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Abstract

Public-private partnerships are cutting edge long-term contractual arrangements between a private contractor and the government. The contractual complexity and the high pre-tender research cost are open sesame for inexperienced contractors to refrain from the opportunity. This study encompasses the bidding framework in a game-theoretical fashion while taking the bidders' heterogeneity into account. A simulation captures the heterogeneous uncertainty of the project outcome. A Nash equilibrium method is proposed to arrive at an equilibrium strategy profile, while a strategy game serves as a competition context in order to find the best response in a particular environment. The dynamics reveal the importance of the controllable and uncontrollable project risk that could result in a reluctance for the inexperienced player and a constriction of the market. This occurrence of an oligopolistic situation might be overcome through the introduction of government compensation policies despite the fact that these could come at a fair price.

1. Introduction

Traditional public contracting is characterized by a one-way communication from a public entity towards some private contractors. The government looks for a, usually low-cost, contractor that can build a particular, well-defined infrastructure project. On the other hand, and relying on arguments of efficiency gains and risk transfers, governments introduced a new way of contracting: public-private partnerships (PPPs). The interplay between the public entity and the private entity or special purpose vehicle (SPV) that consists of multiple contractors and sub-contractors is key in these agreements. The synergies that are considered as value for money and that are realized by not only discussing the realization of the project, but also incurring the design and operation and maintenance afterwards, are the main drivers to apply this recent form of contracting. Since they have seen the daylight, PPPs have gained importance and its number has proliferated. Several attempts have been made to define a PPP (e.g., Van Ham and Koppenjan 2001, Hodge and Greve 2007, Wettenhall 2010), but no real consensus has been established. That might be due to the wide landscape of features that the PPP contract can adopt. For the purpose of this research, all the ornaments and often country- or sector-specific features are removed. A public-private partnership is a settlement between a public party and a private sector company to engage in a long-term contractual agreement for designing, building, operating and/or maintaining capital intensive projects, while trying to attain value for money by the appropriate allocation of risk.

To attain the efficiency gains of a long-term commitment, planning is a necessity. That is where the shoe often pinches. When the government selects a wrong contractor, the consequences might be disastrous. The typical textbook cases of the Eurotunnel project (Flyvbjerg et al. 2009) and the New Southern Rail Project in Sydney (Ng and Loosemore 2007) are well-known examples of negative PPP encounters. Every bidder is in some way opportunistic. A rational approach to the decision model of this particular contractor selection framework is worth the effort. One of the key elements in PPP contractual tendering is the determination as a contractor of how much money to invest in pre-tender research. A higher investment in pre-tender research is supposed to result in a lower variability of the expected project outcome. How much money to invest in advance has not been extensively studied in a bidding context. In traditional contracting, this was also not a large issue, as contractors can usually base their bid on standard price lists. The longer time frames and the flexibility of PPP tendering induce more uncertainty and a higher necessity for investing in upfront research. The simulation models that are presented try to address this inquiry and how the bidding environment will influence the mark-up choice of the different contractors. Private contractors that are characterized by a particular experience level are brought together in a competitive framework. A game-theoretical approach gives insights into their bidding behavior and how it relates to the number of other bidders with their respective experience levels. On the other hand, the government should guarantee that there is a sufficient number of bidders. McAfee and McMillan (1986) claim that a lack of bidders can involve the disruption of the value for money concept and, on the contrary, a large number of bidders might force strong bidders to be reluctant to bid because of the reduced probability of winning, while they are faced with a possibly high sunk cost due to the feasibility studies and upfront tendering costs. Zou et al. (2008) recognize the lack of competition as one of the important reasons for failure. An interesting hypothesis that is tackled is that an appropriate government compensation mechanism where certain players get their bid preparation costs reimbursed, could bring solace and increases the competition. Interestingly, Ho (2008) concludes differently. He argues that only under specific conditions, the compensation mechanism might work and he advises against the introduction of reimbursements.

This research project contributes to the PPP research and the bidding in infrastructure projects literature in several ways. First of all, the model includes the pre-tender research cost as a peculiarity of the PPP competitive dialogue in the decision model. Moreover, the impact of the heterogeneity among bidders is studied. The process takes place in a competitive environment. Last but not least, the dynamics of the bidding behavior are related to the governmental compensation tools.

In the next section, a literature review is presented in order to position the research in the PPP and bidding literature. Afterwards, the game-theoretical model is explained. Subsequently, two simulation models are presented: a model that identifies robust Nash equilibria and a strategy game model that looks

for the best strategy in a particular context. The results and insights from the simulation models are stated in Section 4 and these are translated in decision policies in the concluding Section 5.

2. Literature review

The PPP literature covers a wide range of topics. This is clear from the literature reviews that are published by Al-Sharif and Kaka (2004), Ke et al. (2009), Tang et al. (2010) and De Clerck et al. (2012). Yuan et al. (2009) traces out the PPP research landscape in a process-driven framework. This study is merely active in the procurement stage of the agreement with an emphasis on the public-private relationship and tries to make an abstraction of the sector specificity.

The process steps in the bidding procedure are (1) the launch of the government's proposal, (2) the pre-tender research performed by a contractor, (3) the decision of the contractor whether to bid or not, (4) the determination of the bid based on the cost, the risk and the analysis of the opponents and (5) the evaluation of the bid by the government. The issue of pre-tender research is studied in this paper, as there has not been a lot of research on this topic. Nonetheless, in practice, it is often argued that the pre-tender cost is a burden for the contractor. McAfee and McMillan (1986) comment that a lack of bidders causes a disruption of the value for money concept, while a larger number of bidders is also not convenient. This might force strong bidders to be reluctant to participate because of the reduced probability of winning and because they might face high sunk costs of the feasibility studies and the tendering proposals. Ho (2008) doubts about the impact of a compensation model to reimburse the upfront costs. Anyhow, bidding is costly and bidding wrongly is even more costly. Wang et al. (2006) give an overview of possible methodologies that assist in the decision making process. Also for the mark-up decision itself, the literature on bidding in infrastructure projects offers several possibilities, like entropy methods (e.g., Christodoulou 2010), simulation (e.g., Cagno et al. 2001) or bi-objective optimization (e.g., Iyer and Sagheer 2012). Some researchers also warn for opportunistic behavior that can be expressed by the consideration of beyond contractual rewards (e.g., Lo et al. 2007) or unbalanced bids (e.g., Wang et al. 2006). This research tries to implement a game-theoretical approach to explain why bidders behave as they do.

Of course, some of these methodologies can not be transferred to a PPP environment and one should account for the peculiarities of the PPP arrangement. Before moving on to bidding, the contractor should determine an appropriate price. Standard price lists do not suffice in these highly uncertain contracts with a long-term nature. Not only the monetary aspect is important, but also other price determining factors such as the concession duration and the toll tariff. For price setting, researchers use a restricted number of quantitative techniques like simulations (e.g., Zhang 2009), regression models (e.g.,

Ngee et al. 1997), social marginal cost pricing (e.g., Evenhuis and Vickerman 2010), fuzzy logic (e.g., Ng et al. 2007) and financial methods (e.g., Shen et al. 2002, Cheng and Tiong 2005). Government interventions need an evaluation as well. Fishbein and Babbar (1996) classify governmental support systems in eight categories. The government will install these support systems in order to provoke larger interest in a risky project. Monteiro (2010) reports that the alignment of the private interest with the public interest due to the introduction of appropriate incentive schemes can overcome quality dilapidation problems or other issues that would fall at the government's expense and that follow from the "corrupt" behavior in the bidding stage. Such government support systems have to be reflected in the bid and accordingly need valuation. Ho (2008) studies the subsidy for the pre-tender research cost to which a player is subjected. A well-known problem is the minimum revenue guarantee in the transportation sector. It is a common way to put a cap on the risk that has to be accepted by a private entity. A valuation of this intervention is performed through a real option analysis (Liu and Cheah 2009). Last but not least, the valuation of the regulations like a maximum toll charge or a minimum capacity have been considered by researchers (Chen et al. 2006, Subprasom and Chen 2006).

An important stream of research in the PPP procurement literature originates from one of the main value for money drivers: the ability to transfer risk from the public entity towards a private party (Jin 2010). Grimsey and Lewis (2002) are the pioneers in this field, identifying some particular risks of the complex PPP arrangement. Different risk classification schemes have been introduced (e.g., Li et al. 2005, Loosemore 2007). After the identification of the risks, they should be appropriately assessed. The last step consists of the allocation of the risks. An improper allocation may lead to the harmful renegotiation of the contract (Marques and Berg 2011). The adagio "allocate the risk to the party that is most capable to deal with it" is not always a bed of roses. Both quantitative (e.g., Medda 2007, Lam et al. 2007) as well as qualitative (e.g., Li et al. 2005, Loosemore 2007) methods have been developed to define the role of each stakeholder in the mitigation of a particular risk. As will be supported in the simulation of this paper, transferring extra uncontrollable or controllable risk will require extra compensations (Gruneberg et al. 2007). The number of real calculative models like the one of Eriksen and Jensen (2010) who use the Capital Asset Pricing Model to calculate an acceptable risk premium is rather low.

Pricing is not the same as bidding. The bidding framework explicitly deals with opponents in the field and sets an acceptable mark-up. The PPP bidding context can be identified according to four dimensions. First of all, it is believed that bidders have some kind of heterogeneity. This is acknowledged by prior experimental work of Oo et al. (2010). Other authors in the PPP field do not take this into consideration, assuming that all bidders are equal (e.g., Shen et al. 2007, Ho 2008). The second dimension is related to the extent that it is repetitive. Bidders will not blindly engage in a dozen of projects every month, so it is hard to rely heavily on past bidding behavior. Most of the construction literature assumes a

repetitive behavior because they rely considerably on past bidding behavior (e.g., Oo et al. 2007, Shen et al. 2007). Thirdly, in a PPP context, the government not only decides based on price. In a first round, the quality of the proposed bids will have the overhand, and after the prequalification, the cost determinant comes in (Abudayyeh et al. 2007). Lastly, bids are submitted simultaneously. That means that no sequential bidding will occur and a bidder does not have bidding information on its competitors. The competitive dialogue is the prevalent method, where the government will communicate with every bidder separately in order to optimize the proposal and to clarify certain aspects.

3. Methodology

In the contemporary PPP bidding literature, the competition aspect is usually ignored. Authors look at setting the parameters for the contract on a one-to-one relationship between the preferred contractor and the government (e.g., Chen et al. 2006, Medda 2007). The bidding framework that has been set here tries to overcome this isolation assumption. In the final bidding stage, where prequalification has been performed, a couple of remaining bidders are left. The number of bidders in this competition is not necessarily defined beforehand and is merely dependent on the project under study. Each bidder is assumed to have some characteristics: the risk attitude, the objectives he is aiming for and the experience level. Every bidder will firstly determine an appropriate investment level, i.e. the amount of money to invest in pre-tender research. With the information he attains, the mark-up will be determined. Of course, these decisions are not made independently. External factors will come into play. The strategy that a bidder adopts is influenced by the project itself and by the entailed risk. Moreover, the number of other bidders and their respective experience levels will be reflected in the preferred strategy. Last but not least, the governmental decision process and the proposed compensation policies might trigger a deviating strategy.

3.1 Game-theoretical model

The preferred methodology in this research is a game-theoretical approach. In so doing, it is possible to include the interactions and dependencies of the different players in a model. Game theory has not often been used in the PPP context so far. As stated earlier, Ho (2008) uses game theory to analyze the equilibrium bid behavior of a contractor in case of government compensation. Besides, Ho (2008) studies the problem of renegotiation which means that a contractor who suffers a loss, will require help from the government as the lender of last resort. Shen et al. (2007) rely on game-theoretical insights to determine the appropriate concession period for a contract, while Medda (2007) has set up a risk allocation model through the bargaining process. Last but not least, Tserng et al. (2012) game-theoretically emphasize the importance of national PPP units in promoting PPP projects.

In this paper, it is assumed that the government launches a project. This decision is made by an exogenous force, or nature (symbol N in Figure 1). Afterwards, the number of bidders with their respective experience levels is determined, which is common knowledge for every contractor. Consequently, the number of branches in Figure 1 starting from the initial government node is equal to the number of situations that occur. Each situation, or sub-game, represents a combination of experience levels for the different players. In the simulation model, the experience levels range from zero to ten, where zero represents no experience and ten is used to express maximum experience for this particular project type. The simulation models look at every sub-game separately in order to attain sub-game perfect equilibria. As some sub-games are equivalent to others, the number of proper sub-games (G) is given by a combination with repetition:

$$G = \binom{P + E - 1}{P} = \frac{(P + E - 1)!}{P! * (E - 1)!}$$

with P the number of players and E the number of experience levels. Game theory offers other definitions that need to be taken into account. A strategy in game-theoretical terms defines the behavioral pattern for every situation. A strategy for a certain player subsequently indicates the choice to be made at each decision point or information set. As the investment level and mark-up level are continuous and can be expressed as a percentage, an infinite number of strategies can be composed. In order to limit the number of strategies, discrete levels of investment and mark-up on a scale with equal intervals are established in this simulation. If I represents the number of investment levels and B the number of mark-up levels and given that there are G information sets with I choices and $G * I$ information sets with B choices, the total number of strategies (T) is given by:

$$T = I^G * B^{G*I}$$

In this research, in order to reduce the number of strategies, the investment and mark-up level are combined to form a single choice for each player. This entails game-theoretically that a player who is making a mark-up decision, has forgotten what he has invested before. Nonetheless, this information is inherently present in the pay-off. The remaining strategies add up to:

$$T' = (I * B)^G$$

Finally, the number of strategy profiles equals T'^P . These form all possible combinations of strategies chosen by the players and intrinsically determine the size of the pay-off matrix. In practice, one strives for sub-game perfectness. In the problem under study, this refinement of the equilibrium reduces the complexity of the system and permits to optimize the decision in every sub-game separately. The theoretical number of strategies within a sub-game g is:

$$T_g = I * B^I$$

Applying the relaxation of the simultaneous mark-up and investment decision, the number of strategies left within a sub-game is:

$$T'_g = I * B$$

Table 1 summarizes the values for the different game characteristics as an example. In the next sections, two methods are presented that are applied to tackle the bidding game. The second line of Table 1 represents the parameters for the performed simulation with the Nash equilibrium method and the third and fourth line give the values for the simulation done with the strategy game method.

	<i>P</i>	<i>E</i>	<i>I</i>	<i>B</i>	<i>G</i>	<i>T</i>	<i>T'</i>	<i>T_g</i>	<i>T'_g</i>
(1)	2	2	2	2	3	512	64	8	4
(2)	3	3	6	6	10	2.95×10^{54}	3.66×10^{15}	279,936	36
(3)	3	6	21	51	56	$1.40 \times 10^{2,082}$	4.66×10^{169}	1.52×10^{37}	1,071
(4)	5	6	21	51	252	$4.58 \times 10^{9,369}$	3.21×10^{763}	1.52×10^{37}	1,071

Table 1: The relationship between the characteristics of the game and the complexity of the model

Figure 1: Game tree for a two-player game

3.2 Simulation

Real-life project data are rather scarce due to the highly competitive PPP environment. Practitioners and researchers acknowledge that proper project databases should be set up in order to increase the understanding of the PPP market and the behavior of its stakeholders. Some countries, like India, started

to systematically gather information of projects that would assist in validating the available models in the future.

A simulation approach could bring guidance in the dynamics of the game in an entirely rational, non-cooperative environment. The models that are presented in the next sections rely on simulation to generate data and try to identify for every player stable strategies that are an optimal response given the optimal strategies of the opponents.

It is assumed that the experience level is given and commonly known among all players in the game. The strategy is private information and is chosen in such a way that a player tries to optimize his average pay-off. In so doing, the optimal strategy is not determined based on one project outcome only, but on the average pay-off after, say, one thousand projects. In order to determine a contractor strategy, the simulation model is run for every sub-game, but in the remainder of this section the model is explained for a particular combination of contractors' experience levels and the term "strategy" refers to the partial strategy for this particular sub-game of the PPP bidding environment. A strategy is defined by an investment percentage (i.e., as a percentage of the initial expected project cost μ , e.g., 1,000,000€) and a mark-up level. Two assumptions are key in the different models. First of all, the experience level and the investment level have a knowledge impact (i.e., the knowledge impact assumption). The more experienced a player is and the more he invests, the better will be the expected cost estimate. Secondly, these two factors influence the contractor cost as well (i.e., the cost impact assumption). As experience is enlarged or as investment is undertaken, efficiency gains and innovative disclosures could guarantee a lower cost.

The two methods that are presented in the next section have a similar simulation approach, shown graphically in Figure 2. The simulation results are based on the realization of m project outcomes. For each iteration $r = 1, 2, \dots, m$, an actual project cost X_r is selected from the normal distribution $N(\mu, \sigma^2)$ with μ the mean project cost and σ^2 the project variance or equivalently the uncontrollable project risk. The project variance refers to the variability that can not be accounted for. As the government transfers more uncontrollable risk to the private party, like the demand risk for a toll road, this σ might soar. The actual outcome X_r that is selected, is assumed to be the best estimate for each contractor and it will be the mean value of the cost distribution for each contractor.

For each player, an expected contractor cost X_p is simulated from the contractor's cost distribution. Nonetheless, the variance of the distribution of the contractor cost is different for every player and relates to the experience level and the investment level and is a translation of the knowledge assumption. The contractor's cost distribution is $N\left(X_r, \sigma_c^2\left(e_p, i(s_p)\right)\right)$. For reasons of simplicity, normal distributions for the actual project cost and the contractor's cost have been assumed. In future research,

skewed distributions such as a β -distribution could be considered. The variance of this distribution depends on the one hand on the experience level e_p for each player p , with $p \in \{1, 2, \dots, P\}$ and $e_p \in [0, 10]$. On the other hand, the variance is related to the investment percentage incurred in the strategy $s_p \in S_p$ and $i(\cdot) \in [0, 20]$ given in a percentage value, with S_p the set of partial strategies for player p . The total contractor variance function is modeled as the sum of three variances: the uncontrollable risk variance σ^2 , the variance due to a lack of experience and the variance due to a lack of investment. The latter two terms are modeled as squared negative exponential functions. The general project standard deviation σ could be seen as an uncontrollable project risk. In general, a part of the variability can be controlled through appropriate pre-tender research, but there is still a part, translated into σ , that can not be accounted for. This parameter will also be larger when more risks are transferred from the public entity towards the private partner. The standard deviation that is incurred in the contractor's cost distribution reflects the knowledge impact of investment and experience. Consequently, γ_e mirrors a knowledge requirement or the maximum impact of a lack of experience, accompanied by the experiential learning rate λ_e . Symmetrically, γ_i can be interpreted as an innovation parameter or the maximum impact of a lack of investment together with an investment learning rate λ_i . The resulting total variance function is illustrated in Figure 3 and mathematically gives:

$$\sigma_c^2(e_p, i(s_p)) = \sigma^2 + (\gamma_e e^{-\lambda_e e_p})^2 + (\gamma_i e^{-\lambda_i i(s_p)})^2$$

From Figure 3, it is clear that the move towards a higher investment level and a higher experience level results in a lower standard deviation for the contractor's cost with a floor at the value for the uncontrollable project standard deviation σ , that equals 10% for the example in Figure 3.

Once an expected project cost for each player has been selected, the cost impact assumption that was stated earlier needs to be taken into account. The contractor cost X_p is increased for every player depending on his experience and his investment choice, which is given by the function $g(\cdot)$. The cost impact function $g(\cdot)$ is given by the sum of two negative exponential functions and is dependent on the experience level and the investment choice of the contractor:

$$g(e_p, i(s_p)) = \beta_e e^{-\mu_e e_p} + \beta_i e^{-\mu_i i(s_p)}$$

This cost impact assumption brings along four parameters: an experiential cost disadvantage or efficiency parameter β_e together with the decrease rate μ_e and similarly, β_i together with the rate μ_i reflects that a (rather limited) cost decrease through investment can be realized. This results in the final estimated project cost for each contractor, $c_p = c_p(\cdot) = X_p (1 + g(\cdot))$. The strategy's mark-up level $b(s_p)$ is applied to the estimated cost and determines the contractor proposal for this particular player $y_p = y_p(\cdot) = c_p(\cdot) (1 + b(s_p))$.

Last but not least, also the actual cost needs a correction for the cost impact assumption. The actual project cost X_r will now depend on who was the winner of the tender. So in case that player p has proposed the lowest bid, the function $g(.)$ will be evaluated for player p given his experience level and his investment choice, so that the contractor dependent actual cost is now: $a_p = a_p(.) = X_r(1 + g(.))$.

For every bidding experiment, a pay-off calculation will determine the preferred path to follow. A contractor will look at the strategy that guarantees the largest pay-off with considerable confidence. In this research, the lowest cost assumption is taken for granted. This means that it is assumed that all contractors are suitable on the qualitative level and that the lowest cost is the government selection criterion in this final stage. The pay-off function $f_p(s)$ for a particular player p for the strategy profile $s = (s_1, s_2, \dots, s_p)$ is modeled as follows:

$$f_p(s) = \begin{cases} y_p(.) - a_p(.) - i(s_p)\mu & \text{if } \forall j \neq p: y_p(.) \leq y_j(.) \\ -(1-d)i(s_p)\mu & \text{else} \end{cases}$$

The winner's pay-off is the profit given by the proposal minus the actual project cost $a_p(.)$ and the pre-tender investment, while the others lose the investment entirely (when $d = 0$) or partially (when $d > 0$) if the government has installed a government compensation policy. This compensation policy could level the playing field by giving extra incentives to the players to perform pre-tender research. The parameter d refers to the percentage of the investment cost that the government reimburses to every losing bidder in the competitive dialogue. Consequently, a linear compensation mechanism is assumed. In practice, other compensation schemes are applied as well, for instance a compensation related to the position in the ranking where the percentage decreases as the player is ranked lower. This type of extension will be considered in future research.

Section 3.3 covers the Nash equilibrium method that simulates every player's pay-off for each combination of strategies. Section 3.4 deals with a strategy game that looks for the best response for a particular player to a population of good strategies for his opponents. A homogeneous and heterogeneous game are introduced in Sections 3.4.1 and 3.4.2 respectively to compose the populations.

Figure 2: Representation of the simulation procedure with the initial actual cost distribution and the contractor's cost distribution for a particular player.

Figure 3: Representation of the standard deviation of the contractor's cost distribution

3.3 Nash equilibrium method

The Nash equilibrium method considers every strategy profile, i.e., every possible combination of strategies. P players each have a known experience level e_p with $p \in \{1, 2, \dots, P\}$ and $e_p \in [0, 10]$ and every player p has a set S_p of possible strategies that are the same for each player. This results in a set of strategy profiles $S = S_1 \times S_2 \times \dots \times S_P$. The game under study can be formally written as (S, f) with $f = (f_1(s), f_2(s), \dots, f_P(s))$ the pay-off function for $s = (s_1, s_2, \dots, s_P)$ and $s_p \in S_p$ for every $p \in \{1, 2, \dots, P\}$ or equivalently $s \in S$. Keeping sub-game perfectness in mind, the Nash equilibrium method is run for every possible sub-game. Within a particular sub-game, for every combination of strategies, the pay-off for each player is calculated. For every cell in the pay-off matrix, this calculation is performed for m projects with the actual value from the distribution $N(\mu, \sigma^2)$. When the pay-offs for every combination of strategies are calculated, the equilibrium can be identified. Define s_p as a strategy for player p and s_{-p} a strategy profile of all the players except player p . A Nash equilibrium strategy profile $s^* = (s_1^*, s_2^*, \dots, s_P^*)$ can then be identified if it satisfies $\forall p, s_p \in S_p: f_p(s_p^*, s_{-p}^*) \geq f_p(s_p, s_{-p}^*)$.

The algorithm looks for a Nash equilibrium based on the simulated pay-offs. As in every simulation model, prudence is in order. The pay-offs are the mean of m simulated project outcomes. A confidence interval for these averages for every strategy profile can be constructed. Furthermore, the algorithm only looks into unique Nash equilibria. Sometimes no robust equilibrium is found and sometimes the two-sample t-statistic proves no significant difference with an alternative equilibrium. The mixed strategy equilibrium has not been calculated and conclusions are only drawn based on the robust, unique equilibria and the dynamics of the equilibria when several parameter values are tested. In order to be able to give some interpretative results from the pay-off matrix, the simulation model deals with three players with experience levels $e_p \in \{0, 5, 10\}$, each having six investment choices and six mark-up choices. For this particular sub-game with given experience levels, 36 strategies are installed.

The drawback of analyzing all possible strategies or increasing the number of players or the number of experience levels, is that computation times increase heavily due to the exponential growth of the pay-off matrix. The equilibria will also tend to move towards mixed equilibria. The strategy game method in the following section tries to overcome these issues.

3.4 Strategy game method

The strategy game method attempts to discover the best response to a strategy combination of the opponents within a proper sub-game with a given number of players and their respective experience levels. The approach is somewhat different from the basic game tree as the focus tends to be on a particular player. Consider a specific sub-game $Q = (e_0 | e_1, \dots, e_{P-1})$, where e_0 represents the experience

level of the contractor under study and $e_1, \dots, e_{P-1}$ represent the experience levels for the $P - 1$ opponents. Every opponent $p \in \{1, 2, \dots, P - 1\}$ has a population of n suitable or “good” strategies $R_p = \{r_{p1}, r_{p2}, \dots, r_{pn}\}$ and $R_p \in S_p$, indicating that the opponents are not stupid. For each iteration of the algorithm, a strategy for every opponent is chosen, say the strategy profile $s_{-0} = (s_1, s_2, \dots, s_{P-1})$ (i.e., all the strategies are fixed except for the contractor under study). The player under study, with experience level e_0 , will test all his possible strategies $s_0 \in S_0$ against the installment s_{-0} . The average pay-off with the accompanying standard deviation is considered after a user-defined number of replications. Afterwards, the next iteration starts with the selection of a new strategy profile s_{-0} and again the pay-off for every strategy of player 0 is derived. After m iterations of this algorithm, the average pay-off and the associated standard deviation are calculated and the decision maker sets up a ranking of his strategies according to his utility. Maximizing the expected pay-off could be the preferred strategy by the decision maker. Alternatively, the decision maker can also base his preferred strategy on the appraisal of the pay-off and the invoked standard deviation. Anyhow, it is assumed that only efficient strategies are considered. A strategy is considered efficient when there is no other strategy that can attain the same average pay-off, with lower uncertainty, i.e. a smaller standard deviation. An example is given in Figure 4.

Figure 4: Efficient versus inefficient strategies

One question has been unanswered so far: how to determine the population R_p for every opponent? Hereto, two methods have been introduced: the homogeneous and the heterogeneous method.

3.4.1 Homogeneous method

The homogeneous method doesn't take the heterogeneity of the players into account. All players are assumed to be equivalent and all have the same experience level. This homogeneous analysis is worth the analysis due to the practical applicability as a lot of immature markets deal with homogeneous players. It is often seen that the players that engage for a particular PPP contract, have the same (low) experience in the sector. Moreover, the Nash equilibrium method could not guarantee clear unique equilibria for situations where all the players had the same experience level, leaving in that case mixed equilibria as a solution. The simulation method is actually set up as a tournament with several rounds. The number of rounds is user-defined. Again, P players, but now all with experience level $e = e_1 = \dots = e_P$ are competing. Initially, P^r strategies are randomly selected, with r the number of rounds of the tournament. Recall that a strategy is defined by an investment choice and a mark-up choice. The results that are shown later in this paper assume 21 investment choices (i.e., from 0 to 20%) and 51 mark-up choices (i.e., from 0 to 50%), leading to 1071 possible strategies. The P^r selected strategies are divided in P^{r-1} groups of P strategies. Within each group, the competition between strategies is started and after calculating the pay-offs once a predefined number of actual project outcomes has been performed, the best strategy is selected and the program continues to the next round, where only P^{r-1} strategies are remaining. In the final round, only P strategies are left and the ultimate winner is selected.

This homogeneous game is played for every experience level of opponent $p \in \{1, \dots, P-1\}$ of the initial sub-game Q . When r is large enough, the tournament converges towards a competition between strong strategies in a particular range. Consequently, the P strategies from the final round for every experience level will be transferred to the strategy population R_p .

3.4.2 Heterogeneous method

The remainder of the elements in the strategy population for every opponent is derived through the heterogeneous game. Recall sub-game $Q = (e_0 | e_1, \dots, e_{P-1})$. For every opponent $p \in \{1, 2, \dots, P-1\}$ a heterogeneous game is played. For the heterogeneous game of opponent p , define the alternative sub-game $Q_p = (e_p | e_0, \dots, e_{p-1}, e_{p+1}, \dots, e_{P-1})$. The heterogeneous game now runs quite similarly to the original strategy game. Nonetheless, the opponents in sub-game Q_p will randomly select a strategy from all possible strategies. In other words: $\forall q \in \{0, \dots, e_{p-1}, e_{p+1}, \dots, e_{P-1}\}: R_q = S_q$. Consequently, any possible strategy can be chosen by an opponent. For each iteration, a strategy for every opponent q is chosen, resulting in the strategy profile $s_{-p} = (s_0, \dots, s_{p-1}, s_{p+1}, \dots, s_{P-1})$. Player p , with experience level e_p , will test all his possible strategies $s_p \in S_p$ against the installment s_{-p} . The average pay-off is calculated after a number of replications from the project database. Afterwards, the next iteration will be

performed and a new strategy profile s_{-p} is selected. After m iterations, the best $n - P$ strategies will be added to the P strategies from the homogeneous game and become part of the population R_p for this particular player.

When the homogeneous game and the heterogeneous game are played for every opponent from sub-game Q and the respective strategy populations are filled, the strategy game method starts and will lead to efficient investment and mark-up levels.

4. Results and insights

The two models lead to several management insights and support each other in these findings. The next section describes the interpretation of the parameters and the appropriate values that were used in the simulation models. For each combination of parameter values, a simulation experiment has been set up. Of course, the Nash equilibrium model is computationally intensive and only a limited number of strategies can be considered, while this freedom is larger in the strategy game. An overview of the parameter values can be found in Table 2.

The insights that are given in this section are robust insights based on unique equilibria and within considerable confidence intervals. The Nash equilibrium model reports the equilibrium for a specific scenario, together with the pay-off distribution among the bidders and the average cost for the government in equilibrium. The strategy game method reports the winning strategies that guarantee the highest pay-off or that are on the efficient frontier for a specific bidding environment Q .

4.1 Parameters

A number of parameters were introduced in previous sections. A wrap-up of the parameters and the values that were tested in the model can be found in Table 2.

Parameter	Interpretation	Values
σ	Uncontrollable project risk	5%,10%,15%
γ_e	Maximum impact of a lack of experience	5,10
γ_i	Maximum impact of a lack of investment	5,10,20,50
λ_e	Experiential learning rate	0.25,0.50
λ_i	Investment learning rate	0.25,0.50
β_e	Experiential cost disadvantage	5,10
β_i	Investment cost disadvantage	0,5
μ_e	Experiential cost decrease rate	0.25,0.50
μ_i	Investment cost decrease rate	0.25,0.50
d	Government compensation level	0%,20%,50%,80%,90%

Table 2: Parameter values used in the models

Before heading to the results, a final comment is made on the number of strategies that are dealt with in the two models in order to keep the computation time limited. Table 3 gives an overview.

	Nash equilibrium game	Strategy game
Experience levels	0,5,10	0,2,4,6,8,10
Investment levels	0%,2%,4%,...,10%	0%,1%,2%,...,20%
Bidding levels	0%,8%,16%,...,40%	0%,1%,2%,...,50%

Table 3: Values for situation factors and the decision variables

4.2 Nash equilibrium results

The Nash equilibrium method defines the equilibrium outcome after running a number of m , say 1,000 simulations as in preliminary tests, this seemed to be sufficient for the average pay-offs to converge. The analysis gives intuitions concerning the dynamics of the equilibrium if the parameters are modified. Moreover, the average cost for the government gives insights into how a particular compensation policy affects the total cost to society. The analysis is two-fold. Starting from a base case situation, the ceteris paribus sensitivity analysis looks into the equilibrium change through a parameter modification. Of course, also the interaction effects among the parameters offer an insight into the interplay between variables. For the statements that are made, a reference to Table 4 is added to give an equilibrium example. For the analysis of the government cost, a regression model and an ANOVA study with the second order interaction effects has been set up for the three different levels of the project standard deviation σ .

4.2.1 Parameter effects

1. Impact of σ

In the base case, where all parameters with the exception of β_i stick to their minimum value, an equilibrium is attained where the investment is absent in any combination of the experience levels for the different players. For instance, when the project standard deviation is 5%, a zero-investment and 8% mark-up strategy for all players is defined as the unique equilibrium (Ex. 1). Consequently, not a single player will invest and the pay-offs are distributed according to the experience level, as a more experienced player will obtain a larger pay-off. This standard equilibrium is modified when more uncontrollable uncertainty is incurred in the project. The players will compensate this increased uncertainty through a surge in the mark-up level. The increase is considerable: an average mark-up of 16% in the 10% case and 24% when σ equals 15% (Ex. 2 and Ex. 3). Moving towards a project standard deviation of 20% would leave us with a strategy that reaches the maximum assumed mark-up level, i.e. 40% in this experiment. Besides, both the expected pay-offs for the contractors as well as the government cost increase sharply.

2. Impact of β_e

Another determinant that considerably impacts the mark-up is the cost disadvantage incurred in parameter β_e . Especially the inexperienced players move towards a higher mark-up level when the cost disadvantage of being inexperienced gets larger. On average, the cost for the government goes up (Ex. 4)

3. Impact of γ_i

The key peculiarity of a PPP lies in the long-term commitment that comes along with a necessity to engage in upfront research. It is expected that the investment is related to the contractor's cost standard deviation. A particular project may require a different investment level than another project. A sports infrastructure project might have a more standardized nature than a toll road. The latter inflates the uncertainty when no investment has been performed. This requirement can be controlled through γ_i . It is expected that, when γ_i increases, more investment will be apparent in the equilibrium solution. Nonetheless, this is not the standard case. The investment incentive should be triggered through other mechanisms. The simulation shows that a larger innovation parameter leads to a higher mark-up level (Ex. 5). The contractor compensates for the downside risk. Only when γ_i attains higher values (e.g., $\gamma_i > 20$), some investment will be evident in the equilibrium (Ex. 6). If the government believes it is necessary to invest also in the lower innovation parameter cases, an appropriate compensation policy for the pre-tender investment can be installed.

4. Impact of d

With respect to the simulation, the parameter d , that is expressed as a percentage of the investment cost, is increased when a linear compensation scheme is introduced. The effect anyway depends on the other parameters, but as a general tendency, an increase in the government compensation percentage raises the investment willingness. Logically, the threshold compensation level that makes the equilibrium shift towards a higher investment level is inversely related to the innovation parameter (Ex. 7 versus Ex. 8). Moreover, a more experienced player requires a smaller government intervention than an inexperienced player (Ex. 9 versus Ex. 10). This effect is emphasized when the experience gap between the players is considerable. It was mentioned before that these effects do not appear on a standalone basis. Other parameters make the effects stronger or mitigate the equilibrium change. The efficiency parameter β_e inhibits the movement towards a higher investment level for the less experienced players, so a higher government compensation level remains as a solution (Ex. 11 versus Ex. 12). An adverse effect is the increase in the β_i parameter that contributes to a small investment jump for the less experienced players as investment will now have a direct effect on the contractor's cost (Ex. 11 versus Ex. 13). In the higher γ_i cases, the equilibrium situation prescribes an investment and is usually accompanied by a high mark-up to compensate for the uncertainty. The installment of an average government compensation provokes the

move towards a higher investment level (Ex. 6 versus Ex. 14 and Ex. 15). Simultaneously, due to the government compensation policy, contractors prefer a diminished mark-up level.

5. Impact of γ_e

The knowledge requirement parameter γ_e mainly has a mark-up impact (Ex. 10 versus Ex. 16). The margin rockets up when the parameter increases and puts a break on the investment of an inexperienced player. Even high government compensations can not motivate a player as long as γ_i is not excessively high. If the experience level gains importance, the government should consider whether to support an inexperienced player in order to free up the market or to let the market forces play in a narrow market through the attribution of no or a limited compensation. Eventually, a suitable compensation policy needs to be considered. An overcompensation leads to perverse incentives and could miss the target it is aiming for, while the total cost to society plummets as will be shown in Section 4.2.2 and Figures 7 and 8. Another danger exists when the γ_i parameter reaches high values and demotivates new contractors to invest, leaving the lazy, maximum mark-up solution as the most efficient response. In the case of these projects that are considered as high-end, risky undertakings, expected pay-offs might become negative (Ex. 17). A compensation strategy might only work in a competitive environment with experienced players, while in situations with considerable knowledge differences, the experienced player acts opportunistically. As the equilibrium over the different situations is studied in further detail, a distinction between mark-up levels is identified. An inexperienced player will usually be less cost efficient and requests for higher margins. This distinction is more supported when γ_e is larger.

6. Impact of λ_e and λ_i

The influence of the parameters that affect the decreasing rate of the contractor's cost variance lies in the fact that the investment will happen sooner, which means that a smaller government compensation or a smaller value for γ_i can already guarantee an investment. Additionally, the investment growth through the change of the parameters will be limited. Investment will be more standard, but its ceiling is lower than for the smaller values of λ_e and λ_i (Ex. 7 versus Ex. 18).

4.2.2 Government cost

The question to what extent the parameters contribute to the government cost is studied through an analysis of variance and a regression analysis that includes the second order interaction effects. The input data consist of all the scenarios for which a pure strategy Nash equilibrium was found in the simulation. The other cases are omitted. As σ increases, the number of outcomes that result in a pure strategy equilibrium diminishes. For the simulation, the percentage of scenarios with a pure strategy equilibrium equals 79.6% when σ is 5%, 69.7% in the 10% case and only 53.5% if σ has a value of 15%. The

adjusted R-squared coefficient equals 90.89% (89.63%, 86.05%) for all scenarios for which $\sigma = 5\%$ (10%, 15%). Three effects deserve further attention.

The perverse incentives are clear from Figure 6 (a) and 6 (b). The increase in the parameters γ_e and β_e incur a cost increase for the government, especially in the cases where the experience gap is larger (i.e., the situations 2 and 3 that, according to Figure 5, refer to a situation with two inexperienced players and one experienced player with, respectively, average experience and maximum experience). Moreover, in the situations where there is one inexperienced player and the others are experienced (situations 4, 5 and 6), the cost decreases at a γ_e value of 20. The experience disadvantage for the inexperienced player is too large to compete against the incumbents (Figure 6(a)). A second observation is related to the government compensation policy. Certain government incentives lead towards an investment change for the contractors. Figure 7 shows that without compensation, the main effect of γ_i on the total government cost is limited, while it becomes considerable as the government compensation percentage increases. Interestingly, the extra cost for the government is low when the innovation parameter is within bounds. Together with the former observation that a high compensation is necessary to trigger investment behavior, the recommendation to allow these higher compensation models is justified. As γ_i soars, prudence is in order. The extra government cost will soon become substantial. Apparently, *ceteris paribus*, a slope discontinuity is apparent for the increase in the government compensation (Figure 8 (a) and 8 (b)). When σ equals 5%, this discontinuity appears at $d = 60\%$, while it is at $d = 80\%$ when $\sigma = 15\%$. A comparison of the two graphs also clearly indicates that the extra margin that is asked for by the contractors due to the high uncontrollable risk is reflected in the surge of the average government cost.

The limitations of the Nash equilibrium method (e.g., a limited number of strategies can be tested, and the number of experience levels is small) require a comparison with the results from the strategy game of the following sections.

	Model parameters										Situation			Nash equilibrium Investment/mark-up (simulated pay-off)			Cost to governmen t
Ex.	σ	γ_e	γ_i	λ_e	λ_i	β_e	β_i	μ_e	μ_i	d	e_1	e_2	e_3	s_1^*	s_2^*	s_3^*	
1	5	5	5	0.25	0.25	5	5	0.25	0.25	0	0	5	10	0%/8% (4,309)	0%/8% (23,526)	0%/8% (31,549)	1,083,146
2	10	5	5	0.25	0.25	5	5	0.25	0.25	0	0	5	10	0%/16% (15,633)	0%/16% (37,007)	0%/16% (44,449)	1,116,535
3	15	5	5	0.25	0.25	5	5	0.25	0.25	0	0	5	10	0%/24% (24,330)	0%/24% (44,591)	0%/24% (55,404)	1,144,562
4	5	5	5	0.25	0.25	10	5	0.25	0.25	0	0	5	10	0%/16% (1,087)	0%/8% (29,101)	0%/8% (50,710)	1,107,749
5	5	5	10	0.25	0.25	5	5	0.25	0.25	0	0	5	10	0%/16% (14,303)	0%/16% (37,453)	0%/16% (40,291)	1,117,603
6	5	5	20	0.25	0.25	5	5	0.25	0.25	0	0	5	10	0%/40% (9,002)	2%/24% (40,795)	2%/24% (48,844)	1,161,433
7	5	5	10	0.25	0.25	5	5	0.25	0.25	80	5	5	5	2%/16% (26,565)	2%/16% (27,179)	2%/16% (28,116)	1,162,372
8	5	5	20	0.25	0.25	5	5	0.25	0.25	60	5	5	5	4%/16% (5,026)	4%/16% (7,624)	4%/16% (6,493)	1,159,656
9	5	5	10	0.25	0.25	5	5	0.25	0.25	60	0	5	10	0%/16% (10,599)	2%/16% (29,101)	2%/16% (39,000)	1,143,690
10	5	5	10	0.25	0.25	5	5	0.25	0.25	80	0	5	10	2%/16% (11,240)	2%/16% (34,030)	2%/16% (40,862)	1,170,817
11	5	0	10	0.25	0.25	5	5	0.25	0.25	80	0	5	10	2%/16% (12,188)	2%/16% (31,526)	2%/16% (40,268)	1,167,906
12	5	0	10	0.25	0.25	10	5	0.25	0.25	80	0	5	10	0%/16% (3,240)	2%/16% (35,817)	2%/16% (53,504)	1,169,270
13	5	0	10	0.25	0.25	5	0	0.25	0.25	80	0	5	10	0%/24% (7,078)	2%/16% (27,535)	2%/16% (39,271)	1,129,589
14	5	5	20	0.25	0.25	5	5	0.25	0.25	40	0	5	10	0%/40% (-4,407)	4%/16% (17,071)	4%/16% (23,158)	1,135,921
15	5	5	20	0.25	0.25	5	5	0.25	0.25	80	0	5	10	4%/24% (-2,669)	4%/16% (20,353)	4%/16% (31,608)	1,189,107
16	5	10	10	0.25	0.25	5	5	0.25	0.25	80	0	5	10	0%/24% (3,634)	2%/16% (33,093)	2%/16% (54,650)	1,152,327
17	5	10	50	0.25	0.25	5	5	0.25	0.25	0	0	5	10	4%/40% (-39,638)	6%/24% (-4,513)	6%/24% (-952)	1,138,981
18	5	5	10	0.5	0.5	5	5	0.25	0.25	40	5	5	5	0%/16% (4,689)	2%/8% (10,865)	2%/8% (11,738)	1,087,805

Table 4: Examples of Nash equilibria from the Nash equilibrium model. The results are based on the simulation of 1,000 projects.

			Player 3			
			0	5	10	
Player 1	0	Player 2	0	1	2	3
			5		4	5
	10				6	
	5			7	8	
	10				9	
10			10			10

		Opponent 2						
		0	2	4	6	8	10	
Opponent 1	0	1	2	3	4	5	6	
	2		7	8	9	10	11	
	4			12	13	14	15	
	6				16	17	18	
	8					19	20	
	10						21	

Figure 5: Relationship between the situation number and the experience level of the different players. The left table maps the situations of the Nash equilibrium method. The right table maps the situation number for the strategy game method.

Figure 6: The left pane (a) shows the interaction between γ_e and the bidding situation in relationship with the government cost for all the scenarios with $\sigma = 5\%$. The higher the situation number, the higher the total experience in the environment. A relationship between the situation number and the respective experience levels is given in Figure 5. The right pane (b) relates the efficiency parameter β_e and the bidding situation to the total cost for the government.

Figure 7: The interaction between the government compensation policy and the innovation parameter γ_i related to the government cost for all the scenarios with $\sigma = 5\%$.

Figure 8: The interaction effect of the government compensation policy and the bidding situation related to the total government cost. The left pane (a) represents the case when $\sigma = 5\%$ and the right pane (b) shows the case of $\sigma = 15\%$.

4.3 Strategy game results

Referring to Table 3, recall that the strategy game method can deal with many more strategies and proper sub-games. The conclusions that are set in the previous section can now be tested against the findings from the strategy game and will be confirmed. Moreover, the strategy game offers a more thorough review of the best responses. The results that are presented here are stated in terms of best responses, while the previous results dealt with Nash equilibria. Given a particular situation, or sub-game $Q = (e_0|e_1, \dots, e_{p-1})$, the method looks for the strategy $s_0^* \in S_0$ that is found to be the best answer to any combination of the good strategies' database R_p for every opponent $p \in \{1, \dots, P - 1\}$. The best answer is stipulated as the strategy that results in the highest expected pay-off. The smaller intervals between the investment and bidding levels enhance the insight into the optimal strategies. It is not the standard case that there is an absence of investment, but nonetheless, the investment percentages stay rather limited.

This section discusses the main findings on a ceteris paribus level for a three-player environment. The parameters affect the best response of a player with a particular experience level. The experiments discover some dynamics in the response that both the government as well as the contractors should beware of when they set up or engage in the PPP competitive dialogue. The results that are presented here are derived from a ceteris paribus analysis together with a clustering of all the performed experiments into interaction plots. The significance of the influence of the parameters and the interaction effects is based on an ANOVA analysis. Last but not least, the experiment has also been performed for a four player case and a final comment is made concerning the contractor's decision criterion.

4.3.1 Sub-game analysis

A glance at the output examples in Figures 9 and 10 confirm the general dependency of the optimal response strategy on the sub-game. As all the matrices presented in the figure have a symmetric nature,

the number above the diagonal refers to the simulated best response for the mark-up decision, while the numbers below the diagonal refer to the best response with respect to the investment level for the player with the experience level in the upper-left cell for the given experience levels of the opponents in the left column and the top row.

Two main effects are valid for almost every parameter setting (Figure 11): (1) the more experienced a player gets, the lower will be the mark-up and the higher the investment percentage and (2) the smaller the competitive disadvantage for a given experience level e_0 (i.e., the difference between the experience level e_0 and the levels e_1 and e_2), the lower the mark-up and the higher the investment percentage. Considering the former remark, the installment of a stable strategy appears already quite fast so that the difference between an experience level 4 versus an experience level 8 for instance is rather small. Furthermore, the pay-offs are related to e_0 . The expected pay-off increases on average as the experience level grows larger, but with diminishing scale effects (Figure 12). Two side-remarks are important. First of all, this general tendency is sometimes weakened according to the dynamics that are explained in the sensitivity analysis of the following sections. Secondly, the zero-zero situation (i.e., $e_1 = 0$ and $e_2 = 0$ or situation number 1) is characterized by higher mark-ups as soon as $e_0 > 0$. It seems, as can be seen in Figure 12b, that an incumbent can easily exploit his knowledge and cost advantage over the entrants in that case. Consequently, also the pay-offs in these situations are much higher for an experienced player (see Figure 12c).

4.3.2 Innovation parameter γ_i

The innovation parameter γ_i has a mark-up impact and an investment impact that are shown in Figure 9. The general trend for both impacts is an increasing one. At first, an increase in the innovation parameter makes the contractor ask for a higher mark-up, regardless of his experience level. Notwithstanding this observation, for an inexperienced player (i.e., with experience level zero), the mark-up attains the cap value that was used in the simulation (i.e., 50%) together with a zero-investment. Increasing the uncertainty through a lack of innovation even more results in an investment that goes sometimes hand in hand with a diminished mark-up. An introduction of the β_e parameter accelerates the move towards the maximum mark-up.

This effect of first increasing the mark-up and only invest when the situation becomes really dangerous can be partly resolved through a government compensation scheme (see Figure 10). The introduction of the government compensation triggers a strategy change towards investments with a much lower mark-up instead of the perverse strategy of setting a maximum mark-up, which actually means that the inexperienced contractor is not interested anymore in the project. In this case, government compensation behaves as an incentive mechanism that avoids that inexperienced players become

reluctant. The interaction between the compensation policy and the innovation parameter is significant. With smaller compensation levels, the investment increase only appears with a high innovation parameter, while high compensations incur an investment rise already for lower γ_i values, but the investment increase is ceiled. As is repeated later, the compensation mechanism might succeed in putting all the contractors, with different initial experience levels, at an equal level so that a strategy for a particular player becomes independent of his experience level or the sub-game under study. As a result, the government has a tool at his disposal to level the playing field.

4.3.3 Government compensation d

In general, an increase of the government compensation percentage leads to an increase in the investment level. The reaction of the contractor is related to the experience level. If the experience level is smaller, more incentives are required to trigger an upward investment trend (see Figure 10). Moreover, the movement towards an investment initially manifests itself in situations where the competitor has a competitive strength, i.e., a sub-game in which at least one opponent has an experience level that does not surpass that of the contractor.

Of course, this tendency relies on other determinants as well. The uncontrollable project standard deviation σ is considered to be an inhibitor and postpones the investment decision. Additionally, β_e contributes to the deceleration of the investment increase through the generation of appropriate incentives. The strategy game confirms the equilibrium findings that the investment will be more considerable as the γ_i parameter grows larger. Interestingly, the sensitivity analysis of the government compensation parameter shows that the undesirable effect that a high innovation parameter has, i.e., a move for inexperienced players towards maximum mark-up levels, can be cancelled out. The previous section underlines that, especially in cases where the entrant has a small chance to win against experienced incumbents, the less experienced player will move towards high mark-ups. The introduction of a considerable government compensation turns around the best response strategy. Now, there will be an upward jump in the investment level and a large drop in the mark-up, as is shown in the example in Figure 10 and in the interaction plots of Figures 13 and 14. As a result, the choice lies with the government to what extent they want to increase competition in the PPP market and how much money they are willing to pay for that. Nevertheless, the societal value of the government compensation can be inestimable while the cost for the government is within reason.

A comparison between the best responses according to a player's experience level shows that the government compensation succeeds in diminishing the heterogeneity among players. The best responses get a more stable feature. Of course, the pay-offs for the players will still differ related to the experience level, but the chance of winning converges. The magnitude of the compensation relates to the learning

rate parameter λ_i . If λ_i grows larger, a smaller compensation is required to put the players more or less at the same level. Nonetheless, prudence is in order, as higher compensations might cause unnecessarily high costs to society, as was already shown in the Nash equilibrium results.

4.3.4 Uncontrollable project risk σ

The standard effect of a rise in the uncontrollable project standard deviation σ is a sharp increase in the margin. A graphical example is shown by comparing the mark-up intervals of Figures 13b and 15b. As concluded in the Nash equilibrium method, the strategy game confirms that the increasing behavior is exponential. Apparently, the contractors try to safeguard against the risk of exuberant costs. Moreover, the standard errors of the expected pay-offs are smaller in the case where σ is larger. Consequently, the cost for the government will be much higher in the case of high project uncertainty, but expected pay-offs are rather robust. When σ is only 5%, the pay-offs for the players and the cost for the government are smaller, but the standard deviations of the pay-offs are larger. That might also entail some danger, as when a company runs into high costs, it might get into failure and the threat of renegotiation of the contract might come into play. The interaction with other parameters gives additional insights into the dynamics. The innovation parameter is an important driver for a change in investment behavior. The parameter γ_i has a larger impact when σ is smaller. In the cases where there is a large uncontrollable uncertainty, the mark-up will rise if the innovation parameter gains importance, but the increase is limited. More particularly, for high values of γ_i and in the case where σ equals 5%, the best response is stuck at a maximum mark-up level for an inexperienced player. When the project risk is equal to 10% or 15%, a lower mark-up together with an investment is the best response for any experience level. The high project uncertainty removes heterogeneity among players and the disadvantage of the inexperienced player has vanished. In order to arrive at a competitive level for the lower uncertainty cases, the government compensation can be a major contributor and it will result in a lower mark-up and a higher investment compared to a 10% or 15% standard deviation. With respect to the relationship between the uncontrollable project risk and the pay-offs, a higher value for σ permits a higher mark-up and meanwhile also a much higher pay-off for the participants in the game. The average of all the simulation outcomes for the different combinations of parameter values from Table 2 is significantly different. For the 5% case the average is 19,326, while it rises to 22,500 for the 10% case and reaches the amount of 33,617 in the 15% case.

4.3.5 Other parameters

With respect to the simulation experiment, the effect of the efficiency parameter β_e that is included in the contractor's cost impact function is rather limited. The influence is the clearest for the player with experience level zero. Here, an increase in the efficiency gains due to the experience that has been built,

inhibits the enthusiasm to invest. Consequently, the investment drivers, like γ_i or d , loose a part of their repercussions on the investment behavior.

The knowledge requirement through a lack of experience γ_e also has only a significant effect in the inexperienced case. The best response moves towards a higher mark-up decision as the parameter surges. Nevertheless, a very experienced player seems to exploit his experiential advantage in the sub-game where the other players are inexperienced and the contractor raises the mark-up level.

The last parameters that have been under study in the simulation experiment deal with the learning rates. The effects of changes in these parameter are quite straightforward. The experiential knowledge learning rate λ_e behaves as an accelerator of the investment consideration. When a player has less experience, he will anyway be eager to invest when the value for λ_e increases. The learning rate that is related to the pace of learning through innovation, λ_i , has a particular behavior. The impact on the mark-up is insignificant, but the *ceteris paribus* effect on the investment level depends on the initial best response before the increase of the parameter value. The transition from a zero-investment towards a one per cent investment and from a one per cent investment towards a two per cent investment is easy and occurs faster, i.e., for a smaller γ_i or d or for a smaller experience level e_0 . From then onwards, the move towards a higher investment level slows down, and the investment level of the best response will be equal or lower when λ_i equals 0.5 than when it equals 0.25. Instead, the contractor should modify the mark-up towards lower levels, according to the simulation.

4.3.6 Number of players P

The number of players has an effect on the strategy outcomes. Figure 16 shows the boxplots of the simulation outcomes of the aggregated scenarios for a constant uncontrollable project risk and clearly confirms that in the four-player cases, the best response concerning the investment level is lower and concerning the mark-up level is higher in the four-player case than in the three-player environment. The pay-offs seem to be much lower when the player under study is facing more opponents.

A comparison of the outcomes for every scenario separately admits the generalization of the previous conclusion. Less experienced players are much less willing to invest because they have become reluctant as their chances to win have decreased. The incentives that the government is able to install are also less effective. A government compensation policy will allow a more experienced player to invest more, but misses its target for inexperienced players. As a result, the government should thoroughly reconsider the competitive dialogue procedure. With too many contractors remaining in the final rounds of the competition, the motivation could start lacking and especially entrants would be reluctant to penetrate the market.

4.3.7 Reliance on a particular decision criterion

The previous statements are all made based on the criterion that a contractor will select that particular strategy that will guarantee the highest pay-off. Of course, some players are more risk averse than others. This selection criterion can have a high uncertainty of the expected outcome and a risk averse player might also consider the second objective of minimizing the standard deviation of the expected pay-off. Any strategy on the efficient frontier can be considered as a justifiable strategy. The difference between an efficient strategy and a dominated strategy was given in Figure 4. Consequently, every contractor will evaluate the trade-off between the expected pay-off and the entailed standard deviation. The simulation model shows that the optimal strategy according to a particular decision criterion is directly related to the total contractor's cost standard deviation. Suppose that a contractor wants to optimize the ratio of the expected pay-off and the standard deviation. He will prefer a lower margin and a higher investment when the total contractor's standard deviation $\sigma_c^2(e_p, i(s_p))$ is low. But in case of a high γ_i or a high σ for instance, a higher mark-up with a lower investment percentage is preferred. Nonetheless, the government compensation mechanism could flatten this influence to a certain extent.

Figure 9: Simulation output example for a 3-player experiment with parameter values: $\lambda_1 = \lambda_2 = \mu_1 = \mu_2 = 0.25$, $\gamma_e = 5$, $\beta_e = 5$, $\beta_i = 5$, $\sigma = 0.05$, $d=0$. The value for the innovation parameter is (from left to right) 5, 10, 20, 50 respectively.

Figure 10: Simulation output example for a 3-player experiment with parameter values: $\lambda_1 = \lambda_2 = \mu_1 = \mu_2 = 0.25$, $\gamma_e = 5$, $\gamma_i = 20$, $\beta_e = 10$, $\beta_i = 5$, $\sigma = 0.05$. The government compensation levels are (from left to right) 0%, 50%, 80% and 90% respectively.

Figure 11: Representation of the general relationship between the sub-game and the best response.

Figure 12: The interaction between e_0 and the situation that refers to the experience levels e_1 and e_2 in the right table of Figure 5 in relationship with the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which $\sigma=5\%$.

Figure 13: The interaction between the innovation parameter γ_i and the government compensation level d with the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which $\sigma=5\%$.

Figure 14: The interaction between the experience level e_0 and the government compensation level d with respect to the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which $\sigma=5\%$.

Figure 15: The interaction between the innovation parameter γ_i and the government compensation level d with the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which $\sigma=15\%$.

Figure 16: Boxplots of all the aggregated scenario outcomes for $\sigma = 5\%$ for the 3-player and 4-player case.

5. Discussion and conclusions

Public-private partnerships try to take advantage through the value for money creation. Nevertheless, they might suffer from their own complexity. The dynamics of the competitive tendering game are apparent and a necessity to study the incentives comes into play. The competition feature is often overlooked in contemporary PPP literature. This research copes with the different agents in the bidding game and as it takes the competition into account, the contribution to the existing knowledge base is clear. The game-theoretical modeling is utilized to gain understanding in the rational behavior of the players. The assumptions that are made succeed in representing a major part of the agreement. The parameter setting might be challenging, but from the sensitivity analysis the majority of the effects is clarified.

The project itself is a main determinant for the bidding behavior and the final project outcome. As uncertainty increases, both in an uncontrollable as well as in a controllable fashion, the players try to defend themselves in order to avoid downside risks. It is a popular means of PPPs to distribute the risk among the players according to the adagio of allocating a particular risk to the party that is best able to manage it. Prudence is in order as the transfer of risk is proven to be expensive. This supports the general agreement of the PPP research that a careful consideration of the risk is indeed essential. Both simulation methods that are presented in this paper agree that a contractor behaves opportunistically in the sense that he will prefer the easy option: as uncertainty increases, the contractor will firstly increase the mark-up and in a second instance, when the total risk becomes dangerously high, he will improve his knowledge position through an investment in pre-tender research.

The bidding situation is a determining factor in the decision of one's favored strategy. The position in the market has proven to have a significant impact on the bidding behavior. The heterogeneity in the players was assumed to be common knowledge and should be taken into account when analyzing a particular project both for the contractors as well as for the government. Assuming that all the players have the same experience level might be perceived as cutting the corners too much. The extension of the strategy game towards more players in the final bidding stage proved to have an equilibrium change. The probability of winning shrinks and the experience level becomes more important. Experienced players will now have an even larger advantage over the less experienced opponents. Possible entrants for the PPP market can become unwilling to incur the risk of not winning, leaving the opportunity for an oligopolistic market to develop. Through the simulation, it might be supported that the government should clearly set the targets. Nowadays, the sector suffers from the shilly-shallying of the government, who wants to consider all opportunities until the last moment. The industry often asks for a funneling system so that only a couple of contractors make it to the final bidding stage.

The enthusiasm of inexperienced players might be rather limited in an environment with considerable uncertainty so that they become reluctant to enter the PPP market. A monopolistic or oligopolistic market with only highly-experienced players that cash in on their competitive advantage should be avoided. In order to incentivize the market players to invest in pre-tender research and to allow new players to get into the field, appropriate policies can be generated. There is not a worldwide acknowledgement over the effectiveness of the policies that are currently applied. This simulation investigated the impact of a simple, partial reimbursement of the pre-contractual costs that the contractors carry. A proper incentive scheme triggers the willingness to invest and even withholds a player from setting a high mark-up. A more qualitative proposal is a consequence of a good compensation policy. How good a compensation policy is depends on the parameters of the project and the bidding environment. The incentives will need to be sufficient in order to generate the preferred behavior by the

contractors. Especially in very heterogeneous markets, the government should be willing to incur sufficient costs to give also possibilities to the players with an initial competitive disadvantage. Perverse incentives and moral hazard problems need to be avoided. As shown through the Nash equilibrium experiment, the governmental policy does not necessarily invoke a large cost surge, as it can lower the mark-ups as soon as the players get motivated to invest more.

The models presented here give a simplified but realistic representation of this complex competitive tendering environment in the PPP sector. In order to arrive at this level of abstraction, assumptions were made, leaving possibilities for further research. A more repetitive market, in which projects appear in a sequence and where a player can gain experience in a particular sector, could create new dynamics. The straightforward reimbursement policy that was under study can also be extended to modified policies, for instance a decreasing percentage compensation depending on the final ranking of the proposals. Moreover, the decision criterion by both the government as well as the private contractors might differ relatively to the applied criteria for the purpose of this research. Here, it was assumed that contractors prefer a maximum pay-off strategy and that the public sector selects based on the lowest-cost criterion. Of course, other Pareto optimal decisions can be made. The government makes a trade-off between the quality and the cost, while the contractor balances the pay-off and the uncertainty of the pay-off. This leaves quite some room for further consideration.

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