expects innovations to happen more frequently, for example every 4 years, then the maximum value it could accept is 2.75%. See Table 7.

Table 7. Sensitivity of the expected concessionaire ROE to x and λ

If the government and the concessionaire do not agree on the expected frequency of innovations, a conflict may arise that prevents the signing of the concession contract in the case of the use of option type I.

6 Final comments

To the best of our knowledge, our analysis provides a new approach to analyzing the impact of technology changes on PPPs' management. Research on applied real options theory in public-private partnership agreements in the presence of stochastic operating costs with "jumps" is scarce. In our model a grantor government reserves the right to cut its payments to the concessionaire when the concession's costs are reduced as a result of the implementation of technological innovations that we assume to occur according to a discrete Poisson stochastic function. A school concession project has been chosen for the purpose of assessing the relevance of the proposed model. The paper shows that the opportunity cost to the government of not including a price readjustment clause in the PPP contract can be very significant in reasonable innovation scenarios. Furthermore, the option to reduce payments by a proportion of the actual impact of the innovation on operating costs is more protective than the option where payments are reduced by a fixed proportion when the impact of the innovations on costs is sufficiently high. And above all, the option type II, unlike the option type I, ensures that innovations are adopted in projects. The inclusion of an option type II, however, requires a stronger informational condition.

One future line of research could consist of introducing asymmetry of information, so that the concessionaire has a more precise knowledge than the government regarding the impact of technological changes on operating costs. A second line of research would be to consider that innovations not only affect operational costs but also the quality of the service provided.

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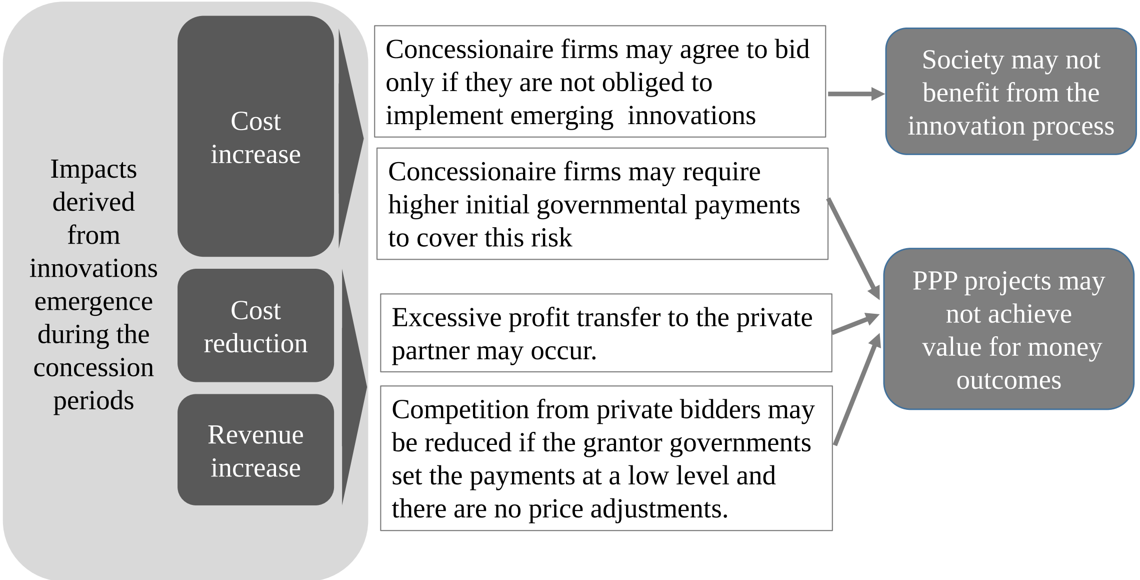
Figure 1: Risks arising from the emergence of innovations in PPP value for money



Source: authors' elaboration.

Table 1. Examples of how technological changes impact on concessionary firms' profitability

Industry	Technology innovation	Type of impact	Impact
Transportation	Electronic collection systems applied in toll motorways concessions	Tech innovation is a source of saving in staff expenses	Cost reduction
	GPS systems allow implementing dynamic toll policies based on traffic level	Tech innovation is a source of revenue optimization	Revenue increase
	New road paving materials	Roads that can recharge electric cars batteries when driving on them contribute to the fight against climate change, but they are still expensive	Cost increase

Energy	Improved quality of photovoltaic panels and windmills.	If governments subsidize the price of renewable megawatts injected into the national electricity system, improving the efficiency of the technology increases the income of generation plants	Revenue increase
Education	Virtual campuses and advanced e-learning systems	Despite their high initial fixed cost, these innovations tend to reduce operating costs in the medium term	Cost reduction
	Virtual and augmented reality technologies	The development of virtual and augmented reality platforms and the generation of contents for immersive experiences are currently quite expensive. If private operators have to apply state-of-the-art technology in the provision of the service there will cost increases	Cost increase
Healthcare	Digitization of medical reports; on-line appointment systems, telematics exchange of healthcare information (data and images); telemedicine systems for real-time or prerecorded interactions between patients and experts.	IT improvements contribute to a significant reduction in operating costs	Cost reduction
	New improved expensive diagnostic systems (3R magnetic resonance devices, ultrasound imaging, genetic tests), laser-	Technological innovations increase the quality of the service but at the	

targeted scalpels, and robotic surgical. More powerful and precise drugs; *nanocarriers* and *nanotrackers*	cost of increasing the costs of providing it.	Cost increase

Source: authors' elaboration.

Table 2. Some studies on the implementation of innovations in PPP projects

Study	Type of analysis	Results
Leiringer (2006)	The paper explores the validity of four common arguments used to promote the PPP procurement route: collaborative working, design freedom, long-term commitment and risk transfer	There is reason to be cautious in fully accepting the purported benefits of the PPP framework regarding the advantage of this procurement approach to generate and apply technological innovations.
Eaton *et al.* (2006)	The paper proposes a theoretical model for the identification of potential innovation stimulants and impediments within this type of procurement. This model is then utilised to evaluate four previously completed PFI projects.	The evaluation demonstrates how ineffective current procedures are.
Ball *et al.* (2007)	The paper uses a combination of participant observation, semi-structured interviewing and document review to find whether the use of PPP results in cost-effective innovative design and operation and maintenance cost savings.	Despite the fact that innovation is believed to be one of the key drivers of cost savings in PPP projects, the paper's findings suggest little evidence of innovation on the part of the private sector.

Russell *et al.* (2006)	The paper identifies 22 factors that can act as drivers or inhibitors of innovation for infrastructure projects as a function of procurement mode and project context.	The paper finds the drivers that were present in innovation processes in two sort of projects (a major transportation project and a large-scale student housing facility)
Gunnigan and Eaton (2008)	This paper sets out to identify the barriers to greater use of innovation in PPP projects. A series of interviews with participants on two closely related PPP projects was used. Data was gathered and analysed to compare the success of the projects in relation to innovation.	The paper identifies two types of innovation – namely cost reducing innovation and product enhancing innovation. It also finds that the systems that are in place for procuring PPPs are focused only on achieving innovation objectives of the cost reduction variety.
Tawiah & Russell (2008)	The framework of the paper provides the project evaluation process with a means of assessing project innovation potential according to the decision on the method of procurement	The paper finds that the choice of procurement mode influenced the application of innovations in two projects (in Scandinavia and the United States)
Barlow & Köberle-Gaiser (2009)	The paper follows a three-stage process. First, authors conduct back-ground interviews with 19 domain experts. Second, 6 short case studies built under a method PFI are undertaken. Third the data collection phase involves detailed case studies of the process for planning and delivering for 7 PFI projects	Innovation seems to be an important "sales factor" when seeking to win bids for new schemes. However, the PFI bidding process stifle innovation, since pressures to use "tried and tested" approaches is exerted by funders to protect their return on investment
	The paper proposes a model to estimate factors that influence	

Rangel & Galende (2010)	innovation in PPPs. The four tested factors are: the type of risk assumed by the private sector; the transfer of design responsibility; the provision for penalties if the infrastructure does not meet the quality factors specified in the contract; and the competition between bidders	The model is applied to a sample of 68 highway concessions in Spain (PPP contracts) between 1996 and 2005. The results show a significant relationship between three characteristics of PPPs and R&D activities
De Valence (2010)	The paper deals with the effects on R&D of procurement methods and on industry structure. Recent developments in the research on the economics of innovation and industrial organization theory are used.	For the Heathrow Terminal 5 project, the appropriability of innovations and the role of the client are analysed. The paper finds that the procurement method appears to be a determining factor in the level of innovation
Bougrain (2012)	The paper investigates the performance of PPPs and the ability of private consortia and public authorities to develop together solutions that reduce building energy consumptions	The papers finds that PPP performs well on issues such as the respect of schedules and contracted prices. However, this method does not appear to promote innovation, and it does not enhance quality of service delivery and life-cycle costing
Hoppe & Schmitz (2013)	The paper considers a model in which innovation effort is unobservable, but the government agency obtains a verifiable but noisy signal on the effort level	The choice between the PPP method or the traditional procurement method by the government agency depends on the information gathering costs, the effort costs, and on the degree to which effort is contractible

Brewer *et al.* 2013)	The paper identifies the influences on value generation through innovation by the facility management function in a PPP in Australia that delivered social infrastructure in multiple locations to a State Government	In PPPs, there is a disconnection between the asset delivery and service delivery phases, which stifles the consortium's capacity to innovate and maximise value
Roumboutsos & Saussier (2014)	To seek the impact on innovation, the paper presents an analytical model based on behavioural economics, with boundary conditions reflecting various contractual configurations in PPPs	The private party in a PPP arrangement has an incentive to invest in low-risk incremental innovations, which impact on, and positively effect, cost savings during construction and operation. Further innovations are hampered by the ability to produce verifiable improvements correlated to performance.
Rose and Manley (2014)	The paper investigates the decision process regarding the adoption of new-to-industry product innovation in road infrastructures. A large quantitative survey is conducted to rank the relative importance of the obstacles constraining the adoption of innovative products.	The paper identifies three important obstacles for innovation: (1) overemphasis on up-front project costs during tender stage; (2) disagreement over who carries the risk of new product failure; and (3) adversarial contract relations
Himmel and Siemiatycki (2017)	The paper examines a public–private partnership project delivery in Ontario, Canada over a decade,	Most innovations realized through the PPP process related to design, construction method, and material selection choices primarily aimed at lowering project cost and risk. More revolutionary innovations are

		not typically achieved through the PPP process
Carbonara and Pellegrino (2019)	The paper offers an econometric analysis to empirically test the hypotheses regarding the relationship between PPP design and innovation. A dataset of 290 PPP projects spanning different countries and sectors extracted by the World Bank PPI Database is used	Findings reveal that the arrangement of PPP projects; the market, contract and network structure, as well as government supports, may affect innovation
Saeed *et al* (2019)	The paper investigates how the PPP process encourages private and public sectors to be innovative. Factors pertaining to both innovation and project performance (project management, asset utilisation and stakeholder management) are examined	The chief innovative feature identified in the Victorian Comprehensive Cancer Centre project is the iconic design that provided flexibility for future expansion, lower operational cost and efficient integration of publicly and privately operated services

Source: authors' elaboration.

Table 3. Comparative summary of features and effects of two types of price-adjustment options

Price-adjustment option	Type I	Type II
Is it mandatory for the concessionaire to implement innovations available on the market?	No	No
In case an innovation is implemented the government payments are reduced in:	a fixed proportion	a fixed proportion of the actual impact of the innovation on costs
Will an innovation be implemented if its impact on operating costs in relation to the expected average impact is	higher? Yes lower? No	It is not necessary to consider an expected level of impact of innovations on costs. All available innovations will be implemented
Does the grantor government experience an opportunity cost if the impacts of innovation on operating costs are higher than expected?	Yes	No

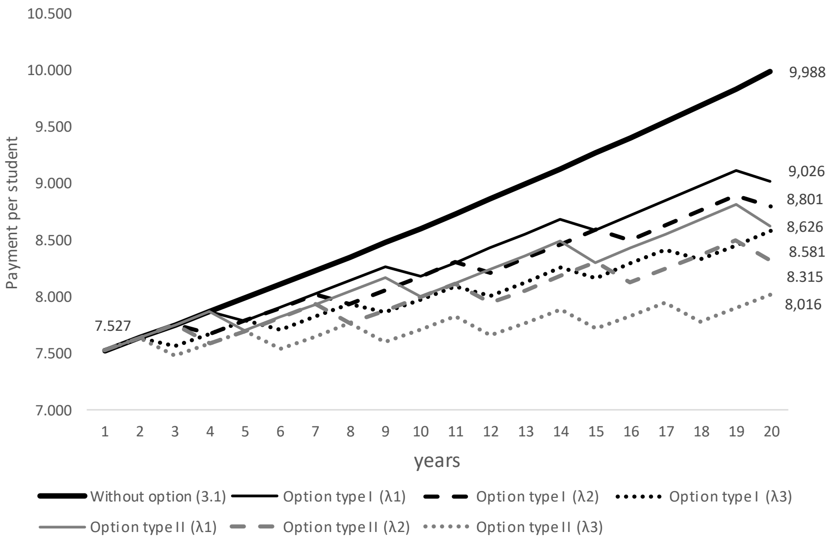
Source: authors' elaboration.

Table 4. Base case scenario

Concession term	20	Years
Construction cost (C)	15.00	million €
School size	32.00	Classrooms
Average classroom size	25.00	Pupils
Total capacity	800.00	Students
Annual expenditure per student (γ_0)	5.000	€
Initial annual governmental utility per pupil (β_0)	7.500	€
Initial annual governmental payment per pupil (α_0)	7.416	€
Average innovation per year (λ)	0.25	
Percentage impact of innovation (Ω)	2.25%	
Economic impact of innovation (c) (average)	112.5	€
Volatility of economic impact of innovation	50.0	€
Reduction of annual payment per pupil (x)	2.50%	
Debt/Construction cost	60%	
Initial debt	9.00	million €
Credit spread	0.00%	
Risk free rate	1.25%	
Debt yield	1.25%	
Corporate tax rate	0.00%	
Average general inflation growth rate (μ_g)	1.50%	
Average specific inflation growth rate (μ_r)	1.60%	

Source: authors' elaboration.

Figure 2. Comparative annual payments per pupil.

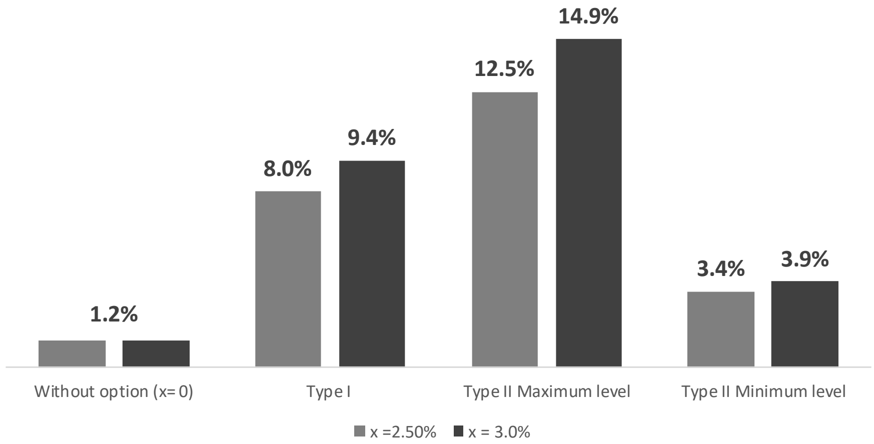


Assumptions

α_0 = 7,416	Ω = 2.25%
λ_1 = 0.2	x = 2.5%
λ_2 = 0.25	Sigma = 50 €
λ_3 = 0.333	μ_g = 1.5%

Source: authors' calculations.

Figure 3. Utility of the government in terms of total cost



Source: authors' calculation.

Table 5. Sensitivity of the value for the government of the option type I to changes in λ and *x* [a]

Λ	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Innovation period[b]	10.00	6.67	5.00	4.00	3.33	2.86	2.50	2.22	2.00
V_g/ (S α_0 f $_{gx}$)	2.7%	4.0%	5.4%	**6.8%**	8.2%	9.6%	11.0%	12.4%	13.8%
Payment reduction % (*x*)	2.00%	2.10%	2.20%	2.30%	2.40%	2.50%	2.60%	2.70%	2.80%
V_g/ (S α_0 f $_{gx}$)	5.4%	5.7%	5.9%	6.2%	6.5%	**6.8%**	7.0%	7.3%	7.6%

a. The value in bold corresponds to the base case scenario

b. Number of years in which an innovation event is expected

Source: authors' calculations.

Table 6. Sensitivity of the value for the government of the option type I to changes in Ω

	Value of x from which the adoption of innovation is not guaranteed								
Cost saving % (Ω)	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%
Critical value (x_0)	0.34%	0.68%	1.02%	1.35%	1.69%	2.02%	2.35%	2.67%	3.00%

Source: authors' calculations.

Table 7. Sensitivity of the expected concessionaire ROE to x and λ

x / λ	0.15	0.20	0.25	0.30	0.35
1.25%	8.44%	8.47%	8.49%	8.52%	8.54%
1.50%	8.35%	8.36%	8.36%	8.36%	8.35%
1.75%	8.27%	8.24%	8.22%	8.19%	8.16%
2.00%	8.18%	8.13%	8.07%	8.02%	7.96%
2.25%	8.10%	8.01%	7.93%	7.85%	7.76%
2.50%	8.01%	7.90%	**7.78%**	7.67%	7.56%
2.75%	7.92%	7.78%	7.63%	7.49%	7.35%

Source: authors' calculations.

Innovation and tariff-adjustment options in public-private partnerships

1. Introduction

There are numerous instruments that the public sector uses to indirectly boost innovation such as offering tax credits, setting regulations and standards that incentivise new ways of doing certain things, and creating markets for innovative ideas. Even more indirectly, public sector can also support education and training and can enhance capacities for knowledge exchange. But the public sector also takes direct measures to spur innovation, for example by funding R&D for specific projects. In addition, public agencies may demand new products for its own use or for the use of third parties. This is what is known today as public procurement for innovation (PPI) (and previously as public technology procurement (PTP), Edquist *et al*. 2000). PPI occurs when a public organization places an order for the fulfillment of certain functions within a reasonable period of time through a new product. There is consensus in the importance of public procurement not only for achieving greater efficiency in public sector spending but also as a vehicle for innovation and economic development. It has been repeatedly stated that PPI is an important policy instrument (Rothwell and Zegveld, 1981, Geroski, 1990, Dalpé, 1994, Edler and Georghiou, 2007, Edquist, 2011, Brammer and Walker, 2011, Tsipouri, 2015 or Uyarra *et al*., 2020) and that the rationale for using public procurement lies in the overall importance of demand-side activities to support innovation (Lundvall 1988; Gregersen 1992; Edquist 2005, Timmermans and Zabala-Iturriagagoitia, 2013).

In recent times there has been a re-emergence of mission-oriented innovation policies for tackling "grand societal challenges" such as climate change and aging societies (Fagerberg *et al*, 2016, Chicot and Matt, 2018), while the concept of innovation is being refocused from a purely technological field to a more open definition (Weber and Rohracher, 2012 and Kattel and Mazzucato, 2018). In this context, innovation in public-private partnerships (PPPs) is becoming of central interest in discussions about social welfare and productivity growth.

On the one hand, a PPP can be broadly defined as an arrangement that brings public and private sectors together in long-term partnerships for mutual benefit (HM Treasury, 2000). A hallmark of procurement through PPPs is the bundling of functions in construction and operation of infrastructure assets. The integration of the life cycle of activities around an asset relating to its design, construction, financing, operation and maintenance may encourage the private consortium to develop innovative thinking to exploit synergies and positive externalities. This is why public-private partnerships can achieve value for money in public spending.

On the other hand, innovation is not a very precise term. Just as many other aspects in management and life, it means different things to different people (Von Stamm, 2003). Among many definitions, one of the most common is from The Oslo Manual, which defines innovation as the implementation of a new or significantly improved product (good or service), or a process, new marketing method, or a new organisational method in business practices, workplace organisation or external relations. Successful innovation results in significant improvements in outcomes efficiency, effectiveness or quality (Albury, 2005).

In binomial innovation/public-private partnerships (PPPs) there are two issues that deserve attention from the economic literature. Firstly, how can PPP schemes be used to exploit R&D projects? A number of papers focus on this approach (e.g. Tawiah and Russell, 2008; Lember *et al.*, 2014, 2015; Scherrer *et al.*, 2016). Secondly, what are the factors that promote or inhibit the introduction of innovations in the construction of public infrastructures and in the provision of public services through PPPs? In the same vein, how are grantor governments affected by innovation in PPPs? This paper addresses the second type of questions. In particular, an attempt is made to assess whether the introduction of options for adjusting fees paid by the public sector can increase the likelihood of available innovations being implemented and reduce opportunity costs for grantor governments

Many public management reforms and programmes identify innovation as their primary goal (Considine and Lewis, 2007). The use of PPPs to build and operate infrastructure aims to incorporate not only the private sector's capital, expertise and risk management, but also its creativity and efficiency. The increasing weight of the public-private partnership as a method of infrastructure delivery in many countries helps explain the growing interest in encouraging the introduction of innovation in PPPs projects.

Uncertainty about the frequency of the emergence of innovations and the magnitude of their impact in long-term concessions is usually high. Innovations may alter the risks assumed by the partners in a PPP. If a solution is not implemented, emerging technologies that impact on revenues or costs may lead to an over-or-under transfer of benefits to the private partner. As a result, initial bidding prices may be sub-optimal and if the concession's contract does not adequately address risk allocation, innovations that would otherwise have been applied may not be implemented. Figure 1 shows the possible impact of risks arising from the emergence of innovations in the absence of tariff-adjustment options.

Figure 1: Risks arising from the emergence of innovations in PPP value for money

Positive and negative effects on revenues and costs of concessionaires resulting from the adoption of technological changes are varied. Table 1 shows some examples for four industries: transport, energy, education and healthcare.

Table 1. Examples of how technological changes impact on concessionary firms' profitability

In PPP projects, contracts are usually long-term and uncertainty about the evolution of certain economic variables affecting income and expenditure can be high. As a result, competition from private partners in tenders may be low. In such cases, governments may grant concessionaires the right to extend or shorten the concession term in certain circumstances or, alternatively, provide them with a minimum income guarantee. On the contrary, when innovations may alter the evolution of operating costs, governments may face significant opportunity costs. To the extent that concessionaires may benefit from large productivity gains, grantor governments would like to reserve the option of early termination of concession contracts or to adjust governmental payments in certain circumstances.

This paper explores the question of whether the inclusion in PPP contracts of options to adjust economic conditions in the face of technological changes may help the adoption of such innovations while reducing the opportunity cost for governments. In particular, the type of option envisaged offers the grantor government the right to cut its payments to the concessionaire when the latter implement technological innovations with a reducing effect on operating costs. The paper addresses the existing gap in the literature regarding the analysis of uncertainty associated with the adoption of innovations in PPPs and the role that options may have in this context. This framework is not exclusive of PPP contracts and can be extended to management contracts as the innovation is not considered to affect the construction stage, but the operation of the infrastructure. We consider a project in which the government pays an annual fee to the private partner to provide a given service to citizens. If a technological innovation that significantly reduces the operating costs of a project occurs, the grantor government is in a better position if it has the option to shorten the concession period and re-tender the project or, alternatively, if it has the right to adjust the economic terms of the concession. Tariff adjustment options can be more efficient than early termination options as they avoid the costs of re-bidding. In addition, tariff-adjustment options may avoid renegotiation processes that involve negotiation costs, may raise doubts about the validity of the concession model and may indicate excessively opportunistic behaviour on the part of governments, with a consequent impact on reputation (Guasch, 2004, Guasch *et al.*, 2006 and 2007). Moreover, the likelihood of renegotiation failure may not be small if the enforcement mechanism is not very effective (Laffont, 2003).

Taking a pragmatic approach, it is assumed that innovation occurs outside the scope of PPP projects and concessionaries have to decide whether or not to implement new technologies becoming available on the market. In the proposed model, innovations occur over time stochastically and their impact on operating costs is also stochastic in nature. As technological innovations take place, tariffs paid by the government are adjusted downwards, so that the concessionaire benefits partially from productivity improvements.

The paper is of interest given that digital transformation and *robotization* can generate relevant productivity improvements in areas where a significant part of the public budget is spent, such as health and education services. Moreover, the topic is relevant since every year new social services in these areas are provided under PPP agreements. The model considers discrete time, as in practice contracts for early termination and economic rebalancing options are exercisable at specific points in time, usually on an annual basis.

One may think that a major limitation of the paper consists of ignoring that private operators may have hidden information about operating costs. The issue of asymmetric information has been profusely treated in the literature on public procurement. However, in the context of the analysis, private partners in a PPP do not have hidden information or influence on the circumstances that give rise to technological developments (e.g. new developments in the Internet of Things, virtual and augmented reality, developments in artificial intelligence, new devices for online communication, etc.). It is assumed that innovation events occur at the margin of both the grantor government and the private partner, so that once a new technology reaches the market its applications and its cost of integration are in the public domain.

This paper delves into the issue of the inherent uncertainty in PPPs in connection to the question of innovation. The paper adds to the existing literature in a number of ways. To our knowledge, no other study exists that quantifies the impact of introducing tariff-adjustment options in PPPs where the concessionaire may decide to implement technological innovations. Research on the application of real option theory to PPP arrangements when operating costs "jump" over time is scarce. This study contributes to the body of knowledge by making novel use of the Poisson probability distribution in this context.

The remainder of the paper is organized as follows. In Section 2 we position this work within the literature. In section 3 we present the model. In section 4 some theoretical results are derived. In Section 5 we provide some numerical simulations to illustrate the merit of the proposed model. The paper concludes in Section 6 with some final comments.

2. Related literature

This paper can be positioned at the intersection of several strands of the literature.

Strictly speaking, it does not integrate with any of the three main lines of the literature on PPI that Obwegeser and Müller (2018) has categorized: i) public procurement for innovation (PPfI); ii) public procurement of innovations (PPoI); and iii) innovative public procurement (IPP). However, as highlighted below, this paper has some common features with this literature.

A variety of PPI taxonomies have been developed (Edler, 2009; Hommen and Rolfstam, 2009; Uyarra and Flanagan, 2010). Traditionally, procurement has been classified in two types: normal vs. innovative. In *regular procurement*, public agencies buy products or services in which no innovation is involved, such that only the price and the quality are taken into account when selecting the supplier. In contrast, in a PPI the development of new products or the dissemination of innovations is an integral part of the programme from the very start of the procurement process. Uyarra and Flanagan, 2010 consider, however, that we should be cautious in dividing up procurement into these two mutually exclusive categories. Our article is a good example of this, as it investigates how a regular PPP, whose contract includes certain options, could incentivise the adoption of innovations.

In connection with pure IPPs, a distinction has been made between those focusing on the missions or needs of the procuring agency and those aimed at supporting innovation across the economy. Our article is closer to the latter as it proposes to introduce certain clauses in PPP contracts to ensure that private partners incorporate innovations that occur in the market, without determining what kind of innovations should be adapted.

On an alternative taxonomy where the relevant dimension refers to whom the user of the resulting product good, service or system is, procurements can be categorized as direct or catalytic (Edquist y Zabala-Iturriagagoitia, 2012). Arguably, by introducing certain clauses as we propose in our paper a PPP may become a catalytic IPP, as the public agency acts to catalyse the development of innovations for wider public use.

According to a second dimension that refers to the character of the result of the procurement process, three types of PPI categories have been identified (Edquist y Zabala-Iturriagagoitia, 2012): i) pre-commercial procurement (PCP) that refers to the procurement of expected research results and is a matter of direct public R&D investments; ii) developmental or creation oriented PPI that aims radical innovation and iii) adaptive or diffusion oriented PPI. The proposal included in this paper would be in the spirit of the latter type.

In addition, according to Cave and Frinkin's, 2003 terminology, our proposal drives *indirect demand-pull impacts*, where innovation is a by-product of government procurement. And according to Cabral *et al*'s (2006) classification of the types *of indirect influence* of public procurement on innovation, our proposal would refer to those that facilitate the adoption of new standards.

Our paper is also in line with the consideration that public procurement may responds to a multi-objective policy, the main objective of which is to ensure the quality of public services and the use of products and services for the public sector, but where innovation can be an explicit secondary objective in certain instances. As Uyarra and Flanigan, 2010 have highlighted it is clear then that procuring 'goods and services that do not exist' is not always a necessary condition and is by no means a sufficient one to generate systemic impacts. We argue in favour of a broader interpretation that recognises that public procurement serves specific public needs and that innovation should be encouraged, where possible, as a 'by-product' of the procurement process.

Edler and Georghiou (2007) also distinguishes between the *general procurement* practice and the *strategic procurement*. In the first, government procurement is organised such that innovation becomes an essential criterion in the election of suppliers. In the second, the demand for certain technologies, products or services is encouraged in order to stimulate the market. The proposal included in this paper would be in the spirit of the *strategic procurement.*

Finally, Lembert *et al.* (2014) point out that there is a need to take into account wider strategic factors through which governments create capacity to undertake PPI and they envision four strategies for the future: i) PPI as experimental innovation policy; ii) from fiscal policy under austerity to PPI; iii) mission-oriented PPI and iv) shifts in administrative culture towards PPI. Our work would be proposing a fifth strategy aimed at managing regular PPPs with the consideration of fostering innovation.

The number of studies on effects and possible solutions when there is uncertainty in PPP projects is far from scarce in the economic literature. One solution explored in this context has been the explicit introduction of options in PPP contracts. This paper is in the line of the already extensive research using real option valuation applied to PPPs.

The mechanism analysed in this paper also falls within the scope of the debate between the price cap and the rate of return regulation. On the one hand, the price cap regulation limits the highest price the concessionaire could possibly charge in each year of the concession for the services it provides at the minimum required standards. Some incentive schemes have incorporated profit sharing into price caps. This incentive regulation aims to ensure that, at least in some circumstances, shareholders and/or managers of the regulated firm are better off if production costs are reduced. On the other hand, the rate of return regulation, determined in part based on the cost of capital to the industry to which the project belongs, considers the ‘necessary’ costs to set the required level of revenues. The price is regulated to ensure that the resultant revenues are just sufficient to cover the costs incurred. If the revenues are less than the required amount, the price will be increased and/or the excessive revenues in previous years are used to compensate for the revenue shortage in the current year, and to ensure adequate revenues for future years. Conversely, revenues in excess of the required amount are reverted to the public sector and/or prices are frozen or even reduced for the following years. Since there are both advantages and drawbacks to both systems, in practice, hybrid regulation schemes are often adopted. See Laffont and Tirole (1993), Ergas and Small (2001), Cowan, 2002, Carbonara *et al.* (2016) and many others.

Finally, the topic of this paper is related to the literature investigating the existence and the consequences of innovation when the PPP method is used in the provision of social services. Innovations that can be implemented in a PPP project include a wide range of creative ideas, from minor incremental improvements (Bugge and Bloch, 2016 and Fuglsang, 2010) to disruptive or transformative innovations that completely alter or replace processes or services (Osborne and Brown, 2011). In particular, these innovations basically concern new or improved services, new ways to deliver services, new processes, and changes in administrative and organizational systems. One of the key arguments in favor of PPPs is that new technologies tend to be earlier applied into infrastructures and social service projects when the manager is a private partner. On the contrary, it has been argued that in the traditional procurement method, the adoption of new technologies may be delayed. Table 2 shows a summary of findings by papers that focus on the factors that encourage and restrain the adoption of innovations in PPP projects. Some scholars find that private partners are able to provide better and more innovative solutions to deliver infrastructure and services but other conclude that it does not always happen.

Table 2. Some studies on the implementation of innovations in PPP projects

In contrast to our paper, none of the mentioned studies in Table 1 make use of a probability distribution relative to innovation events nor apply an option pricing method.

3. Model description

We consider a public procurement model with two players: a concessionaire firm and a governmental agency that tenders a PPP project for the provision of a social service (e.g. schooling). The provision of this service involves the construction of an infrastructure asset (e.g. a school building) by the concessionaire with a cost of C. At the end of the concession period, the asset reverts free of charge to the public sector. For simplicity's sake, we suppose that the construction can be instantaneously carried out. The expected return on equity by concessionaire shareholders to incur this cost must be at least r. In order to finance the construction cost, concessionaire shareholders provide equity E and borrow a bullet debt for the amount of L, such that $C = E + L$. The expected return r on the equity provided by concessionaire's shareholders equals the yield i of the concessionaire debt plus a required risk premium r, such that $r = i + z$. We assume that the temporal structure of interest rates is flat and stable; that shareholders of any new concessionaire have the same risk premium z over time, being this independent of the concession's term. In a low interest rate regime, such as the current one, these assumptions do not alter the results of the model. To simplify, the return on equity is calculated with a single final dividend that is the result of capitalizing cash flows at the risk-free rate. The credit spread of the debt issued by the concession firm is assumed to be nil. These assumptions significantly simplify the analysis, without altering the results of the model.

The evolution of the demand for educational services in the concession period is given by:

$$S = S_1 = S_2 = \cdots = S_n \qquad [1]$$

It is assumed that the school operates each year at the limit of its capacity and therefore, the annual number S of students is constant over time. This is an assumption that fits reality.

The concessionaire provides the service free of charge to the students and receives a certain amount α_t per pupil in year t from the government.

3.1. A scenario without technological innovations

In a scenario without technological innovation, the annual payment per student by the government can be written as

$$\alpha_t = \left(1 + \pi_{g,t}\right) \alpha_{t-1} \qquad [2]$$

where the linear stationary process $\pi_{g,t}$ is assumed to be Gaussian. We make the additional assumption of $\pi_{g,t}$ being Markovian, with intercept and parameters, μ_g and ϕ_g respectively (see Contreras and Angulo, 2017).

The rationale for this public expense is that schooling provides a social utility per student β_t, such that

$$\beta_t = \left(1 + \pi_{g,t}\right) \beta_{t-1} = \beta_0 \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [3]$$

and

$$E[\beta_t] = \beta_0 \left(1 + \mu_g\right)^t \qquad [4]$$

It is assumed that β_t reflects the sum of individual utilities for those who benefit from education and the positive externality for society.

The utility of the government in annual period t can be expressed as

$$G_t = S\left(\beta_t - \alpha_t\right) \qquad [5]$$

Therefore, the value of the concession for the government is given by

$$G = \sum_{t=1}^{n} G_t \left(1 + i\right)^{-t} \qquad [6]$$

Note that for simplicity purposes, we ignore the tax collection arising from the net income of the concessionaire's firm, which is the same as assuming that the corporate tax rate $\tau = 0$. This assumption significantly simplifies the analysis, while the results are only marginally impacted.

In a context without innovations, the cash flow of the concessionaire in period t, B_t, is given by

$$B_t = S\,(\alpha_t - \gamma_t) - iL \qquad [7]$$

for $1 \leq t < n$, where γ_t is the operating cost per student faced by the concessionaire in time t . This unit cost includes salaries of teachers, administrators and staff, as well as the cost of maintenance and renewal of equipment, such that

$$\gamma_t = \left(1 + \pi_{r,t}\right) \gamma_{t-1} \qquad [8]$$

where $\pi_{r,t}$ denotes the specific inflation of the inputs used in the productive process of the relevant industry. Note that the concessionaire firm faces the risk of an adverse deviation between the expected values of the stochastic rate of change of the tariffs paid by the government $\pi_{g,t}$ and of its operating costs $\pi_{r,t}$. The linear Gaussian stationary process $\pi_{r,t}$ behaves according to an evolution with intercept $\mu_r \neq \mu_g$ (normally $\mu_r > \mu_g$). From now on, for simplicity, and without loss of validity, we assume that $\phi_g = \phi_r = 0$.

For period n, the concessionaire's cash flow will be given by

$$B_n = S\,(\alpha_n - \gamma_n) - (1 + i)L \qquad [9]$$

Therefore, the value of the concession for the private partner is given by

$$B = -L + \sum_{t=1}^{n} B_t\,(1 + i)^{-t} \qquad [10]$$

Note that in period *n*, the bullet loan is amortized.

3.2 Option type I: concessionaire's remuneration is reduced by a fixed proportion of the expected impact of technological innovations on costs.

In this section we consider a PPP contract that includes a clause according to which government payments are reduced by a fixed proportion of the expected impact of technological innovations on costs. This scheme is in the spirit of price caps regulation, but the private concessionaire may have an upside in profits if the impact of innovations on operating costs exceeds what was initially expected. The scheme requires an informational-weak condition since in order to apply a cut on the payments made to the concessionaire firm, the grantor government just needs to observe whether an innovation event (in particular, the implementation of an innovation) has occurred. Note that according to the concession contract, the concessionaire is not obliged to implement any innovation available on the market.

For the purpose of introducing the impact of technological innovations on costs, we assume the existence of a second component of costs. Non-recurring cost $\gamma_{a,t}$ starts with a zero initial value and adopts average negative values when technological improvements take place. We assume that the stochastic process of the occurrence of innovation events behaves according to a discrete Poisson stochastic function of λ parameter, appropriate for modeling the stochastic behavior of *rare events*. It is assumed that $\gamma_{a,t} = -\lambda\, c_t$ where c_t represents the expected average value of the economic impact of an innovation in period t. The starting value c_0 (for $t = 0$) can be expressed as $c_0 = \Omega_0\, \gamma_0$ being γ_0 the starting value of the operating costs. Evidently, the proportionality Ω_t between c_t and γ_t does not remain constant over time. Although c_t is a random variable, which could be well described under a Gaussian density (with both positive and negative values possible), for the sake of simplicity, we consider here that it takes positive average values.

It is assumed that the impact on costs occurs in the same year that the technological innovations are implemented, and that the introduction of a new technology reduces the operating costs net of the expenses derived from its implementation. Therefore, if payments made by the government were not adjusted, there would be , an increase in the operating margin of the concessionaire firm. Our model considers however that the government has the right to reduce annual fees paid, in a proportion x, each time a technological innovation takes place. For each pair of values for λ and Ω_0, there is a value x^0 below which concession's managers have the incentive to implement new technologies when available. Above this value, the innovation will not be adopted in the relevant PPP project.

In a scenario with innovation the government annual payment per student will be given by

$$\alpha_t = \left(1 + \pi_{g,t}\right) (1 - x)^{w_{t-1}} \alpha_{t-1} \qquad [11]$$

As it seems reasonable, it is assumed that both relevant inflation rates, $\pi_{g,t}$ and $\pi_{r,t}$, are not correlated with Poisson's stochastic process. The non-negative integer number w_t describes the stochastic behavior of innovations and represents the number of such events occurring in period t, such that the probability $P_{k,t} = P[w_t = k_t]$ is given by

$$P_{k,t} = e^{-\lambda} \frac{\lambda^{k_t}}{k_t!} \qquad [12]$$

being λ a parameter representing the average number of innovations that occur annually. Therefore, $P_{0,t} = P[w_t = 0] \simeq 1 - \lambda$, $P_{1,t} = P[w_t = 1] \simeq \lambda$, when λ is small enough, and

$$\alpha_t = \alpha_0 \, (1-x)^{\sum_{l=1}^{t} w_l} \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [13]$$

Therefore, it may be deduced that

$$E[\alpha_t] = \alpha_0 \left\{ e^{-\lambda x} \left(1 + \mu_g\right) \right\}^t \qquad [14]$$

Denoting γ_t as the total operating costs per student and $\gamma_{a,t}$ as atypical costs due to innovations. Regarding cost savings arising from technological innovations, we can express

$$\gamma_{a,t} = -c_0 \;\, w_t \;\prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [15]$$

The parameter c_0 represents the initial unitary economic impact of an innovation in time 0, and it is revalued every year with the inflation rate. Therefore, it is possible to rewrite [15], in terms of expected value, as

$$E\left[\gamma_{a,t}\right] = - \; \Omega_0 \, \gamma_0 \, \lambda \left(1 + \mu_g\right)^t \qquad [16]$$

So, we can write

$$\gamma_t = \left(1 + \pi_{r,t}\right) \gamma_{t-1} + \gamma_{a,t} \qquad [17]$$

And

$$E[\gamma_t] = \left\{ \gamma_0 - c_0 \, \lambda \prod_{j=1}^{t} \left(\frac{1 + \mu_g}{1 + \mu_r} \right)^j \right\} (1 + \mu_r)^t \qquad [18]$$

Since μ_g and μ_r are small amounts of the same order of magnitude and therefore the difference $\mu_{g-}\mu_r$ is small enough, we can propose the approximated expression

$$E[\gamma_t] = \{\gamma_0 - c_0 \, \lambda \, t \,\} \, (1 + \mu_r)^t \qquad [19]$$

and, if $c_0 \, \lambda \, t \ll \gamma_0$ is met, it is possible to use the approximation

$$E[\gamma_t] = \gamma_0\{e^{-\lambda\Omega_0}\ (1+\mu_r)\}^t \qquad [20]$$

It is interesting to compare equations [14] and [20] based on the (α_0, γ_0), (x, Ω_0), and (μ_g, μ_r) value pairs.

In this scenario, we denote the government utility as G_1, so that the expected net present value of G_1 is given by

$$E[G_1] = E\left[\sum_{t=1}^{n} G_{1,t}(1+i)^{-t}\right] = E\left[\sum_{t=1}^{n} S\ (\beta_t - \alpha_t)\ (1+i)^{-t}\right] \qquad [21]$$

It is assumed that innovations do not produce an increase in service quality, so that β_t is not affected.

Taking into account [4] and [13] we get

$$E[G_1] = S\ (\beta_0 f_g - \alpha_0 f_{g,x}) \qquad [22]$$

where

$$f_g = \sum_{t=1}^{n}\{(1+\mu_g)(1+i)^{-1}\}^t\ = \sum_{t=1}^{n} h_g^t \qquad [23]$$

$$f_{g,x} = \sum_{t=1}^{n}\{e^{-\lambda x}(1+\mu_g)(1+i)^{-1}\}^t\ =\ \sum_{t=1}^{n} h_{g,x}^t \qquad [24]$$

being h_g and $h_{g,x}$ two discounted growth factors. Therefore, $h_{g,x} = e^{-\lambda x} h_g \leq h_g$. As it is observable, f_g and $f_{g,x}$ are two finite geometric series that obviously verify $f_{g,x} \leq f_g$. Although, as is known, the sum of the terms of a finite geometric series can be expressed explicitly easily, we use the above expressions for convenience of notation.

A particularly interesting scenario is one in which innovation events occur but they do not lead to changes in the concessionaire's remuneration, such that $x = 0$. In this case, if we denote the governmental utility as G_1^0, we can obtain from [23] that

$$E[G_1^0] = S\, f_g(\beta_0 - \alpha_0) \qquad [25]$$

By calling ΔG_1^x the increase in the utility of the government based on the x compensation, such that $\Delta G_1^x = E\,[G_1] - E\,[G_1^0]$, we get

$$\Delta G_1^x = S\,\alpha_0\left(f_g - f_{g,x}\right) \qquad [26]$$

The cash flow $B_{1,t}$ received by the concessionaire throughout the concession period can be expressed as

$$B_{1,t} = S\,(\alpha_t - \gamma_t) - iL \qquad [27]$$

for $1 \leq t < n$, and

$$B_{1,n} = S\,(\alpha_n - \gamma_n\,) - (1+i)L \qquad [28]$$

Therefore, the expected net present value of the concession value B_1 is given by

$$E[B_1] = E\left[\sum_{t=1}^{n} B_{1,t}(1+i)^{-t}\right] = -L + E\left[\sum_{t=1}^{n} S\,(\alpha_t - \gamma_t)\,(1+i)^{-t}\right] \qquad [29]$$

That is,

$$E[B_1] = -L + S\sum_{t=1}^{n}\left\{\alpha_0 e^{-\lambda x t}\left(1+\mu_g\right)^t - \gamma_0 e^{-\lambda \Omega_0 t}\,(1+\mu_r)^t\right\}(1+i)^{-t} \qquad [30]$$

or, equivalently,

$$E[B_1] = -L + S\left\{\alpha_0 f_{g,x} - \gamma_0 f_{r,\Omega}\right\} \qquad [31]$$

where

$$f_{r,\Omega} = \sum_{t=1}^{n} \left\{ e^{-\lambda \Omega_0 t} \; (1+\mu_r)(1+i)^{-1} \right\}^t \; = \sum_{t=1}^{n} h_{r,\Omega}^t \qquad [32]$$

being $h_{r,\Omega}$ a discounted growth factor such that $h_{r,\Omega} = e^{-\lambda \Omega_0 t} \; (1+\mu_r)(1+i)^{-1}$. We call f_r the gamma value of $f_{r,\Omega}$ when $\lambda = 0$, because, in this case, Ω_0 has no impact.

3.3 Option type II: concessionaire's remuneration is reduced by a proportion of actual impacts of technological innovations on costs.

Innovations, depending on their more or less disruptive nature, affect production costs to a different extent. A priori, it is not possible to know when innovations with more or less intense effects on costs will occur. This section considers a different clause for the PPP contract, according to which the government has the option to reduce the concessionaire's remuneration in proportion to the actual impact of each innovation event on operating costs. It brings the scheme closer to the rate of return regulation approach. The informational condition in this scenario is stronger, since the government has to know not only when an innovation is adopted in the project, but also its impact on operating costs.

We start from equations [13] y [15], which now adopt the form

$$\alpha_t = \alpha_0 \left(1 - \frac{x}{c_0} c_t\right)^{\sum_{l=1}^{t} w_l} \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [33]$$

$$\gamma_{a,t} = - \; c_t \, w_t \; \prod_{j=1}^{t} \left(1 + \pi_{g,j}\right) \qquad [34]$$

where c_t is a random Gaussian variable with mean c_0 and standard deviation σ_c. The ratio between c_0 and σ_c will ensure that the probability of obtaining negative values for c_t is virtually zero. In the previous section we worked with expected values. Now, taking a step further, we will consider that α_t and $\gamma_{a,t}$ are random variables resulting from the joint effect of random variables innovation w_t, impact c_t and inflation $\pi_{g,t}$. Since it does not alter the results related to the question under analysis, it is assumed that inflation behaves in a deterministic way. We assume the scenario in which the two variables are mutually independent.

In addition, since the x quantity is considered small enough, we will use the following approximation, for α_t,

$$\alpha_t = \alpha_0\left(1+\mu_g\right)^t \left(1 - \frac{x}{c_0}\sum_{l=1}^{t} c_i w_l\right) \quad [35]$$

assuming that α_t does not come close to negative values.

Calling $\sigma(\alpha_t)$ to the volatility of α_t, we get

$$\sigma(\alpha_t) = \alpha_0 \; x \; q \; \sqrt{\lambda t} \; \left(1+\mu_g\right)^t \quad [36]$$

where the q factor is given by the expression:

$$q = \left\{1 + (1+\lambda)\frac{\sigma_c^2}{c_0^2}\right\}^{\frac{1}{2}} \quad [37]$$

We denote the volatility of the governmental utility G_2 as $\sigma(G_2)$. In order to estimate that volatility, it is necessary to know $\rho\left(G_{2,t}, G_{2,s}\right)$, that is, the correlation between $G_{1,t}$ and $G_{s,t}$ (for $s, t = 1, n$). This correlation is given by

$$\rho\left(G_{2,t}, G_{2,s}\right) = \frac{Min(t,s)}{\sqrt{t}\sqrt{s}} \quad [38]$$

Consequently, we get

$$\sigma(G_2) = S \; \alpha_0 \; x \; q \; \sqrt{\lambda} \; \left\{\sum_{t,s=1}^{n} h_g^{t+s} \; Min(t,s) \; \right\}^{\frac{1}{2}} \quad [39]$$

or, equivalently,

$$\sigma(G_2) = S\ \alpha_0\ x\ q\ \sqrt{\lambda}\ \left\{\sum_{t=1}^{n} t h_g^t \sum_{s=t}^{n} h_g^s\right\}^{\frac{1}{2}} \qquad [40]$$

We already have two measures, $E\ [G_2]$ and $\sigma(G_2)$, which characterize a Gaussian distribution. Although G_2 is not, it could be handled as an acceptable approximation of a Gaussian distribution.

Additionally, the expression of the volatility $\sigma(\gamma_t)$ of γ_t, is given, analogously, by

$$\sigma(\gamma_t) = \gamma_0\ \Omega_0\ q\ \sqrt{\lambda t}\ \ (1+\mu_r)^t \qquad [41]$$

so that we can estimate

$$\sigma(\alpha_t - \gamma_t) = \sigma(\alpha_t) - \sigma(\gamma_t) = (\alpha_0 x -\ c_0)\ q\ \sqrt{\lambda t}\ \left(1+\mu_g\right)^t \qquad [42]$$

These expressions are achieved under several assumptions as discussed below. It is assumed that values $\mu_g$and μ_r are similar enough, allowing $\left(1+\mu_g\right)^t$ to be used as a common factor. It has also been assumed that the correlation between α_t and γ_t is high enough to consider it almost equal to 1. Finally, since $\sigma(\alpha_t - \gamma_t)$ must be non-negative, they are considered values of *x* such that $x \geq\ \alpha_0^{-1} c_0$.

Moreover, the volatility of B_2 (defined for this case from expressions [7] and [8]) is denoted by $\sigma(B_2\ )$. Its estimation is necessary to know the correlation between $B_{2,t}$ and $B_{2,s}$ (for $s, t\ = 1, n$), be it $\rho\left(B_{2,t}, B_{2,s}\right)$. For all of the above, we can also write

$$\rho\left(B_{2,t}, B_{2,s}\right) = \frac{Min(t,s)}{\sqrt{t}\sqrt{s}} \qquad [43]$$

The volatility $\sigma(B)$ of the value B of the concession takes the expression

$$\sigma(B_2) = \mathrm{S}(\alpha_0 x -\ \gamma_0 \Omega_0)\ q\sqrt{\lambda}\left\{\sum_{t=1}^{n} t h_g^t \sum_{s=t}^{n} h_g^s\right\}^{\frac{1}{2}} \qquad [44]$$

Therefore, we have the rough probabilistic distribution B_2, on which the same considerations previously made with regard to the distribution of G_2 can be made.

Table 3 provides a comparison of features and effects of the two types of adjustment options on the fees paid by the government to the concessionaire in the presence of innovation events.

Table 3

From the government's perspective, the fact that it is not mandatory to implement innovations ensures sufficient private competition in tenders in both cases, but option II is more protective in the presence of a strong cost reduction impact.

From the perspective of the concessionaire, protection occurs in both cases. In contracts involving option I, the private partner will not implement those innovations whose cost impact is lower than the revenue reduction, but when the magnitude of the impact is high, there is a relevant potential upside in profits. In the case of option II, an improvement in margins is always guaranteed and innovations are more likely to be adopted, but the upside is lower.

4. Theoretical results

In this section we offer a number of theoretical outcomes. We start with those involving the model of Section 3.2, where the government has the option to reduce the concessionaire's remuneration by a fixed proportion when innovations occur.

First, for any strictly positive value of x, the expected utility of the grantor government is positively affected by increases in the frequency of innovation events, such that $\frac{\partial E[G_1]}{\partial \lambda} \geq 0$.

Second, as is obvious, the expected government utility increases with the proportion by which annual fees paid are reduced when an innovation event occur $\frac{\partial E[G_1]}{\partial x} \geq 0.$.

Third, we investigate the critical value that ensures innovations are implemented. In other words, the $1 - x$ value above which the concessionaire benefits from the implementation of a new technology. Let us now call B_1^0 the value of the concession when $\lambda = 0$, that is, when innovations do not take place, and, therefore, $x = 0$. Then, it is evident that

$$E[B_1^0] = -L + S\{\alpha_0 f_g - \gamma_0 f_r\} \quad [45]$$

Since λ is exogenous and x is a value to be determined by the government when designing the tender specifications, there is a critical value of the reduction in payments applied for each innovation that we denote x^0. For a given value of λ, we have $E[B_1] = E[B_1^0]$. Then, the following condition is only satisfied when $x = x^0$.

$$\sum_{t=1}^{n} \left\{\alpha_0 e^{-\lambda x^0 t}\left(1+\mu_g\right)^t - \gamma_0 e^{-\lambda \Omega_0 t}(1+\mu_r)^t\right\}(1+i)^{-t} = \alpha_0 f_g - \gamma_0 f_r \quad [46]$$

or, equivalently,

$$f_{g,x^0} = f_g + \frac{\gamma_0}{\alpha_0}\left(f_r - f_{r,\Omega}\right) \quad [47]$$

being f_{g,x^0} the discounted growth factor for revenue when the innovation reduction coefficient is x^0. That is, $f_{g,x^0} = \sum_{t=1}^{n} h_{g,x^0}^t$ where $h_{g,x^0} = e^{-\lambda x^0}\left(1+\mu_g\right)(1+i)^{-1}$.

For any technological innovation that may occur, if $\lambda > 0$, any value of $x > 0$ benefits the government. However, the concessionaire only benefits when $x < x^0$.

Fourth, we focus on valuing the option of the government to reduce its payment when innovations are implemented. To that end, let us define the amount G_1^0, which represents the utility for the government in a context where innovations do not occur. We can reasonably propose that the non-negative value V_g of the option for the government is given, from [26], by

$$V_g \; = S \, \alpha_0 \left(f_g - f_{g,x} \right) \qquad [48]$$

Regarding the V_c value of the option from the perspective of the concessionaire, we propose the following expression $V_c = E\,[B_1] - E\,[B_1^0]$, from [31] and [45]. Therefore,

$$V_c = S \left\{ \alpha_0 \left(f_{g,x} - f_g \right) - \gamma_0 \left(f_{r,\Omega} - f_r \right) \right\} \qquad [49]$$

Now, it can be verified that the asymmetric relationship [50] is met.

$$V_c = -V_g \; - \; S\gamma_0 \left(f_{r,\Omega} - f_r \right) \qquad [50]$$

Finally, we analyze the role of the return on the equity r, obtained by concessionaire's shareholders, such that

$$r = -1 + (1 + i) \left\{ \frac{E[B]}{E} \right\}^{\frac{1}{n}} \qquad [51]$$

where $E[B]$ is given by [14]. So, the risk premium z is given by

$$z = (1 + i) \left[-1 + \left\{ \frac{E[B]}{E} \right\}^{\frac{1}{n}} \right] \qquad [52]$$

Further results from the comparative analysis of the two types of options are presented below. In both cases, the assessment of the government's utility is based on paths describing its expected value. However, in the second scenario, this trajectory is representative of a multiplicity of possible trajectories, depending on the behavior of random factors associated with the possible innovations. In this context, the introduction of a type II option ensures that any available innovation will be implemented while reduces the opportunity cost of the grantor government.

Assuming a Gaussian behavior of g, it could be affirmed that, with a probability of 50%, the value G_2^M of G_2 would be above $E[G_2]$. Therefore, a value representing all the trajectories of this set could be estimated by

$$G_2^M = E[G_2] + \sqrt{2\pi^{-1}}\,\sigma(G_2) = E[G_2] + 0.80\,\sigma(G_2) \qquad [53]$$

In general, given a α confidence level (such that $\alpha = P\left[\frac{G_2 - E[G_2]}{\sigma(G_2)} > \lambda_\alpha\right]$, the average G_2^α of all government utility values that fall within that confidence level can be estimated by the following expression

$$G_2^\alpha = E[G_2] + \bar{\lambda}_\alpha\,\sigma(G_2) \qquad [54]$$

where $\bar{\lambda}_\alpha = e^{-\frac{\lambda_\alpha^2}{2}} / \{\sqrt{2\pi} N(-\lambda_\alpha)\}$, being $N(\bullet)$ the cumulative standard Gaussian distribution.

Similarly, expressions could be obtained for confidence levels between any lower λ_{α_m} and higher λ_{α_M} values, which allow a number of optionality analysis.

5 Numerical simulations

5.1. Base case

In this section we apply the previous theoretical framework by considering a school concession project with the representative values listed in Table 4. It is worth mentioning that the base case data correspond to a hypothetical project, but the values are plausible according to the empirical experience of the sector – see Gwang-Hee *et al.*, 2013 and Public School Review, 2019. One of the technological implementation projects with the greatest economic impact on school management is that of virtual campuses (Turoff, 1997, Cartelli, *et al.*, 2008, Stansfield *et al.*, 2009 among others).

Table 4. Base case scenario

5.2. Results

We start by discussing the evolution of government payments per student. Among the infinite number of possible scenarios, Figure 2 shows seven hypothetical scenarios of the evolution of the per-student payment that, ex-post, would have to be made by the government. The scenarios differ, on the one hand, in that innovations do not take place or occur every three, four or five years and, on the other hand, in the type of choice in favour of the government. In this regard, in one of the scenarios, the government has no option to adjust its payments, in three other scenarios it has the option to reduce its payments by a fixed proportion each time there is an innovation event (option type I), and in the last three scenarios, government payments are reduced by a percentage of the actual reduction in operating costs caused by the innovation (option type II). As can be seen, for the same percentage of reduction x, if the government has the option to reprice , the greater the frequency of innovations, the lower the growth rate of payment per student. Moreover, in the case of the option type II, this rate is lower than in the case of option type I, because the impact on costs has been considered to be above the expected average.

Figure 2. Comparative annual payments per pupil.

Secondly, we discuss how innovation and contractual clauses affect the utility of the government. In the presence of innovations, the government is obviously more protected when it has the option to renegotiate its payments than when it does not. In addition, the option type II protects it more than the option type I, when the impact of innovations on costs is high enough. And above all, option type II, unlike option type I, ensures that all innovations are adopted in the projects. For x levels between 2.50% and

3.00%, the government's utility in terms of the amounts paid when there is no option to adjust fees is 1.2%. In the case of option type I, this rate is in the range between 8.0% and 9.4%. In the case of option type II, since the volatility of the impact of the innovations on operating costs is transferred to the government's utility, it can range from 3.4%-3.9% to 12.5%-14.9%. See Figure 3.

Figure 2. Utility of the government in terms of total cost

Third, we discuss to what extent the value of the government option to reduce its payments positively depends on the expected frequency of innovation events. For one innovation event expected every four years (λ= 0.25) and the values of the rest of the parameters being those of the base case, the value of the option represents a significant percentage of 6.8 % of the aggregate amount paid by the grantor government during the concession period. For a range of λ between 0.10 (an expected average innovation every ten years) and 0.50 (an expected average innovation every two years), this value ranges between 2.7% and 13.8%. See Table 5.

Table 5. Sensitivity of the value for the government of the option type I to changes in λ and x

Next, we carry out a simulation exercise to evaluate to what extent the value of the option depends on the percentage reduction in the annual government payment when a technological innovation is implemented.. The estimates indicate that the value of the option in terms of the total amount of government payments during the concession period ranges from 5.4 % to 7.6 % for a range of values of x between 2.0% and 2.8%. See Table 5.

Another simulation is carried out to determine the sensitivity of the equilibrium values corresponding to the percentage reduction of government payments x^0 for different levels of cost savings implied by technological innovations in terms of the initial recurrent operating cost, Ω. The simulation results indicate that the value of x^0 ranges from 0.64% % to 3.00% % for a range of Ω values from 0.5% to 4.5%. See Table 6.

Table 6. Sensitivity of the value for the government of the option type I to changes in Ω

Finally, we discuss the impact of expectations regarding the innovation process in the design of PPP contracts. If the concessionaire considers that the frequency of innovation events will be high enough, it will accept a higher percentage of revenue reduction. For example, if the concessionaire needs a minimum return of 7.78% and expects innovations every 5 years ($\lambda = 0.20$), then it would accept a value for x of 2.50%. However, if the concessionaire expects innovations to happen more frequently, for example every 4 years, then the maximum value it could accept is 2.75%. See Table 7.

Table 7. Sensitivity of the expected concessionaire ROE to x and λ

If the government and the concessionaire do not agree on the expected frequency of innovations, a conflict may arise that prevents the signing of the concession contract in the case of the use of option type I.

6 Final comments

To the best of our knowledge, our analysis provides a new approach to analyzing the impact of technology changes on PPPs' management. Research on applied real options theory in public-private partnership agreements in the presence of stochastic operating costs with "jumps" is scarce. In our model a grantor government reserves the right to cut its payments to the concessionaire when the concession's costs are reduced as a result of the implementation of technological innovations that we assume to occur according to a discrete Poisson stochastic function. A school concession project has been chosen for the purpose of assessing the relevance of the proposed model. The paper shows that the opportunity cost to the government of not including a price readjustment clause in the PPP contract can be very significant in reasonable innovation scenarios. Furthermore, the option to reduce payments by a proportion of the actual impact of the innovation on operating costs is more protective than the option where payments are reduced by a fixed proportion when the impact of the innovations on costs is sufficiently high. And above all, the option type II, unlike the option type I, ensures that innovations are adopted in projects. The inclusion of an option type II, however, requires a stronger informational condition.

One future line of research could consist of introducing asymmetry of information, so that the concessionaire has a more precise knowledge than the government regarding the impact of technological changes on operating costs. A second line of research would be to consider that innovations not only affect operational costs but also the quality of the service provided.

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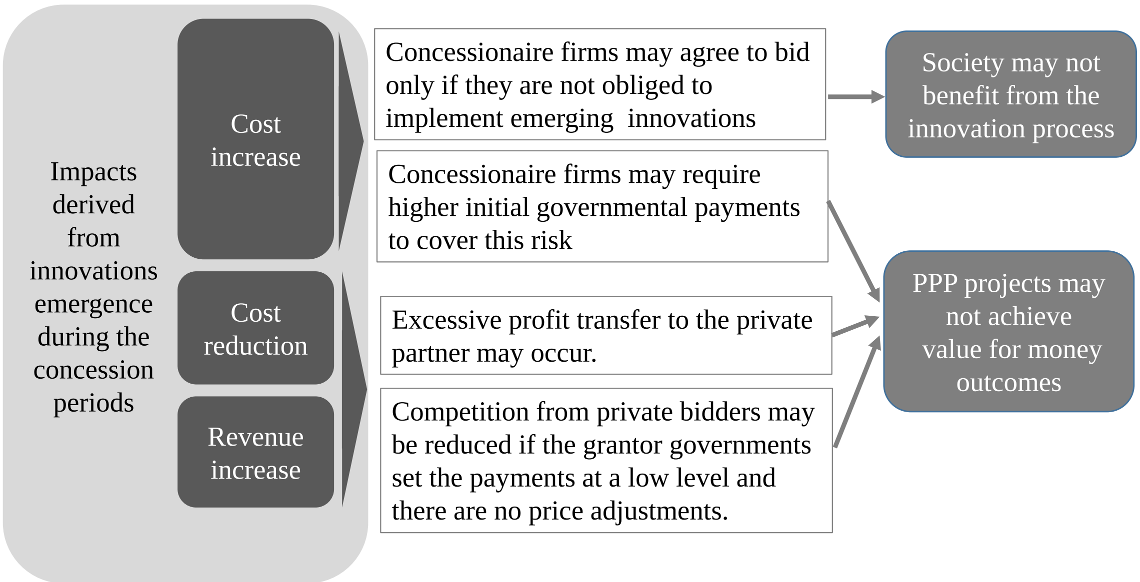
Figure 1: Risks arising from the emergence of innovations in PPP value for money



Source: authors' elaboration.

Table 1. Examples of how technological changes impact on concessionary firms' profitability

Industry	Technology innovation	Type of impact	Impact
Transportation	Electronic collection systems applied in toll motorways concessions	Tech innovation is a source of saving in staff expenses	Cost reduction
	GPS systems allow implementing dynamic toll policies based on traffic level	Tech innovation is a source of revenue optimization	Revenue increase
	New road paving materials	Roads that can recharge electric cars batteries when driving on them contribute to the fight against climate change, but they are still expensive	Cost increase

Energy	Improved quality of photovoltaic panels and windmills.	If governments subsidize the price of renewable megawatts injected into the national electricity system, improving the efficiency of the technology increases the income of generation plants	Revenue increase
Education	Virtual campuses and advanced e-learning systems	Despite their high initial fixed cost, these innovations tend to reduce operating costs in the medium term	Cost reduction
	Virtual and augmented reality technologies	The development of virtual and augmented reality platforms and the generation of contents for immersive experiences are currently quite expensive. If private operators have to apply state-of-the-art technology in the provision of the service there will cost increases	Cost increase
Healthcare	Digitization of medical reports; on-line appointment systems, telematics exchange of healthcare information (data and images); telemedicine systems for real-time or prerecorded interactions between patients and experts.	IT improvements contribute to a significant reduction in operating costs	Cost reduction
	New improved expensive diagnostic systems (3R magnetic resonance devices, ultrasound imaging, genetic tests), laser-	Technological innovations increase the quality of the service but at the	

targeted scalpels, and robotic surgical. More powerful and precise drugs; *nanocarriers* and *nanotrackers*	cost of increasing the costs of providing it.	Cost increase

Source: authors' elaboration.

Table 2. Some studies on the implementation of innovations in PPP projects

Study	Type of analysis	Results
Leiringer (2006)	The paper explores the validity of four common arguments used to promote the PPP procurement route: collaborative working, design freedom, long-term commitment and risk transfer	There is reason to be cautious in fully accepting the purported benefits of the PPP framework regarding the advantage of this procurement approach to generate and apply technological innovations.
Eaton *et al.* (2006)	The paper proposes a theoretical model for the identification of potential innovation stimulants and impediments within this type of procurement. This model is then utilised to evaluate four previously completed PFI projects.	The evaluation demonstrates how ineffective current procedures are.
Ball *et al.* (2007)	The paper uses a combination of participant observation, semi-structured interviewing and document review to find whether the use of PPP results in cost-effective innovative design and operation and maintenance cost savings.	Despite the fact that innovation is believed to be one of the key drivers of cost savings in PPP projects, the paper's findings suggest little evidence of innovation on the part of the private sector.

Russell *et al.* (2006)	The paper identifies 22 factors that can act as drivers or inhibitors of innovation for infrastructure projects as a function of procurement mode and project context.	The paper finds the drivers that were present in innovation processes in two sort of projects (a major transportation project and a large-scale student housing facility)
Gunnigan and Eaton (2008)	This paper sets out to identify the barriers to greater use of innovation in PPP projects. A series of interviews with participants on two closely related PPP projects was used. Data was gathered and analysed to compare the success of the projects in relation to innovation.	The paper identifies two types of innovation – namely cost reducing innovation and product enhancing innovation. It also finds that the systems that are in place for procuring PPPs are focused only on achieving innovation objectives of the cost reduction variety.
Tawiah & Russell (2008)	The framework of the paper provides the project evaluation process with a means of assessing project innovation potential according to the decision on the method of procurement	The paper finds that the choice of procurement mode influenced the application of innovations in two projects (in Scandinavia and the United States)
Barlow & Köberle-Gaiser (2009)	The paper follows a three-stage process. First, authors conduct back-ground interviews with 19 domain experts. Second, 6 short case studies built under a method PFI are undertaken. Third the data collection phase involves detailed case studies of the process for planning and delivering for 7 PFI projects	Innovation seems to be an important “sales factor” when seeking to win bids for new schemes. However, the PFI bidding process stifle innovation, since pressures to use “tried and tested” approaches is exerted by funders to protect their return on investment
	The paper proposes a model to estimate factors that influence	

Rangel & Galende (2010)	innovation in PPPs. The four tested factors are: the type of risk assumed by the private sector; the transfer of design responsibility; the provision for penalties if the infrastructure does not meet the quality factors specified in the contract; and the competition between bidders	The model is applied to a sample of 68 highway concessions in Spain (PPP contracts) between 1996 and 2005. The results show a significant relationship between three characteristics of PPPs and R&D activities
De Valence (2010)	The paper deals with the effects on R&D of procurement methods and on industry structure. Recent developments in the research on the economics of innovation and industrial organization theory are used.	For the Heathrow Terminal 5 project, the appropriability of innovations and the role of the client are analysed. The paper finds that the procurement method appears to be a determining factor in the level of innovation
Bougrain (2012)	The paper investigates the performance of PPPs and the ability of private consortia and public authorities to develop together solutions that reduce building energy consumptions	The papers finds that PPP performs well on issues such as the respect of schedules and contracted prices. However, this method does not appear to promote innovation, and it does not enhance quality of service delivery and life-cycle costing
Hoppe & Schmitz (2013)	The paper considers a model in which innovation effort is unobservable, but the government agency obtains a verifiable but noisy signal on the effort level	The choice between the PPP method or the traditional procurement method by the government agency depends on the information gathering costs, the effort costs, and on the degree to which effort is contractible

Brewer *et al.* 2013)	The paper identifies the influences on value generation through innovation by the facility management function in a PPP in Australia that delivered social infrastructure in multiple locations to a State Government	In PPPs, there is a disconnection between the asset delivery and service delivery phases, which stifles the consortium's capacity to innovate and maximise value
Roumboutsos & Saussier (2014)	To seek the impact on innovation, the paper presents an analytical model based on behavioural economics, with boundary conditions reflecting various contractual configurations in PPPs	The private party in a PPP arrangement has an incentive to invest in low-risk incremental innovations, which impact on, and positively effect, cost savings during construction and operation. Further innovations are hampered by the ability to produce verifiable improvements correlated to performance.
Rose and Manley (2014)	The paper investigates the decision process regarding the adoption of new-to-industry product innovation in road infrastructures. A large quantitative survey is conducted to rank the relative importance of the obstacles constraining the adoption of innovative products.	The paper identifies three important obstacles for innovation: (1) overemphasis on up-front project costs during tender stage; (2) disagreement over who carries the risk of new product failure; and (3) adversarial contract relations
Himmel and Siemiatycki (2017)	The paper examines a public–private partnership project delivery in Ontario, Canada over a decade,	Most innovations realized through the PPP process related to design, construction method, and material selection choices primarily aimed at lowering project cost and risk. More revolutionary innovations are

		not typically achieved through the PPP process
Carbonara and Pellegrino (2019)	The paper offers an econometric analysis to empirically test the hypotheses regarding the relationship between PPP design and innovation. A dataset of 290 PPP projects spanning different countries and sectors extracted by the World Bank PPI Database is used	Findings reveal that the arrangement of PPP projects; the market, contract and network structure, as well as government supports, may affect innovation
Saeed *et al* (2019)	The paper investigates how the PPP process encourages private and public sectors to be innovative. Factors pertaining to both innovation and project performance (project management, asset utilisation and stakeholder management) are examined	The chief innovative feature identified in the Victorian Comprehensive Cancer Centre project is the iconic design that provided flexibility for future expansion, lower operational cost and efficient integration of publicly and privately operated services

Source: authors' elaboration.

Table 3. Comparative summary of features and effects of two types of price-adjustment options

Price-adjustment option	Type I	Type II
Is it mandatory for the concessionaire to implement innovations available on the market?	No	No
In case an innovation is implemented the government payments are reduced in:	a fixed proportion	a fixed proportion of the actual impact of the innovation on costs
Will an innovation be implemented if its impact on operating costs in relation to the expected average impact is	higher? Yes lower? No	It is not necessary to consider an expected level of impact of innovations on costs. All available innovations will be implemented
Does the grantor government experience an opportunity cost if the impacts of innovation on operating costs are higher than expected?	Yes	No

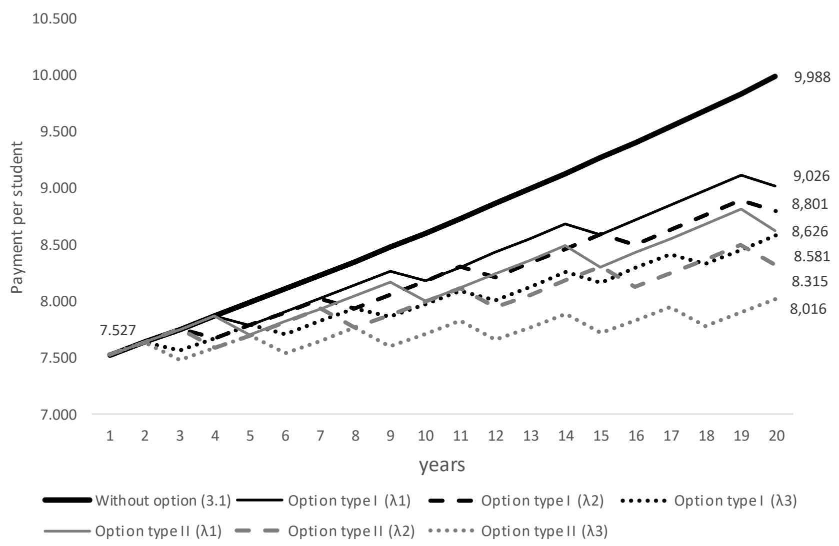
Source: authors' elaboration.

Table 4. Base case scenario

Concession term	20	Years
Construction cost (C)	15.00	million €
School size	32.00	Classrooms
Average classroom size	25.00	Pupils
Total capacity	800.00	Students
Annual expenditure per student (γ_0)	5.000	€
Initial annual governmental utility per pupil (β_0)	7.500	€
Initial annual governmental payment per pupil (α_0)	7.416	€
Average innovation per year (λ)	0.25	
Percentage impact of innovation (Ω)	2.25%	
Economic impact of innovation (c) (average)	112.5	€
Volatility of economic impact of innovation	50.0	€
Reduction of annual payment per pupil (x)	2.50%	
Debt/Construction cost	60%	
Initial debt	9.00	million €
Credit spread	0.00%	
Risk free rate	1.25%	
Debt yield	1.25%	
Corporate tax rate	0.00%	
Average general inflation growth rate (μ_g)	1.50%	
Average specific inflation growth rate (μ_r)	1.60%	

Source: authors' elaboration.

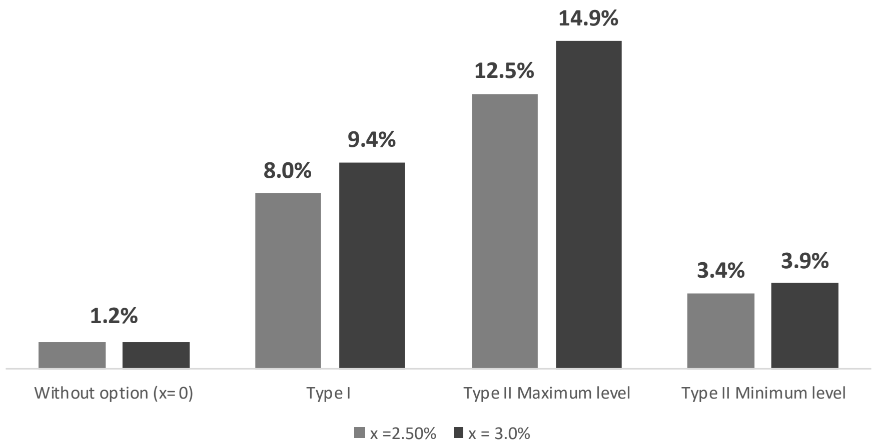
Figure 2. Comparative annual payments per pupil.



Assumptions	α_0 =	7,416	Ω =	2.25%
	λ_1 =	0.2	x =	2.5%
	λ_2 =	0.25	Sigma =	50 €
	λ_3 =	0.333	μ_g =	1.5%

Source: authors' calculations.

Figure 3. Utility of the government in terms of total cost



Source: authors' calculation.

Table 5. Sensitivity of the value for the government of the option type I to changes in λ and x [a]

Λ	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
Innovation period[b]	10.00	6.67	5.00	4.00	3.33	2.86	2.50	2.22	2.00
V_g/ (S α_0 f $_{gx}$)	2.7%	4.0%	5.4%	**6.8%**	8.2%	9.6%	11.0%	12.4%	13.8%
Payment reduction % (x)	2.00%	2.10%	2.20%	2.30%	2.40%	2.50%	2.60%	2.70%	2.80%
V_g/ (S α_0 f $_{gx}$)	5.4%	5.7%	5.9%	6.2%	6.5%	**6.8%**	7.0%	7.3%	7.6%

a. The value in bold corresponds to the base case scenario

b. Number of years in which an innovation event is expected

Source: authors' calculations.

Table 6. Sensitivity of the value for the government of the option type I to changes in Ω

	Value of x from which the adoption of innovation is not guaranteed								
Cost saving % (Ω)	0.5%	1.0%	1.5%	2.0%	2.5%	3.0%	3.5%	4.0%	4.5%
Critical value (x_0)	0.34%	0.68%	1.02%	1.35%	1.69%	2.02%	2.35%	2.67%	3.00%

Source: authors' calculations.

Table 7. Sensitivity of the expected concessionaire ROE to x and λ

x / λ	0.15	0.20	0.25	0.30	0.35
1.25%	8.44%	8.47%	8.49%	8.52%	8.54%
1.50%	8.35%	8.36%	8.36%	8.36%	8.35%
1.75%	8.27%	8.24%	8.22%	8.19%	8.16%
2.00%	8.18%	8.13%	8.07%	8.02%	7.96%
2.25%	8.10%	8.01%	7.93%	7.85%	7.76%
2.50%	8.01%	7.90%	**7.78%**	7.67%	7.56%
2.75%	7.92%	7.78%	7.63%	7.49%	7.35%

Source: authors' calculations.