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Abstract

Due to the extensive timeframes and the transfer of risk towards the preferred special purpose vehicle, there is more value at stake in public-private partnership projects in relation to traditional public procurement projects. The contractual complexity and the high bidding cost are open sesames for inexperienced contractors to refrain from the opportunity. Governments are currently seeking for mechanisms to increase competition, like reimbursing losing bidders for their research efforts. This study encompasses the bidding framework in a game-theoretical fashion while taking discrepancies in the bidders' experience levels into account. A contractor's strategy is composed of the pre-tender investment willingness and the targeted mark-up. Approximation algorithms to derive the Nash equilibrium are proposed. Furthermore, it is investigated how governmental policies may modify the bidding equilibrium. The theoretical findings are triangulated by a qualitative discussion with practitioners from the PPP field. 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.

Keywords: public-private partnership procurement, project management, bidding, game theory, simulation

1. Introduction

In the early nineties, public-private partnerships (PPPs) appeared on the scene as a cutting-edge long-term contractual arrangement between a private contractor and the government. PPPs were believed to guarantee greater value for money compared to traditional public contracting in which the contractor was just responsible for building a particular well-defined infrastructure project. PPPs do not only incur the realization of the infrastructure project, but also consider the design and operation and the maintenance afterwards. Therefore, synergies are realized because of efficiency gains by and risk transfers towards the private entity or special purpose vehicle (SPV). Since they have seen the daylight, PPPs have gained importance and their number has proliferated. The PPP landscape is wide which is proven by the variety in definitions (e.g., Van Ham & Koppenjan, 2001; Hodge & Greve, 2007; Wettenhall, 2010). For the purpose of our research, all the ornaments and often country- or sector-specific features are removed. A public-private partnership is defined as a settlement between a public party and a private sector consortium 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. Because of the long-term feature of these projects, PPPs are not always a bed of roses. Typical textbook cases of the Eurotunnel project (Flyvbjerg et al., 2009) and the New Southern Rail Project in Sydney (Ng & Loosemore, 2007) underline the possible disastrous outcomes and form another argument to put an emphasis on carefully planning these risky projects (Zwikael & Sadeh, 2007).

This paper offers a theoretical approach in analyzing the procurement stage of PPP projects. Because of its complexity and riskiness, long-term PPP projects require more preparation than traditional infrastructure projects. After an initial prequalification of interested consortia by the government, qualified concessionaires are invited for tender. The consortia have to prepare a proposal that will be submitted to the government which involves pre-tender research costs (e.g., consulting costs, design costs and market studies). Empirical evidence by KPMG (2010) reports average research costs of 1.5% to 2% of the total project cost. These pre-tender research costs or bidding costs are claimed to be a burden for contractors and concessionaires because they do not guarantee to be awarded with the contract (Carrillo et al., 2008). Basically, each consortium will first determine how much money to invest in pre-tender research and secondly he will have to determine the appropriate mark-up. Due to the complexity, the high contingencies and the bidding costs, policy makers often argue that the market is too narrow in some jurisdictions, like in Australia, New Zealand or western European countries where often only two or three private entities show interest in particular high-risk PPPs. In order to open up the playing field and incentivize entrants, the public institutions sometimes introduce reimbursements for the incurred pre-tender investment costs. However, there is no global agreement on the magnitude of these compensations (KPMG, 2010). In contrast to Australia for instance, Canada and France apply considerable compensations. Consequently, the scope of this paper is two-fold. On the one hand, the PPP procurement process is translated into an abstract analytical bidding model that addresses the questions what the equilibrium amount of pre-tender investment is and which mark-up is rationally convenient. More particularly, the dynamics of the strategic equilibrium are underlined and it is analyzed how a consortium's behavior is influenced by the competitive position in the market and by the project complexity. On the other hand, the scope is directed towards the government to assess the effectiveness of common governmental policies with an emphasis on the impact of the introduction of a partial reimbursement of the pre-tender cost on the bidding equilibrium. This results in a set of policy guidelines in both the public as well as the private sector’s interest. These stem from theoretical findings and are triangulated by practitioners’ experiences. Next to its contribution to the PPP procurement literature, this paper also supports the algorithmic game theory and auction theory from a methodological perspective.

The next section gives an overview of the relevant literature that relates to the PPP procurement process and highlights the bridge with traditional auction theory. Section 3 covers the analytical foundation and subsequently describes two algorithmic approaches that are implemented for the equilibrium identification. Section 4 lists the theoretical findings from the simulation output and the sensitivity study, while the discussion section introduces the experience and feedback from practice. A general policy proposal together with the opportunities for further research conclude this paper.

2. Literature review

Also in the academic journals, PPPs have gained increasing attention and different authors have classified papers according to their research topics (Al-Sharif & Kaka, 2004; Ke et al., 2009; Tang et al., 2010; De Clerck et al., 2012). The literature reviews show that the drivers and success factors for PPPs are a well-established topic. Concerning the procurement process itself, the focus has mainly been on the risk identification, its assessment and the allocation between the government and the contractor. This is proven by the number of empirical (e.g., Li et al., 2005; Jin, 2010; Chan et al., 2011) and, to a lesser extent, theoretical studies (e.g., Medda, 2007; Khazaeni et al., 2012) that have appeared in the literature. Bidding models that focus on the PPP competitive dialogue are scarce. From a theoretical stretch, it are especially pricing peculiarities of PPPs that have been considered. Firstly, an important field is the pricing of governmental support interventions to guarantee a minimum revenue in the course of the operation (e.g., Cheah and Liu, 2006; Brandao and Saraivo, 2008; Ashuri et al., 2012) and the impact of governmental capacity regulations (Subprasom and Chen, 2006). A second aspect involves the determination of the concession period (e.g., Ng et al., 2007; Shen et al., 2007; Zhang, 2009). Last but not least, a multi-interest analysis of the financial, the social and the corporate stakes is introduced by Liou et al. (2011). These studies do not explicitly take the competition aspect into account. This is in contrast to Iyer and Sagheer (2012) who consider the bid winning potential of a mark-up and Xu et al. (2012) who have built a system dynamics model based on past experiences for pricing the concession. The bidding model presented in this paper makes abstraction of the elements that determine the final price and represents the mark-up as a single figure for the consortium as a whole. On the other hand, the added complexity lies in the introduction of a competitive environment and the bidding costs. Consequently, we hypothesize that the contractor's behavior is significantly influenced by his opponents. Moreover, it is necessary not to overlook the bid preparation efforts.

Empirically, it is acknowledged that bidding for PPPs is expensive (Carrillo et al., 2008; Chen and Doloi, 2008). Moreover, the government as a buyer prefers qualitative suppliers and aims to limit uncertainty (Riedl et al., 2013). Ho (2008) questions game-theoretically whether the quality of bidding would increase if the government reimburses the second-best bidder for his bidding costs. Ho (2008) argues against the reimbursement but considers homogeneous bidders, which deviates from empirical findings of Oo et al. (2010). Furthermore, Ho (2008) does not consider any contingencies. In contrast to Ho (2008), the model in this paper introduces differences in the experience levels between bidders and also includes uncertainty in the project outcome. This is a more realistic approach and eventually results in the definition of circumstances where compensation is advised. Because of possible project risks, winning a contract is not a guarantee for a long-term profit. An attempt to combine the risk a winner faces and the current competitive mark-up determination in a non-PPP context was performed by Chao and Liou (2007) and Islam and Mohamed (2009). The PPP model additionally takes the investment option into account. Investment might reduce the long-term project risk and might result in a higher quality bid.

The study of this PPP tendering format relates to auction theory and the competitive bidding literature that was initiated by Friedman (1956). In a first instance, this particular bidding setting introduces uncertainty in the cost estimates, which was introduced by Curtis & Maines (1973) and Naert & Weverbergh (1978). Takano et al. (2014) extend the single-project environment with uncertain project cost estimates towards a dynamic model with a sequence of projects and resource constraints. These models only consider the mark-up decisions, while the PPP model that is presented in this paper also examines a pre-tender investment choice. Through the investment choice, a contractor can reduce the cost uncertainty and directly increase his bid winning potential. In order to be able to analytically characterize the equilibrium, traditional auction theory often assumes homogeneous bidders and studies symmetric equilibria. The PPP simulation model does not take these simplifications into account and might therefore attain more insights. Another stream of research within the auction theory field studies the introduction of investment incentives in auctions and where investments lead to distributional upgrades of the cost distributions. Tan (1992) is the initiator considering ex-ante symmetric firms. More recent work does consider the heterogeneity among bidders (e.g., Skitmore, 2008) and explores the introduction of subsidies for investments towards inefficient bidders (i.e., bidders with a cost disadvantage) in procurement auctions (e.g., Tan, 1992; Arozamena & Cantillon, 2002; Rothkopf et al., 2003). Arozamena & Cantillon (2002) study the investments for cost reductions and conclude that incentives actually have an inhibiting effect on investment due to the expectation of fiercer competition. The PPP model of this paper acknowledges that compensations result in fiercer competition but this does not necessarily mean that the investment behavior is reduced for the players. Rothkopf et al. (2003) are more in favor of subsidies and show that it lowers the expected procurement cost, while the PPP model requires some necessary differentiations and acknowledges that incentives may raise the government cost. A similar type of incentive creation in the R&D procurement literature is studied in Zhang et al. (2013) who elaborate on the competitive investment equilibrium. Through a sharing rate of the investment between the contractor and the principal, investment incentives are created. In the PPP model, the compensation is introduced in the market for fairness purposes and is not only attributed to a specific inefficient bidder or minority, but every ex-post losing bidder possibly gets compensated. Moreover, to the best of our knowledge there is no research that also includes the knowledge impact assumption in which upfront investments also reduce the uncertainty of the project cost.

3. Methodology

In order to grasp the main characteristics of the PPP procurement process, interviews with contractors, investment companies and public institutions have been performed next to a thorough analysis of former academic PPP research, publications and secondary data. The complexity of the PPP procurement environment has been reduced to a mathematically manageable level of abstraction, while maintaining generalizability through flexible parameterization which allows for an extensive sensitivity analysis. This analytical approach of course inhibits to get full insight in all the tendering dynamics. Moreover, it is a daunting task to collect data from the industry for validation purposes as it is a narrow and highly competitive market. Nonetheless, the analytics and the simulation approach succeed in gaining insights into the bidding behavior dynamics and have been presented to practitioners in the field before moving on to define concrete policy recommendations.

3.1 The procurement procedure

The PPP procurement process is often country and sector specific. After the public communication, consortia can express their interest for the project. A consortium or special purpose vehicle consists of several companies like designers, construction contractors, subcontractors, suppliers and maintenance companies. In the remainder of the text, a consortium will be referred to as “a contractor or bidder” and we make abstraction of the internal structure of the special purpose vehicle. Generally, a prequalification mechanism will shortlist a number of contractors who are invited for tender. The number of shortlisted bidders is determined by the decision maker (the government). In practice, this number varies between two to four and in a rare case five bidders, depending on the jurisdiction, the interest and the complexity of the project. The shortlisted contractors will develop a project proposal that includes the design as well as process, management and financial information. This entire process is called the competitive dialogue: a government will communicate separately with each candidate concessionaire for reasons of clarification or adaptation, without sharing information from other bidders. In order to develop a competitive yet profitable project proposal, the contractor will perform investments in research and he will determine his mark-up. Assuming that all shortlisted bidders are known, the proposed bidding model considers each bidder’s strategic behavior for the bid preparation. After the proposal submission, the government is going to select the preferred bidder who is granted the project. This is essentially based on a cost/quality trade-off.

3.2 The decision variables

Each contractor has to make two decisions for a particular project. On the one hand, the bidder has to determine the level of pre-tender research. This is the monetary effort that he will put into developing the project proposal and could consist for instance of consultancy costs, lobbying costs and design costs. In line with recent R&D research (Martzoukous and Zacharias, 2013) and project management research (Lippman et al., 2013), the investment amount can have a two-fold impact. Firstly, the more a contractor invests in research, the more accurate will be the cost estimate. Secondly, the more upfront investment is undertaken, efficiency gains and innovative disclosures could guarantee a lower overall cost. On the other hand, the contractor has to determine a mark-up percentage for the project. The combination of the percentage of the project cost that is spent on pre-tender investments on the one hand and the mark-up percentage on the other hand is called a strategy. The purpose is to determine the equilibrium strategy for each player and will refer to the investment level a contractor is willing to undertake and the mark-up percentage he is aiming for.

Moving the scope to the public sector, the government has the ability to decide on particular dimensions of the bidding process. Firstly, the government determines the number of candidate concessionaires who are up for the final bidding stage. Secondly, the public sector oversees the decision mechanism for the selection of the preferred bidder and could therefore opt for a lowest cost perspective, a maximum quality perspective or a trade-off between monetary and qualitative aspects. Thirdly, a topic of major concern is the fact whether the government should reimburse a fraction of the pre-tender research cost to any of the losing bidders so as to increase the investment incentives of the candidate contractors.

3.3 Assumptions

During the interviews with several contractors and advisors (Table 5), they have confirmed that they do not consistently apply the same strategy for every project. Its risk attitude, its maturity in the market and the bidding environment (i.e., the number of competitors and their respective experience levels) are factors that influence a company's bidding behavior. Ho (2008), who has addressed the bid compensation question before, considers all bidders being equal, while the heterogeneity of bidders was experimentally shown by Oo et al. (2010) and is explicitly confirmed by the interviewees. Therefore, an experience scale has been introduced. A player p has an experience level $e_p \in [0,10]$. The experience level is an assessment of how familiar a particular contractor is with a particular market and could in practice easily be observed by the number of past projects within this specific field and within this particular jurisdiction.

Assumption 1: The bidding environment information that consists of the number of bidders and their respective experience levels is common knowledge.

The experience level of a player contributes in a two-fold way. First of all, more experience will result in a higher probability of winning the tender. It could be stated that the government reduces the bid price with a discount that represents the value it attributes to a higher experience level. Model-wise, one might say that the expected value of the cost function of a more experienced contractor is lower than that of his less experienced counterparts. Another interpretation is that experience results in a direct cost impact because of economies of scale, efficiency gains and the familiarity with the market. Secondly, experience has a knowledge impact in terms of the accuracy of the estimated project cost. Equivalently to the impact of the experience, a contractor's pre-tender investment contributes in two ways to the transformation of the cost curve. Pre-tender investment shifts the cost curve to the left due to innovative disclosures and efficiency gains, resulting in a direct increase in the probability of winning. Besides, the variance of the cost distribution decreases as investment leads to more accurate cost estimates. The variance of the cost distribution reflects the complexity or the risk of the project. For reasons of simplicity, risk is categorized in two types: an uncontrollable part that is the same for all contractors (e.g., force majeure risk, risk of contract renegotiation by the government or macroeconomic risk) and a controllable part (e.g., demand risk, project risk) that can be reduced or mitigated through the appropriation of experience or the performance of research investments. When a project has a fairly repetitive nature, experience will be the main contributor to the uncertainty reduction, while if it is highly innovative, the investment is of paramount importance. In summary, this results in three assumptions.

Assumption 2: The complexity or risk of a project is translated into the variance of the cost distribution and consists of a controllable part and an uncontrollable part.

Assumption 3: The more experienced a player is and the more a contractor has invested in pre-tender research, the lower the variance of the cost distribution (knowledge impact assumption).

Assumption 4: The more experienced a player is and the more a contractor has invested in research, the higher the probability of winning and the lower the expected project cost (direct cost impact assumption).

The quantitative impact of assumption 3 for player p will be given by a fraction g_p and for assumption 4 by σ_p^2. In the modeling procedure, the government will select the lowest-bidding contractor. Nevertheless, assumption 4 inherently also reflects the cost/quality trade-off: if the government would put a greater emphasis on quality and experience, the contractor's cost distribution shift would be more significant if he invests more in research or has more experience. So in fact assumption 4 puts a monetary value on the preference for more qualitative bids or for more experienced contractors by rewarding them with a discounted bid, which makes the next assumption valid in a PPP context.

Assumption 5: The government selects the lowest bidding contractor. If the government installs a percentage-wise bidding cost reimbursement policy, bid compensations are equally attributed to all losing bidders.

Before moving on to put these assumptions into numerical terms, it is necessary to consider assumption 6.

Assumption 6: All participants in the game are able to make accurate estimations of the parameters that are related to assumptions 2 to 4.

This assumption is in line with practical experience. Both contractors as well as the government are able to assess the degree of complexity of a project, based on for instance similar previous experiences. A social housing project is less complex than a toll road or a specialized hospital project. Last but not least, assumption 7 summarizes the contractors' preference:

Assumption 7: Contractors maximize the expected pay-off.

Contractors should consider Pareto optimal strategies. These are strategies that result in a maximum expected pay-off for a given standard error of the pay-off. These strategies are on the efficient frontier. The results that are presented look at the strategy that was found to generate the highest expected pay-off.

3.4 The game-theoretical model

Game theory succeeds in dealing with multiple agents who will optimize their strategy while taking into account their competitors and their possible strategies. The introduction of game theory within the PPP procurement literature is not entirely new, but has mainly considered the relationship between the government and a single (preferred) contractor:

- Shen et al. (2007) considered the determination of the appropriate length of the concession period;
- Medda (2007) has set up a risk allocation model through the bargaining process;
- the problem of contract renegotiations has been studied by Ho (2008) and Menezes and Ryan (forthcoming);
- Tserng et al. (2012) emphasize the importance of national PPP units in promoting PPP projects;
- the synergy effects received attention by Fandel et al. (2012) who introduce the Cobb/Douglas production function to determine the Nash solution of the cooperative game among different partners in a social PPP.

To the best of our knowledge, only Ho (2008) theoretically studies the competition between candidate PPP contractors and how bidding is influenced by government compensation of the research cost.

In our research, the project is initiated by the government (N, which stands for nature in Figure 1). According to assumption 1, the number of shortlisted bidders and their experience is common knowledge for all players. Consequently, a sub-game $e = (e_1, e_2, \dots, e_P)$ is identified for each combination of the experience levels. A discrete number of experience levels on a scale from zero (i.e., no experience) to ten (i.e., maximum experience) is set up. A game with P players and E levels of experience would lead to $G = \frac{(P+E-1)!}{P! * (E-1)!}$ sub-games or bidding environments. Relying on the notion of sub-game perfectness (Gibbons, 1992), all contractors p will determine their optimal strategy s_p^* for each sub-game. The strategy s_p is a combination of which percentage $i(s_p)$ is invested in pre-tender research and which mark-up percentage $m(s_p)$ is applied to the estimated cost. It is in our goals to determine the Nash equilibrium strategy profiles of a sub-game. In a Nash equilibrium, none of the bidders has an incentive to deviate from its current strategy s_p^*, given the strategy profile of its competitors s_{-p}^*. In other words, a Nash equilibrium strategy profile $s^* = (s_1^*, s_2^*, \dots, s_P^*)$ can then be identified if it satisfies $\forall\, p, s_p \in S_p : f_p(s_p^*, s_{-p}^*) \geq f_p(s_p, s_{-p}^*)$.

[FIGURE 1 TO BE INSERTED HERE]

3.5 The analytical model

This section analytically characterizes the equilibrium strategy profile for a sub-game $e = (e_1, e_2, \dots, e_p)$. Figure 2 serves as an example with two players and normal distributions.

[FIGURE 2 TO BE INSERTED HERE]

Initially, a contractor p has a cost distribution function c'_p which is a function of his experience level e_p. According to assumptions 3 and 4 and without considering any investment, a player with more experience has an initial cost distribution c'_p with both a smaller expected value as well as a smaller variance. Relying on assumption 2, the uncontrollable risk σ^2 is the same for all players while the controllable part, quantified in σ_p^2 is experience and strategy dependent. The controllable risk can be accounted for through experience which explains why a more experienced player already has a knowledge advantage that is translated into a smaller variance of the function c'_p.

Investing in research also reduces the controllable risk. For the construction of a toll road, a contractor engages in market studies in order to grasp the demand for the toll road and he may consequently align the findings with the capacity of the road. Eventually, σ_p^2 is calculated for a given investment percentage and a given experience level and is expressed as a percentage value of the initial actual cost. The investment percentage transforms the cost distribution: because of the knowledge impact, the controllable risk decreases, which results in a smaller variance and because of innovations, the expected cost is shifted to the left. The combination of the experience level and the investment effort results in the cost distribution c_p. The second element of the strategy is the mark-up. When the mark-up choice is introduced, the cost curves are shifted to the right, resulting in the bidding functions b_p for each player p.

Assume a P-player environment for which the experience levels are given by the vector $e = (e_1, e_2, \dots, e_P)$ and the strategy profile by $s = (s_1, s_2, \dots, s_P)$. Given the bidding function b_p for player p and the associated cumulative bidding function B_p, the probability of winning for a player p is $q_p(s|e)$ and is calculated as:

$$q_p(s|e) = \int_{-\infty}^{+\infty} b_p(x_p) \left[\prod_{k=1,\, p\neq k}^{P} \left(1 - B_k(x_k)\right) \right] dx_p$$

A player's pay-off is dependent on the fact whether the player has won or lost the tender. When a player wins, he receives the money that he required according to the submitted proposal and the actual project cost is subtracted, together with the investment in research. In the case of a loss, the investment in research will be partly incurred, conditional on whether the government reimburses a fraction $d \in [0,1]$ of the research cost or not. It is assumed that each player wants to optimize the expected pay-off (assumption 7), which is given for a player p by the function:

$$E\left[\pi_p(s|e)\right] = q_p(s|e)\left(E\left[\widetilde{B_p}\middle|p\ has\ won\right] - A_p\left(s_p\middle|e_p\right) - i(s_p)\mu\right) \\ - \left(1 - q_p(s|e)\right)(1-d)i(s_p)\mu$$

The pay-off function consists of the following building blocks:

- s_p or the strategy for a player p which is associated with an investment choice $i\left(s_p\right)$ and a mark-up choice $m\left(s_p\right)$;
- $q_p(s|e)$ or the probability that player p wins the tender with s the vector of strategies $(s_1, s_2, \dots, s_P)$ and e the vector of experience levels $(e_1, e_2, \dots e_P)$;
- $A_p(s_p|e_p)$ or the actual cost, taking into account that player p has won. It equals the expected value of the cost function c_p that belongs to the winning contractor p. If $g: \mathbb{R}^2 \to \mathbb{R} \in [0,1]$ is the function that reflects the fractional direct cost impact (assumption 4) that results from player p's experience level e_p and the investment percentage $i(s_p)$ related to strategy s_p, then we have $A_p = 1 + g(s_p, e_p)$;
- d is the fraction of the investment cost that is reimbursed by the government;
- μ is a scaling factor;
- the term $E\left[\widetilde{B_p}\middle|p\ has\ won\right]$ refers to the expected proposal that is made by player p on the condition that he has won the tender with $\widetilde{B_p}$ a random variable from the bidding function b_p.

The latter term of the pay-off function is calculated as a conditional expectation as we know that a bidder has won the tender (according to assumption 5). Therefore, that gives analytically:

$$E\left[\widetilde{B_p} \middle| \widetilde{B_p} < \widetilde{B_k},\ \forall k \neq p\right] = \int_{-\infty}^{+\infty} x_p \frac{b_p(x_p) \prod_{k=1,p\neq k}^{P} \left(1 - B_k(x_p)\right)}{q_p} dx_p$$

This is obtained in line with the general idea behind the conditional expectation of a random variable X given an event Y, or $E[X|Y] = \int_{-\infty}^{+\infty} x \frac{f_{XY}(x,y)}{f_Y(y)} dx$.

Consistent with Pareto efficiency, a contractor will prefer a strategy that generates the highest pay-off for a minimum variance of this pay-off. Let us assume that all contractors prefer to optimize their expected pay-off. When all the bidders simultaneously optimize their expected pay-off function, the following system of $2 * P$ equations needs to be solved and consists of the partial derivatives for each player's pay-off with respect to both his investment level as well as his mark-up level:

$$\begin{cases} \partial E[\pi_p(s^*|e)] \big/ \partial i(s_p^*) = 0 \\ \partial E[\pi_p(s^*|e)] \big/ \partial m(s_p^*) = 0 \qquad \forall p \in \{1,2,\dots,P\} \end{cases}$$

The competition occurs among the contractors, but in fact the government is responsible for setting the bidding context. The government might for instance prefer to set a compensation level that minimizes the total expected payment, which would be translated into the objective function:

$$min_d \sum_{p=1}^{P} q_p(s|e) \left(E\left[\widetilde{B_p} \middle| \widetilde{B_p} < \widetilde{B_k}, \forall k \neq p\right] + \sum_{k=1,k\neq p}^{P} d * i(s_k)\mu \right)$$

Fundamentally, this is a bi-level programming problem in which the government is the leader and the competition among the contractors serves as the lower level problem. Other governmental policies that have an influence on the lower level equilibrium are for instance the determination of the number of players allowed to send a proposal, the objective of the government itself (e.g., preferring a minimum cost approach or introducing a cost/quality trade-off) and the number of projects in the pipeline. Albeit feasible, it is computationally intensive to calculate the pay-offs of a strategy profile. Analytically solving the system of differential equations is complex if we deal with an infinite number of strategies and multiple equilibria may exist. Therefore, the next section describes the discretization of the problem. Moreover, finding a Nash equilibrium is generally acknowledged to be a hard problem, which is proven by the complexity studies of Conitzer and Sandholm (2003) and Daskaladis et al. (2006). As a result, meta-heuristic procedures to approach a Nash equilibrium are described in Section 3.7.

3.6 The procurement simulation

An experiment has been set up in order to study the dynamics of a contractor's bidding behavior. A bidding simulation approach is the favored methodology for three reasons. Firstly, the simulation of costs, bids and pay-offs avoids the computationally intensive analytical calculations. Secondly, the Monte Carlo simulations go beyond the expected value of the pay-offs, but also give insight into its distribution. Thirdly, the simulation approach allows for considerable flexibility as different distributions can be easily tested.

In line with the rationality of dealing with the total variance as the sum of the partial variances and the philosophy of diminishing scale effects, the knowledge impact assumption (assumption 3) is implemented as follows: $\sigma_p^2 = \sigma_p^2\left(e_p, i(s_p)\right) = \mu^2\left(\sigma^2 + \left(\gamma_i e^{-\lambda_i i(s_p)}\right)^2 + \left(\gamma_e e^{-\lambda_e e_p}\right)^2\right)$.

This formula introduces the project complexity parameters. γ_i is the maximum impact of a lack of investment. The larger this parameter, the greater the importance of investment on the accuracy of the cost estimate. Equivalently, γ_e is the maximum variance contribution of a lack of experience and quantifies the knowledge advantage of being experienced. λ_i and λ_e represent the respective associated growth parameters. μ is a scaling parameter and will be set to € 1,000,000. The implementation of the cost impact assumption equivalently relies on diminishing scale effects and is given by: $g_p = g_p\left(e_p, i(s_p)\right) = \beta_i e^{-\mu_i i(s_p)} + \beta_e e^{-\mu_e e_p}$ with β_i the innovation parameter related to the investment efforts and β_e the efficiency parameter related to the experience. The resulting value lies in the interval [0,1]. Referring to the alternative interpretation of assumption 4, an increase in both parameters could also be interpreted as a government that favours experience and investment or quality more than purely the required price and then expresses the monetary bid price discount for experience and quality.

Recall that the experience vector e is given and commonly known. Each player determines his strategy s_p which refers to an investment percentage $i(s_p)$% and a mark-up percentage $m(s_p)$%. The strategy profile s is then the combination of the strategies of all P players and given by a vector $(s_1, s_2, \dots, s_P)$. This is the input for the simulation of the final pay-offs. The output of the procedure is a pay-off distribution for each player. The average pay-offs for a particular strategy profile $s = (s_1, s_2, \dots, s_p)$ are given by the pay-off vector $f = \left(f_1(s), f_2(s), \dots, f_P(s)\right)$.

Consider Gaussian cost and bidding distributions. In a single iteration, an actual cost and a bid for each player are generated. The reference actual cost Ã is a random variable that is drawn from the distribution $N(\mu, \sigma_u^2)$ with $\mu = €1{,}000{,}000$ and $\sigma_u^2 = (\mu * \sigma)^2$ and that is the same for all players. The final actual cost will be different, because it is related to the particular cost distribution of the winner of the tender. The expected project cost for a particular player p results then from the linear transformation $\tilde{A}_p = \tilde{A}(1 + g_p)$, which is set to the mean of the cost estimate function c_p for player p. Hence, c_p is a nested function (El Otmani and Maul, 2009) of the form $c_p \sim N\left(\mu(1 + g_p), (1 + g_p)^2(\sigma_u^2 + \sigma_p^2)\right)$. The contractor's estimated cost $\widetilde{C_p}$ is randomly selected from c_p and eventually, a contractor applies the mark-up level $m(s_p)$, resulting in the bid: $\widetilde{B_p} = (1 + m(s_p))\widetilde{C_p}$. In summary, the form of the bidding function b_p in this procurement simulation is:

$$b_p \sim N\left(\mu(1 + m(s_p))(1 + g_p), (1 + m(s_p))^2(1 + g_p)^2(\sigma_u^2 + \sigma_p^2)\right)$$

The minimum of these simulated bids is the winning proposal and its pay-off is determined, where the actual bid is $\widetilde{A_w}$ for winner w. The losers' pay-offs equal the fraction of the pre-tender investments that are not reimbursed by the government. As soon as a predefined number of replications m has been reached, the simulation algorithm stops and a pay-off distribution for each player can be determined.

3.7 Equilibrium approximation algorithms

Another simplification of the analytical model lies in the discretization of the problem. Instead of allowing an infinite number of strategies, discrete numbers of integer investment and mark-up percentages are studied. Consider I investment choices and M mark-up choices for each player. Consequently, a player has $I * M$ strategies to choose from. The set of strategies for a player p is S_p. This results in $(I * M)^P$ strategy profiles, which will be referred to as $S = S_1 \times S_2 \times \ldots \times S_P$. A strategy profile is given by $s = (s_1, s_2, \ldots, s_P)$ and $s \in S$. The pay-off vector of a particular strategy profile s is $f = \left(f_1(s), f_2(s), \ldots f_P(s)\right)$.

3.7.1 Algorithm A: Nash equilibrium algorithm

A first heuristic calculates the pay-off distribution for each strategy profile s. For an experience vector e, each combination of strategies is sent to the simulation procedure explained in Section 3.6. The output is an average pay-off vector f and the variance of the pay-offs. When all the pay-off calculations of the pay-off matrix cells have been performed, the algorithm identifies the pure strategy Nash equilibria. Define s_p as the strategy for player p and s_{-p} a strategy vector of all players except player p. If all players prefer to optimize their expected pay-offs, a strategy profile $s^* = (s_1^*, s_2^*, \dots, s_P^*)$ is a Nash equilibrium if it satisfies $\forall p, s_p \in S_p : f_p(s_p^*, s_{-p}^*) \geq f_p(s_p, s_{-p}^*)$. Moreover, we need to take into account that the pay-offs are based on simulations, so we add an additional constraint: the two-sample t-statistic needs to prove that the expected pay-off is significantly greater than the pay-off of a differing strategy. Nonetheless, there is no guarantee to find a unique Nash equilibrium and computation times increase exponentially when more players and/or more strategies are included. Algorithm B tries to overcome these issues.

3.7.2 Algorithm B: Strategy game algorithm

A second algorithm approximates the Nash equilibrium by determining a best response for a player p after first restricting the strategy space S_{-p} for the competitors. Given the experience vector $e = (e_1, e_2, \dots, e_P)$, we want to determine the best response for player $p \in \{1,2,\dots,P\}$ with experience level e_p. The algorithm will now do a prequalification of the strategies for all the $P-1$ competitors of player p. Initially, every competitor q has a set of strategies S_q and the heuristic will reduce this set to a set of shortlisted strategies R_q with n elements. The prequalification is done in two stages: a homogeneous stage to grasp the project characteristics in the shortlisted strategies and a heterogeneous stage to emphasize the competition aspect. After the prequalification, the strategy game algorithm is executed. A detailed overview of the algorithms is given in Appendix 1.

3.7.2.1 Homogeneous stage

Player q with experience level e_q has a set of strategies S_q at his possession. The homogeneous stage resembles a knock-out tournament. A predefined number of rounds r is set and the experience levels are set equal to q's experience level e_q for all players. In the first round P^r strategies are selected randomly and divided in P^{r-1} groups of P strategies. For each group of strategies, the average pay-offs are calculated and the best performing strategy continues to the next round where only P^{r-1} strategies are remaining. The procedure continues until P strategies remain and these are transferred to the set of shortlisted strategies R_q.

3.7.2.2 Heterogeneous stage

In this second stage, we keep the original experience vector e and for each competitor q an intermediate game is played in which all his strategies are assessed against random strategies for his opponents. In each iteration of the algorithm, random strategies from the complete set of strategies are selected for the competitors of player q. This results in the vector s_{-q} which represents the strategy profile for the opponents of player q. Next, the expected pay-off and its variance is calculated for all the possible strategies from the set S_q given the strategy profile s_{-q} for his competitors and the experience vector e. In the next iteration, new strategies are randomly selected for player q's competitors. After a user-defined number of iterations k_1, the pay-off distribution for each strategy of player q is derived and the best strategies are selected to be part of the shortlisted strategy list R_q.

3.7.2.3 Strategy game algorithm

When the shortlisting is performed for each competitor q of player p, the final assessment stage will start. For each iteration of the algorithm, strategies are selected for the competitors of player p. For competitor q, these strategies are generated from the respective shortlisted sets R_q. This results in a strategy profile s_{-p}. Player p will now calculate the pay-off for each of the strategies of his set S_p. In the next iteration, new strategies are selected for the opponents of player p and the pay-offs for this scenario are calculated. After k_2 iterations, the average over all scenarios is calculated for each of the strategies from the set S_p and the best performing strategy for player p is assumed to be a good proxy for the equilibrium strategy for this player.

3.7.2.4 Example

Assume a three-player environment with experience vector $e = (2,4,6)$. If we want to define the equilibrium strategy for player 1 with experience level $e_1 = 2$, the algorithm commences with the shortlisting of strategies for player 2 by playing a homogeneous game with experience levels $(4,4,4)$ and a heterogeneous game with vector $(2,4,6)$ in which random strategies are created for players 1 and 3. Afterwards, shortlisting is executed for player 3 through the homogeneous game with experience vector $(6,6,6)$ and a heterogeneous game with vector $(2,4,6)$, but now with a random strategy generation for players 1 and 2. If this stage is finished, the actual best response determination for player 1 can start. In each iteration, a strategy is selected from the respective shortlists for players 2 and 3 and the expected pay-off is calculated for each possible strategy of player 1.

3.8 Experimental setting

Both algorithms were implemented in Microsoft Visual Studio 2010. Tables 1-3 recapitulate the explanation of the parameter values, the tested strategies and the algorithm specifications. An extensive sensitivity study has been performed together with an ANOVA analysis of all the scenarios. The output of the Nash equilibrium algorithm is the pure strategy Nash equilibrium strategy profile, while the strategy game algorithm output reports the approximate equilibrium strategy for a single player. The results are presented in Table 4 and Figures 3-12 and focus on the dynamics of the equilibrium behavior.

[TABLES 1-3 TO BE INSERTED HERE]

4. Experimental results

4.1 Performance of the heuristics

The Nash equilibrium heuristic has the advantage that it considers the entire search space and calculates the pay-offs for each strategy profile. Consequently, the computation times skyrocket when more strategies are taken into account. As the heuristic only looks into unique Nash equilibria, sometimes no equilibrium is reported (which occurred in 32.4% of the cases). On the other hand, sometimes multiple equilibria are found and then a pay-off dominance mechanism selects the highest pay-off generating equilibrium. Equilibrium examples for the Nash equilibrium heuristic are shown in Table 4. The strategy game heuristic reduces computation times, but has the disadvantage that it limits the search space, so that we might end up in a local optimum.

[TABLE 4 TO BE INSERTED HERE]

4.2 Bidding environment

The bidding environment refers to the number of competitors and their respective experience levels. In practice, governments usually opt for three shortlisted contractors, but evidence for two to five contractors can be found. Figures 3 and 4 are the output of the two sensitivity studies of a strategy game with three players and report the equilibrium response for a reference contractor with the experience level e_1 tabulated in the upper left corner of each matrix and the competitors' experience levels on the horizontal and vertical axes. Each strategy consists of an investment level (i.e., elements below the diagonal) and a mark-up level (i.e., elements above the diagonal). A glance at both figures confirms the general dependency on the bidding situation. If the experience levels increase, the outcome is modified. But also within each matrix, the reported optimal investment levels and mark-up levels significantly vary according to the experience levels of the other two players. Eventually, the introduction of heterogeneity seems useful as the equilibria modify according to the sub-game. Ceteris paribus, two main effects are apparent: (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 compared to the level of the opponents, the lower the mark-up and the higher the investment percentage. Even for small experience gaps, the least experienced player is not or only limitedly motivated to perform the risky upfront investment. The latter effect is more outspoken in the lower experience cases, but flattens out as soon as $e_1 \geq 4$. The interaction plot of Figure 6 visualizes the statements and reveals some opportunistic behavior in the case where an experienced player is playing against two new contractors. The incumbent exploits his knowledge and cost advantage over the entrants by setting a higher mark-up.

[FIGURES 3, 4, 5 AND 6 TO BE INSERTED SOMEWHERE AROUND HERE]

The behavioral dynamics differ according to the experience-related parameters (see Figure 7). In case of an increase of the cost disadvantage parameter β_e, inexperienced players move towards higher mark-up levels, especially when the cost disadvantage enlarges. This is the result of a larger shift of the cost curves that gives rise to higher winning probabilities for experienced players. In other words, if governments would attribute more attention to past experience, inexperienced players will be reticent to come up with a competitive proposal, which could lead to a saturation of the market. A similar effect is related to the knowledge requirement parameter γ_e when a project's complexity necessitates more knowledge. The margin rockets up and puts a break on the investment of inexperienced players, thus limiting competition. An increase in these parameters leads to a surge in the expected government cost (Figure 7(a,b)). For an increase in γ_e, the government cost goes up faster in the case of two inexperienced players, while it is stable or decreasing when there are at least two experienced players due to the competitive forces.

[FIGURE 7 TO BE INSERTED HERE]

Another characterization of the bidding environment is the number of players. Figure 8 shows the boxplots of the simulation outcomes of the aggregate scenarios for a constant uncontrollable project risk and confirms that in the four-player cases, the optimal investment response is lower and the optimal mark-up level is higher than in the three-player environment while the pay-offs are significantly lower. Less experienced players are much more reluctant to invest because of the decreased probability of winning and will in fact stay out of the market. Possible government incentives will be less effective, especially for the incentive creation of inexperienced players.

[FIGURE 8 TO BE INSERTED HERE]

Two-player results look more promising from a competition perspective (Figure 9): there is a more levelled behavior of the players. Inexperienced players tend to be aware of their reasonable probability of winning and the combination of competitive forces and the avoidance of the winner's curse actually keeps them in the market. Nevertheless, the mark-ups soar, so that a higher government cost might be expected.

[FIGURE 9 TO BE INSERTED HERE]

4.3 Project characteristics

PPP projects are wide-ranging in their complexity. One could argue that transportation infrastructure projects have a more complex nature and deal with greater contingencies than social housing PPPs for instance. The model accounts for complexity and uncertainty in the form of the variance of the contractor's cost distribution function. Risk is classified in two categories: controllable and uncontrollable risk. Looking at the controllable risk share, the influence of the innovation parameter γ_i deserves particular attention. It is the uncertainty that can be accounted for by performing pre-tender research (e.g., surveys, feasibility studies, R&D) and is that part of the risk that is not determined by past project experience. One could claim that γ_i attains higher values for highly complex transportation projects than for social housing projects, leading to more uncertainties in incomes and expenses. The innovation parameter has a mark-up impact and an investment impact regardless of the experience level as shown in Figure 3. Nevertheless, the behavior differs according to the experience level. Experienced players move towards a high mark-up together with a higher investment once γ_i increases. Inexperienced players (i.e., $e_1 = 0$) move towards the cap mark-up value of 50% without investment which inherently means that they do not participate. This is accelerated when also the experiential cost disadvantage parameter β_e or the uncertainty due to a lack of experience γ_e increases.

The uncontrollable risk is related to force majeure risk or an unaccountable part of the demand risk for instance and has an exponential impact on the preferred mark-up. The uncontrollable project risk is an inhibitor for investment behavior. The players safeguard against the downside risk of exuberant costs, but because of the normal distribution modeling, the outcome might be positive as well. As a consequence, both the average pay-off for the player as well as the government cost increase sharply and the standard errors of the expected pay-offs will decrease (Figure 10 versus Figure 11). Interestingly, as the share of the uncontrollable project risk gets larger, ceteris paribus, the heterogeneity among players and the disadvantage of the inexperienced player is dissolving and the players' behavior converges towards an equal investment level which is related to the complexity of the project γ_i and a relatively higher mark-up. As a consequence, the expected government cost soars. As it comes at a large expense, the public entity should beware of transferring uncontrollable risk.

[FIGURES 10 & 11 TO BE INSERTED HERE]

4.4 Government intervention

This paper introduces a percentage-wise compensation d to all the losing bidders. In line with the expectations, a surge in the government compensation level leads to a significant increase in the average investment level, but the effect's magnitude and the threshold d that shifts the equilibrium interacts with other parameters that define whether and when a reimbursement is justified. Assume again a common three-player environment as the base case. The response is clearly dependent on the contractor's experience level. As in Figure 4, a less experienced player demands a higher compensation contribution. 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. The threshold compensation level that makes the equilibrium shift towards higher investment levels is inversely related to the innovation parameter γ_i. In the larger γ_i-cases which refer to highly complex and risky projects, players behave differently according to their experience level when no compensations are introduced. But, once a sufficiently high reimbursement is introduced, the playing field seems to become levelled and all the players behave likewise. Figure 4 suggests that a compensation of 50% of the investment cost can convince players with experience level $e_1 = 4$ to actively participate, regardless of the competitive position of its opponents. According to the algorithm output, compensations of 80% trigger participation for players with $e_1 = 2$ regardless of the competition and $e_1 = 0$ if the knowledge gap is within bounds. It works as an incentive mechanism that refrains inexperienced players from becoming reluctant. As shown in Figure 4 and in the interaction plots of Figures 10 and 12, there is an overall investment jump and a large drop in the mark-up. Also in the case with a small controllable uncertainty, the government might be willing to stimulate innovation and research by attributing reimbursements. If no research would be performed, a chance exists of selecting a wrong contractor who might fail to complete the contract which would lead to renegotiation issues. In that case, the compensation levels should be even higher (i.e., 90%) compared to highly uncertain projects. Of course, other determinants will modify these dynamics. The uncontrollable risk, for instance, is an inhibitor and postpones the investment decision for less experienced players. Additionally, β_e contributes to the deceleration of the investment increase.

[FIGURE 12 TO BE INSERTED HERE]

As a conclusion, a percentage-wise compensation policy by the government succeeds in diminishing the heterogeneity among players. The best responses get a more stable feature. The pay-offs for the players will still differ based on the experience level, but the probabilities of winning converge, just like the expected pay-off (e.g., Figure 10). Of course, this compensation comes at a cost for the government (Figure 7(c)). In the low uncertainty cases, the compensation does not seem to incur a huge cost increase, even for high levels of d, while if γ_i grows larger, a trade-off should be made concerning to what extent they want to increase competition in the PPP market. Nevertheless, the societal value of the government compensation can be inestimable on the longer term while the cost for the government is within reason.

Extending our view towards a four-player bidding environment, the reimbursements do not succeed in incentivizing inexperienced players to enter the market with a reasonable investment, because the belief of the winning probability is low. The two-player case suggests lower reimbursement percentages in low-risk projects and Figure 9 indicates that the competitive forces deliver enough incentives for reasonable pre-tender investments for all players which makes the introduction of reimbursements to equalize the market obsolete and makes it just more expensive for the government.

4.5 Other findings

With respect to the simulation experiments, the effects of the efficiency parameter β_e and the uncertainty due to an experiential lack γ_e mainly affect less experienced players. When these parameters surge, the enthusiasm to invest (more) falls back and usually a higher mark-up is preferred. Moreover, very experienced players exploit their advantage and can insist on a higher mark-up. They consequently charge extra for their maturity. The learning rate parameters λ_e and λ_i make players more eager to invest faster. For λ_i 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 percent investment occurs faster and slows down more rapidly, reaching a ceiling at a lower investment level than for a high learning rate. We refer to Table 4 for examples.

4.6 Robustness tests

The assumptions are in line with industrial tendencies and the extensive sensitivity analysis contributes to the robustness of our findings. Moreover, two slightly different assumptions have been tested.

First of all, the analytical model was implemented with cost and bidding functions that are normally distributed. In order to capture the possible asymmetry of the project cost, a gamma distribution has been implemented for which the parameters were calculated given the variance and the expected value of the project cost, in line with the set-up of Section 3.6. No significant differences in the dynamics were found. The major difference lies in the higher equilibrium mark-ups in nearly all scenarios, resulting in greater expected pay-offs.

Secondly, all the statements so far are based on the highest pay-off generating strategies. Contractors could prefer another efficient, justifiable strategy that guarantees a smaller expected pay-off but with greater certainty (i.e., with a smaller standard error). Nevertheless, the simulation outcomes remain close to the previous ones and the compensation policy still succeeds in leveling the playing field under the assumption that all contractors have equal preferences.

5. Discussion of the results

The sensitivity analysis from the previous sections leaves room for discussion on the practical implications of the findings. PPPs are complex agreements and the long-term nature comes along with considerable risk. Diverse jurisdictions deal differently with the procurement issues. The theoretical findings will now be triangulated with qualitative insights from practitioners in the international PPP field. The list of respondents can be found in Table 5.

[TABLE 5 TO BE INSERTED HERE]

The bidding environment, which consists of the number of bidders and their respective experience levels, plays a significant role in the determination of the strategy equilibrium. Recall that the model represents the bidding mechanism after prequalification of the contractors who expressed interest. The results claim for a clear funneling principle. Neither the government nor the contractors benefit from an environment where four contractors are selected for the tender when considerable investments are required. Respondent A could agree with this finding for complex projects, but found it a bit surprising for less complex projects. In the latter case, it is mostly inexperienced contractors that suffer from their disadvantageous position. In the case with two bidders, both are incentivized to establish high-quality documents. Nonetheless, a government might fear for oligopolistic mechanisms and soaring bid prices, so they might prefer a three-player environment in order to reduce the government cost. The results agree that mark-ups will be lower, but they also state that, especially in markets with large gaps in the experience levels, the entrant will face a low probability of winning and will therefore not be enthusiastic to put a lot of effort in the bid preparation. And indeed, bid costs consisting of design, but also the consortium’s working cost could amount up to two million euro for large Belgian projects (respondent G) and even 20 million dollar for mega-projects in Australia (respondent F). This is very sector specific. Respondent H experienced intrinsically attractive projects in the port and power sectors with fairly low bidding costs relative to the rewards of winning, while they are high in rail projects that are subject to market risk, attracting far less bidders. Respondent D acknowledges that firms are reluctant to invest in bid preparation if they are not rewarded for the effort. He claims that the amount of investment should be positively correlated with the weight of the quality aspect in the selection process. In other words, the direct investment impact β_i should be sufficient to overcome experience disadvantages.

Moreover, the model supports that opportunistic behavior is apparent: incumbent firms use their experience advantage as a motive to require higher mark-ups, while inexperienced players tend to be averse for losing the upfront investments and in general initially apply higher mark-ups, while the investment is only considered in a second instance. Consequently, the heterogeneity requires particular attention. Practitioner views tend to support the majority of the findings. Respondent A confirms that they will apply a different strategy if they approach a less competitive Australian market or a highly competitive, standardized and efficient market. When they first entered the international market, a lot of upfront bidding costs were spent on consultancy costs as they were not familiar with some jurisdictions and actually had a competitive disadvantage on incumbent firms. Appealed by the clear agenda of future projects and also by the government reimbursement package, the long-term risks were reduced, making these markets, although very competitive, still very attractive. Canada may serve as an example. Respondent B also notes that high investment requirements serve as barriers for entry and are often perceived as an advantage for bigger companies with robust financial backgrounds. Respondent G adds that large Belgian PPP projects usually attract the same bidding audience, but respondent I claims that the interest is still sufficient. Last but not least, only respondent F claimed that Australian construction costs are escalating at a rate above the inflation rate, while the other governmental and consultancy respondents believe the project costs for the government remained stable regardless of inflation and the increased financing cost after the financial crisis.

A reason could be that players are still building up maturity and are still facing serious competition or that through experiential learning on both the public as well as the private side efficiencies have been realized not only in the execution itself but also in the procurement process through standardization and the increased ability to more accurately estimate working costs (respondent G).

The complexity of a project was translated into a risk measure to model the uncertainty of the project outcome. The famous PPP adagio of allocating the risk to the party that is best able to manage it, needs to be studied from a competitive point of view. The transfer of uncontrollable risk results in soaring mark-ups. Respondent B confirms that the transfer of tricky risks like the demand risk and the permits risk involves that the contractors will require high compensations, supported by the argument that if a contractor gets into trouble, the whole project becomes troublesome. Respondent H gives the example that in a developing country like Nigeria, with possible political instability and uncontrollable uncertainty, port and energy projects are financially very attractive because of the inefficient public sector alternative. On the other hand, the bidder should deal with the controllable risk like the operational risk and the capital expenditure risk. In contrast to large-scale, risky PPPs that require considerate investments in legal advice, less investment is usually necessary in low-risk projects with a more repetitive nature (e.g., sewage infrastructure, social housing) (respondent F). Inexperienced players will play on their mark-ups and will try to be the cheapest in order to obtain a position in the market and not necessarily by investing more upfront (respondent A). For more complex and more risky projects, the dynamics of the analytical results change. Players with experience will be more eager to perform pre-tender investments depending on the experience level they already have obtained and depending on the experience of their opponents. In mature markets, the competitive mechanism seems to work well and qualitative bids ought to be expected. Respondent I supports that contractors are keen to take up risks, because if managed well, these projects allow for considerably higher profits compared to classic building projects where margins are under pressure. Nonetheless, banks will of course ask for considerable guarantees. According to the simulation results, inexperienced contractors are rather skeptical to enter the PPP market and to run the risk of the high investments. In the three-player case, often the least experienced player leaves the deal. In a situation with four players, relatively new contractors will be even less incentivized. This is in contrast with the two-player environment. But, as has been argued before, inviting only two entities for the tender might be more expensive and risky for the government.

The study of a research compensation was then instigated. At the first sight, a sufficiently high compensation triggers a levelled behavior for all players regardless of the experience levels. In low-risk projects, all players will start to invest and the mark-ups remain stable. Nevertheless, compensation levels should be up to 80 or even 90% according to the results. A government compensation proves to give more prospering results for high-risk projects. A partial compensation of 80% triggers proper incentives for both incumbents as well as entrants. It enables the willingness to invest and withholds a player from setting a high mark-up. Respondent I believes that the introduction of government compensations triggers contractors' incentives. He refers to the Dutch market in which principally only two consortia kept interest in PPPs as, together, they won all initial PPPs. The compensation of losing bidders in this context restored other bidders' interest. Respondent A claims that compensations of at least 50% could start to make a significant difference, while respondent E believes the entire reimbursement to the prequalified SPVs would give positive results in the South African context. The initial heterogeneity among players becomes hazy and probabilities of winning get levelled.

Nevertheless, the awarding authority does not always have the budget to offer sufficient compensations and might only attribute amounts that can barely cover the design costs (respondent G). Admittedly, this might come at a considerable cost in the short run, but the societal value in the long run might be enormous: the compensation refrains the market from becoming oligopolistic and the probability of failure and renegotiations will shrink. The view of practitioners is ambiguous. At the private side of the interviewees, there was an agreement that compensations could be beneficial. Nonetheless, they claim there should only be compensations for complex projects and not for low-risk projects as this might trigger the trial-and-error behavior of contractors, unless the market is still developing (respondents A, B). Respondent F also believes that less attractive projects could become more attractive if compensations are introduced. Indeed, also theoretically, the investment percentages rise, but bids do not tend to become more aggressive, in contrast to what happens when compensations are introduced in complex projects. Respondent B believes in a threefold impact of bid compensations: more bidders will be attracted, bidding prices will be lower and it could enable also smaller projects to be delivered by PPPs. Within the public entity, there is no real agreement between jurisdictions. The KPMG report already pointed out the big dissimilarities among countries and also the interviews underline the differences. For instance, South Australia does not have a policy of providing compensation for bid costs, preferring to determine this on a case by case basis. South Australia also noted from its own experience that competition for PPP’s in SA had been strong even without a government commitment to provide compensation for bid costs (respondent C). On the other hand, its neighboring state Victoria sometimes does rely on compensations to open up the market. Respondent F is in favor of compensations if it is impossible to attract two bidders without compensations. In the Chilean context, compensations have been attributed to the second and third runner-up because of the requirement of detailed design plans, which would refrain potential bidders to participate. This resulted in more bids than compensations. Authorities now often take the design out of the bidding process or assist data access to reduce bidding costs or they reduce the risk by packaging concession opportunities, like bundling high and low volume port terminals (respondent H). Nonetheless, both the KPMG repost as well as respondent F claim that the impact of a clear project pipeline might give more prospering results than the reimbursements. Respondent E calls the absence of a continuity of projects the major shortcoming in South Africa. Moreover, a contractor will always consider its current position and its other investment opportunities in order to determine the bidding strategy (respondents F,G) and most consortia are even not substantial enough to carry out more than two PPPs (respondent G). But through this pipeline, a contractor has the opportunity to recover the bid costs from previous lost tenders (respondent C,F). Although, sometimes it is not feasible to build this pipeline because of changes in government or the magnitude of projects (respondent H).

6. Conclusions and future work

This paper studied the procurement procedure of Public-Private Partnerships, agreements that usually involve high upfront research costs. A reasonable number of jurisdictions are looking for mechanisms to open up the market, but there is no agreement on possible policies to install. This paper contributes to the PPP research and auction theory field. The complex tendering procedure was translated into an auction format in which a contractor, who is characterized by a level of experience, first determines the amount of money to invest in research and in a second instance which mark-up is applicable. A Monte Carlo simulation was set up to model the bidding behavior and the resulting pay-off functions while approximation algorithms were developed to identify the Nash equilibrium.

The heterogeneity of the contractors has an important impact on the bidding equilibrium. It are especially new entrants that have difficulties to enter an already mature market if the project has a high degree of complexity and risk. The theoretical model advises governments to limit the number of players that are invited for the tender. On the other hand, a two-player environment can result in oligopolistic behavior. Instead, a three-player environment seems to work well. Both the theoretical model and the majority of practitioners agree that a reimbursement of bidding costs can help in opening up the market in the long run. The models suggest compensation levels of 80% which is a high fraction, but not uncommon in French and Canadian jurisdictions (KPMG, 2010) and also practitioners suggest a minimum reimbursement of 50% in order to be effective. According to the interviewees, this compensation seems to be less necessary in low-risk projects and this could even lead to opportunistic bidding behavior. In summary, the combination of theoretical results and practical validation has led to three concise policy recommendations:

- The government should control the competition in heterogeneous markets through an appropriate funneling strategy;
- A reduction of the complexity results in more incentivized bidders and lower costs;
- In complex projects, bidding cost reimbursements succeed in levelling the playing field and increasing competition.

These outcomes differ from previous conclusions in the academic PPP field that argued against reimbursements. The results that are presented are based on a single-shot auction. Future research focuses on an environment with a pipeline of projects, as in practice it is believed that this could serve as an appropriate incentive for entrants. This will lead to a proliferation of strategy choices and more powerful algorithms will need to be developed. Nevertheless, one should also consider the resource limitations of contractors, so that contractors might not be able to engage in all projects.

Moreover, the model leaves other possibilities for extensions that were suggested by practitioners: how do the dynamics change when the compensation policy is based on the ranking of the bids, when the compensation is paid by the winning bidder or when the research knowledge is shared among all competitors. Moreover, quantitative empirical research on investment and bidding data could highly contribute to the field.

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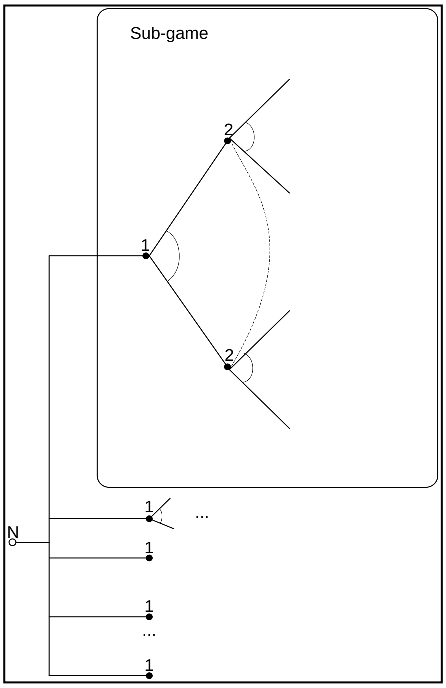


Figure 1: Game tree for a two-player game. Each branch leaving from the initial node N refers to a combination of experience levels, represented by the vector $e = (e_1, e_2)$.

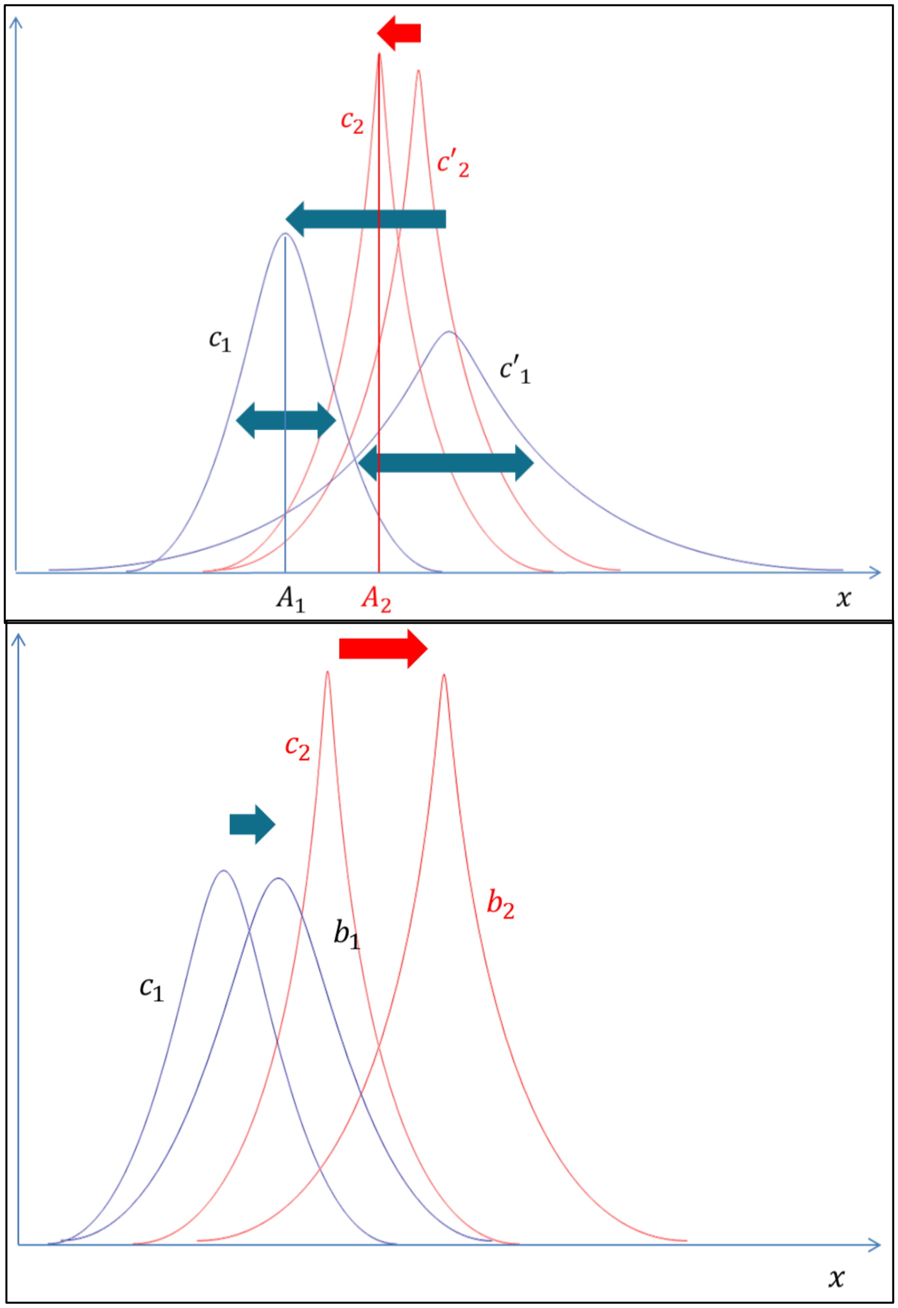


Figure 2: Illustration of the theoretical distributions. c_1' and c_2' are the distributions for two players, where player 2 has more experience than player 1. Player 1 applies a high investment strategy and because of the direct cost impact, his function considerably shifts to the left and the variance decreases due to the knowledge impact assumption, resulting in the cost function c_1. Player 2 made a low investment choice and arrives in c_2. A_1 and A_2 represent the actual cost in occurrence of winning for that respective player. In the lower pane, both players apply their preferred mark-up choice (a low mark-up for player 1 and a high mark-up for player 2) arriving in the respective bidding functions b_1 and b_2.

Parameter	Interpretation	Values
σ	Uncontrollable project risk	5%,10%,15%
γ_e	Maximum risk impact of a lack of experience	0.05,0.10
γ_i	Maximum risk impact of a lack of investment	0.05,0.10,0.20
λ_e	Experiential learning rate	0.25,0.50
λ_i	Investment learning rate	0.25,0.50
β_e	Experiential cost disadvantage	0.05,0.10
β_i	Investment cost disadvantage	0,0.05
μ_e	Experiential cost decrease rate	0.25,0.50
μ_i	Investment cost decrease rate	0.25,0.50
d	Government compensation level	0,0.2,0.5,0.8,0.9

Table 1: Parameter values used in the models

	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%
Mark-up levels	0%,8%,16%,…,40%	0%,1%,2%,…,50%
Number of strategies	36	1,071

Table 2: Values for situation factors and the possible choices for the investment percentages and the mark-up percentages

Parameter	Interpretation	Value
μ	Initial mean project cost	1,000,000
m	Number of simulation runs for pay-off calculation	1,000
n	Number of elements in strategy database R_q	10
k_1	Number of iterations in the strategy game method	100
k_2	Number of iterations in the heterogeneous game	1,000
r	Number of rounds in the homogeneous game	6

Table 3: Used values in the experiments for the different heuristics

	Model parameters										Situation			Nash equilibrium Investment/mark-up (simulated pay-off)			Cost to government
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^*	
4.3 Project risk (uncontrollable)																	
1	0.05	0.05	0.05	0.25	0.25	0.05	0.05	0.25	0.25	0	0	5	10	0%/8% (4,309)	0%/8% (23,526)	0%/8% (31,549)	1,083,146
2	0.1	0.05	0.05	0.25	0.25	0.05	0.05	0.25	0.25	0	0	5	10	0%/16% (15,633)	0%/16% (37,007)	0%/16% (44,449)	1,116,535
3	0.15	0.05	0.05	0.25	0.25	0.05	0.05	0.25	0.25	0	0	5	10	0%/24% (24,330)	0%/24% (44,591)	0%/24% (55,404)	1,144,562
4.3 Project risk (controllable)																	
4	0.05	0.05	0.1	0.25	0.25	0.05	0.05	0.25	0.25	0	0	5	10	0%/16% (14,303)	0%/16% (37,453)	0%/16% (40,291)	1,117,603
5	0.05	0.05	0.2	0.25	0.25	0.05	0.05	0.25	0.25	0	0	5	10	0%/40% (9,002)	2%/24% (40,795)	2%/24% (48,844)	1,161,433
4.4 Government intervention																	
6[a]	0.05	0.05	0.1	0.25	0.25	0.05	0.05	0.25	0.25	0.6	0	5	10	0%/16% (10,599)	2%/16% (29,101)	2%/16% (39,000)	1,143,690
7[a,e]	0.05	0.05	0.1	0.25	0.25	0.05	0.05	0.25	0.25	0.8	0	5	10	2%/16% (11,240)	2%/16% (34,030)	2%/16% (40,862)	1,170,817
8[b,f]	0.05	0.05	0.1	0.25	0.25	0.05	0.05	0.25	0.25	0.8	5	5	5	2%/16% (26,565)	2%/16% (27,179)	2%/16% (28,116)	1,162,372
9[b]	0.05	0.05	0.2	0.25	0.25	0.05	0.05	0.25	0.25	0.6	5	5	5	4%/16% (5,026)	4%/16% (7,624)	4%/16% (6,493)	1,159,656
10[c]	0.05	0.05	0.2	0.25	0.25	0.05	0.05	0.25	0.25	0.4	0	5	10	0%/40% (-4,407)	4%/16% (17,071)	4%/16% (23,158)	1,135,921
11[c]	0.05	0.05	0.2	0.25	0.25	0.05	0.05	0.25	0.25	0.8	0	5	10	4%/24% (-2,669)	4%/16% (20,353)	4%/16% (31,608)	1,189,107
12[d]	0.05	0	0.1	0.25	0.25	0.05	0.05	0.25	0.25	0.8	0	5	10	2%/16% (12,188)	2%/16% (31,526)	2%/16% (40,268)	1,167,906
13[d]	0.05	0	0.1	0.25	0.25	0.1	0.05	0.25	0.25	0.8	0	5	10	0%/16% (3,240)	2%/16% (35,817)	2%/16% (53,504)	1,169,270
4.5 Other findings																	
14[d]	0.05	0.05	0.05	0.25	0.25	0.1	0.05	0.25	0.25	0	0	5	10	0%/16% (1,087)	0%/8% (29,101)	0%/8% (50,710)	1,107,749
15[e]	0.05	0.1	0.1	0.25	0.25	0.05	0.05	0.25	0.25	0.8	0	5	10	0%/24% (3,634)	2%/16% (33,093)	2%/16% (54,650)	1,152,327
16[f]	0.05	0.05	0.1	0.5	0.5	0.05	0.05	0.25	0.25	0.4	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 algorithm. The equilibria and respective pay-offs are based on the simulation of 1,000 projects.

[a] Players react differently to compensation according to experience levels.

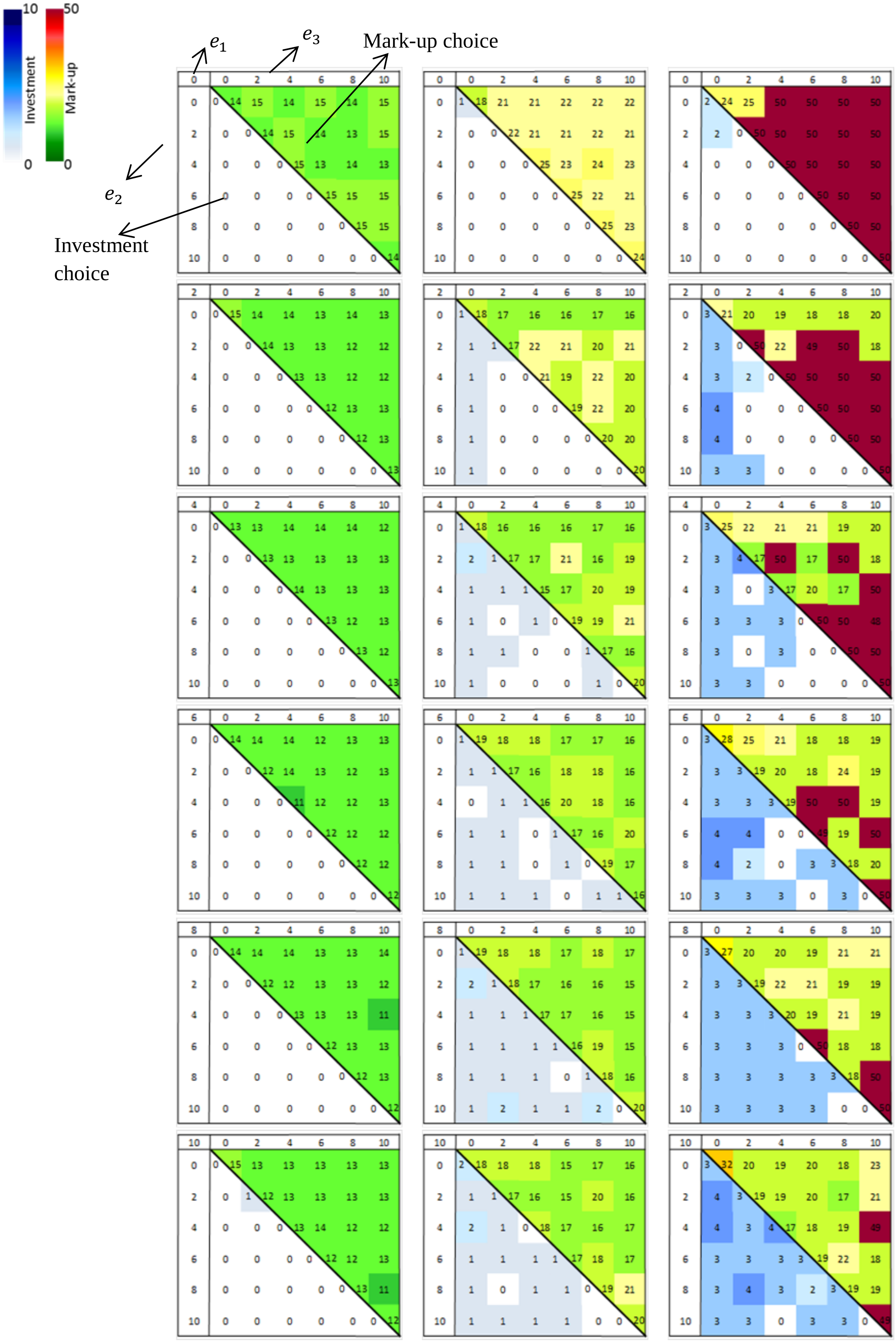
[b] Higher innovation parameter is incentive to invest sooner.

[c] Compensation helps to open up the market.

[d] The efficiency parameter affects investment and mark-up behavior of inexperienced players.

[e] The experiential knowledge requirement affects the inexperienced player’s strategy.

[f] The learning rates affect the speed of the compensation effect.



0	0	2	4	6	8	10
0	0 14	15	14	15	14	15
2	0	0 14	15	14	13	15
4	0	0	0 15	13	14	13
6	0	0	0	0 15	15	15
8	0	0	0	0	0 15	15
10	0	0	0	0	0	0 14

2	0	2	4	6	8	10
0	0 15	14	14	13	14	13
2	0	0 14	13	13	12	12
4	0	0	0 13	13	12	12
6	0	0	0	0 12	13	13
8	0	0	0	0	0 12	13
10	0	0	0	0	0	0 13

4	0	2	4	6	8	10
0	0 13	13	14	14	14	12
2	0	0 13	13	13	13	13
4	0	0	0 14	13	13	13
6	0	0	0	0 13	12	13
8	0	0	0	0	0 13	12
10	0	0	0	0	0	0 13

6	0	2	4	6	8	10
0	0 14	14	14	12	13	13
2	0	0 12	14	13	12	13
4	0	0	0 11	12	12	13
6	0	0	0	0 12	12	12
8	0	0	0	0	0 12	12
10	0	0	0	0	0	0 12

8	0	2	4	6	8	10
0	0 14	14	14	13	13	14
2	0	0 12	12	13	13	12
4	0	0	0 13	13	13	11
6	0	0	0	0 12	13	13
8	0	0	0	0	0 12	13
10	0	0	0	0	0	0 12

10	0	2	4	6	8	10
0	0 15	13	13	13	13	13
2	0	1 12	13	13	13	13
4	0	0	0 13	14	12	12
6	0	0	0	0 12	12	13
8	0	0	0	0	0 13	11
10	0	0	0	0	0	0 12

0	0	2	4	6	8	10
0	1 18	21	21	22	22	22
2	0	0 22	21	21	22	21
4	0	0	0 25	23	24	23
6	0	0	0	0 25	22	21
8	0	0	0	0	0 25	23
10	0	0	0	0	0	0 24

2	0	2	4	6	8	10
0	1 18	17	16	16	17	16
2	1	1 17	22	21	20	21
4	1	0	0 21	19	22	20
6	1	0	0	0 19	22	20
8	1	0	0	0	0 20	20
10	1	0	0	0	0	0 20

4	0	2	4	6	8	10
0	1 18	16	16	16	17	16
2	2	1 17	17	21	16	19
4	1	1	1 15	17	20	19
6	1	0	1	0 19	19	21
8	1	1	0	0	1 17	16
10	1	0	0	0	1	0 20

6	0	2	4	6	8	10
0	1 19	18	18	17	17	16
2	1	1 17	16	18	18	16
4	0	1	1 16	20	18	16
6	1	1	0	1 17	16	20
8	1	1	0	1	0 19	17
10	1	1	1	0	1	1 16

8	0	2	4	6	8	10
0	1 19	18	18	17	18	17
2	2	1 18	17	16	16	15
4	1	1	1 17	17	16	15
6	1	1	1	1 16	19	15
8	1	1	1	0	1 18	16
10	1	2	1	1	2	0 20

10	0	2	4	6	8	10
0	2 18	18	18	15	17	16
2	1	1 17	16	15	20	16
4	2	1	0 18	17	16	17
6	1	1	1	1 17	18	17
8	1	0	1	1	0 19	21
10	1	1	1	1	0	0 20

0	0	2	4	6	8	10
0	2 24	25	50	50	50	50
2	2	0 50	50	50	50	50
4	0	0	0 50	50	50	50
6	0	0	0	0 50	50	50
8	0	0	0	0	0 50	50
10	0	0	0	0	0	0 50

2	0	2	4	6	8	10
0	3 21	20	19	18	18	20
2	3	0 50	22	49	50	18
4	3	2	0 50	50	50	50
6	4	0	0	0 50	50	50
8	4	0	0	0	0 50	50
10	3	3	0	0	0	0 50

4	0	2	4	6	8	10
0	3 25	22	21	21	19	20
2	3	4 17	50	17	50	18
4	3	0	3 17	20	17	50
6	3	3	3	0 50	50	48
8	3	0	3	0	0 50	50
10	3	3	0	0	0	0 50

6	0	2	4	6	8	10
0	3 28	25	21	18	18	19
2	3	3 19	20	18	24	19
4	3	3	3 19	50	50	19
6	4	4	0	0 49	19	50
8	4	2	0	3	3 18	20
10	3	3	3	0	3	0 50

8	0	2	4	6	8	10
0	3 27	20	20	19	21	21
2	3	3 19	22	21	19	19
4	3	3	3 20	19	21	19
6	3	3	3	0 50	18	18
8	3	3	3	3	3 18	50
10	3	3	3	3	0	0 50

10	0	2	4	6	8	10
0	3 32	20	19	20	18	23
2	4	3 19	19	20	17	21
4	4	3	4 17	18	19	49
6	3	3	3	3 19	22	18
8	3	4	3	2	3 19	19
10	3	3	0	3	3	0 49

Figure 3: Impact of the controllable uncertainty on the bidding behavior. Player 1's strategy output (in percentage values) for a 3-player strategy game experiment with parameter values: $\lambda_1 = \lambda_2 = \mu_1 = \mu_2 = 0.25$, $\gamma_e = 0.05$, $\beta_e = 0.05$, $\beta_i = 0.05$, $\sigma = 0.05$ and $d = 0$. The value for the innovation parameter γ_i is (from left to right) 0.05, 0.1 and 0.2 respectively.

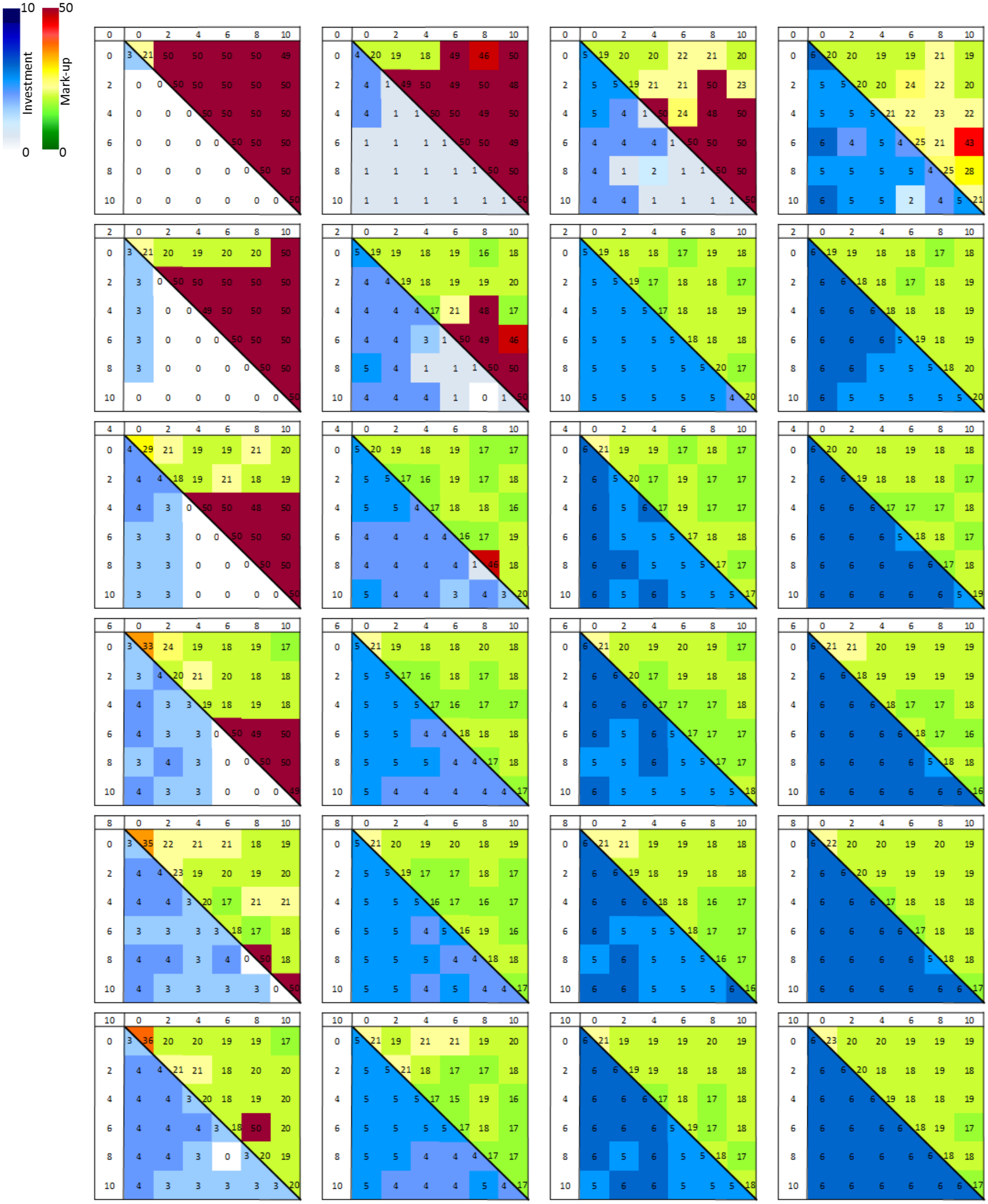


Figure 4: Impact of the compensation on the bidding behavior. Strategy output (in percentage values) for player 1 in a 3-player strategy game experiment with parameter values: $\lambda_1 = \lambda_2 = \mu_1 = \mu_2 = 0.25$, $\gamma_e = 0.05$, $\gamma_i = 0.20$, $\beta_e = 0.10$, $\beta_i = 0.05$ and $\sigma = 0.05$. The government compensation levels d are (from left to right) 0%, 50%, 80% and 90% respectively.

				Player 3 - e_3		
				0	**5**	**10**
Player 1 - e_1	**0**	**Player 2 - e_2**	**0**	1	2	3
			5		4	5
			10			6
	5		**5**		7	8
			10			9
	10		**10**			10

		Opponent B - e_3					
		0	**2**	**4**	**6**	**8**	**10**
Opponent A - e_2	**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: Codification of the bidding environment. Relationship between the situation number and the experience level of the different players. The left table maps the situations of the Nash equilibrium method (for Figure 7). The right table maps the situation number for the strategy game results (for Figure 6).

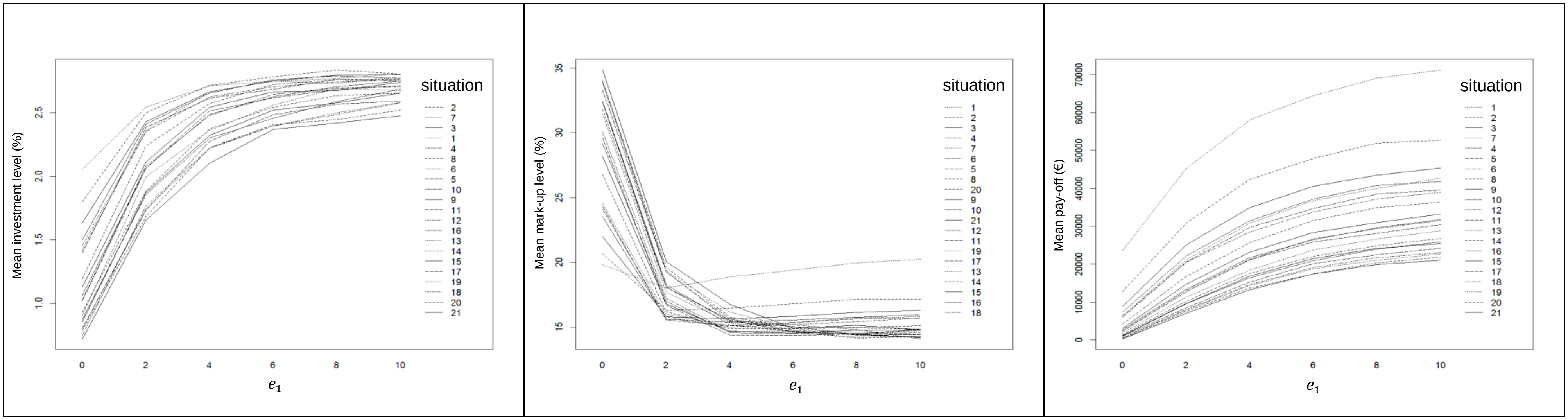


Figure 6: [strategy game algorithm] The interaction between e_1 and the situation that refers to the experience levels e_2 and e_3 in the right table of Figure 5 in relationship with the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which σ=5%.

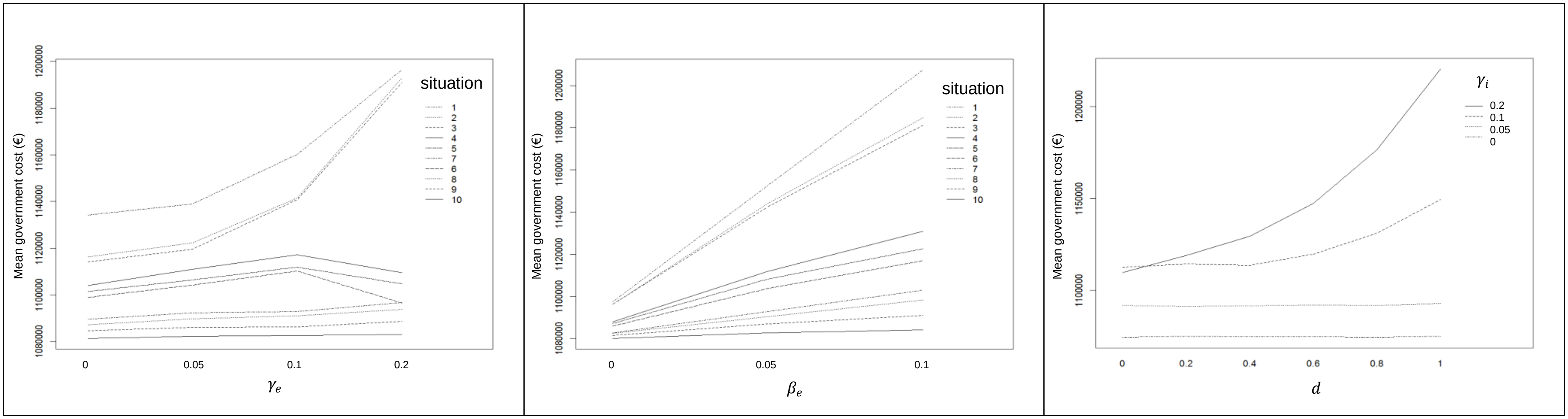


Figure 7: [Nash equilibrium algorithm] The left pane (a) shows the interaction between γ_e and the bidding situation in relationship with the government cost for all the scenarios with σ = 5%. A relationship between the situation number and the respective experience levels is given in the left table of Figure 5. The middle pane (b) relates the efficiency parameter β_e and the bidding situation to the total cost for the government. The right pane (c) shows the interaction between the government compensation policy and the innovation parameter related to the government cost for all scenarios with σ = 5%.

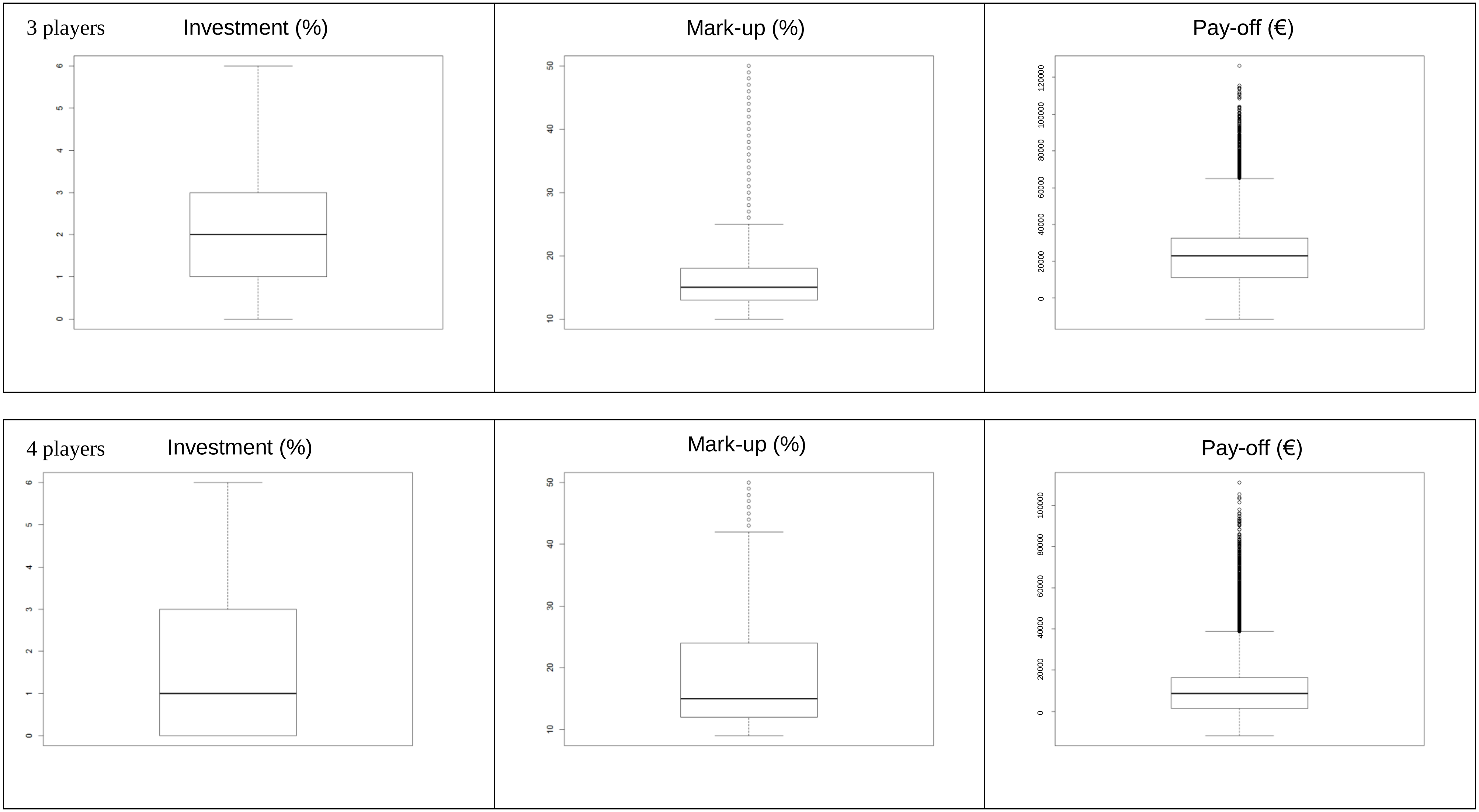
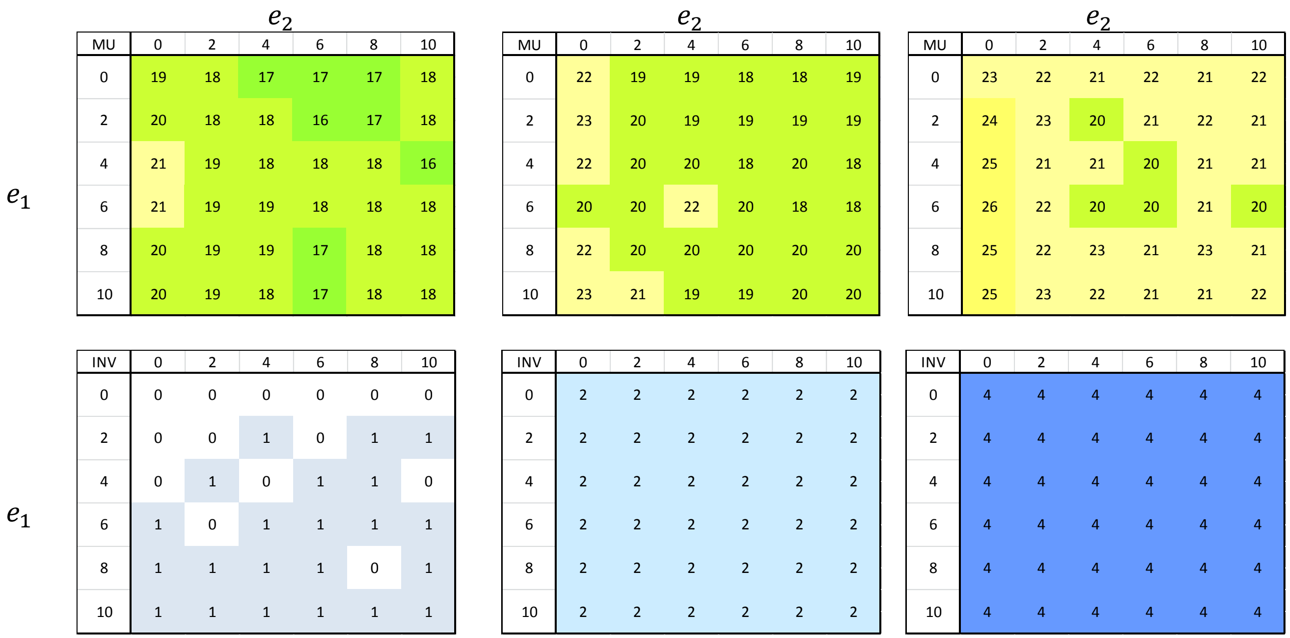


Figure 8: [strategy game algorithm] Boxplots of all the aggregated scenario outcomes for σ = 5% for the 3-player and 4-player case



MU	0	2	4	6	8	10
0	19	18	17	17	17	18
2	20	18	18	16	17	18
4	21	19	18	18	18	16
6	21	19	19	18	18	18
8	20	19	19	17	18	18
10	20	19	18	17	18	18

MU	0	2	4	6	8	10
0	22	19	19	18	18	19
2	23	20	19	19	19	19
4	22	20	20	18	20	18
6	20	20	22	20	18	18
8	22	20	20	20	20	20
10	23	21	19	19	20	20

MU	0	2	4	6	8	10
0	23	22	21	22	21	22
2	24	23	20	21	22	21
4	25	21	21	20	21	21
6	26	22	20	20	21	20
8	25	22	23	21	23	21
10	25	23	22	21	21	22

INV	0	2	4	6	8	10
0	0	0	0	0	0	0
2	0	0	1	0	1	1
4	0	1	0	1	1	0
6	1	0	1	1	1	1
8	1	1	1	1	0	1
10	1	1	1	1	1	1

INV	0	2	4	6	8	10
0	2	2	2	2	2	2
2	2	2	2	2	2	2
4	2	2	2	2	2	2
6	2	2	2	2	2	2
8	2	2	2	2	2	2
10	2	2	2	2	2	2

INV	0	2	4	6	8	10
0	4	4	4	4	4	4
2	4	4	4	4	4	4
4	4	4	4	4	4	4
6	4	4	4	4	4	4
8	4	4	4	4	4	4
10	4	4	4	4	4	4

Figure 9: Impact of the controllable uncertainty on the bidding behavior. Player 1's strategy output in percentage values (mark-ups in the upper panes and investment in the lower matrices) for a 2-player strategy game experiment with parameter values: $\lambda_1 = \lambda_2 = \mu_1 = \mu_2 = 0.25$, $\gamma_e = 0.05$, $\beta_e = 0.05$, $\beta_i = 0.05$, $\sigma = 0.05$ and $d = 0$. The value for the innovation parameter is (from left to right) 0.05, 0.1 and 0.2 respectively.

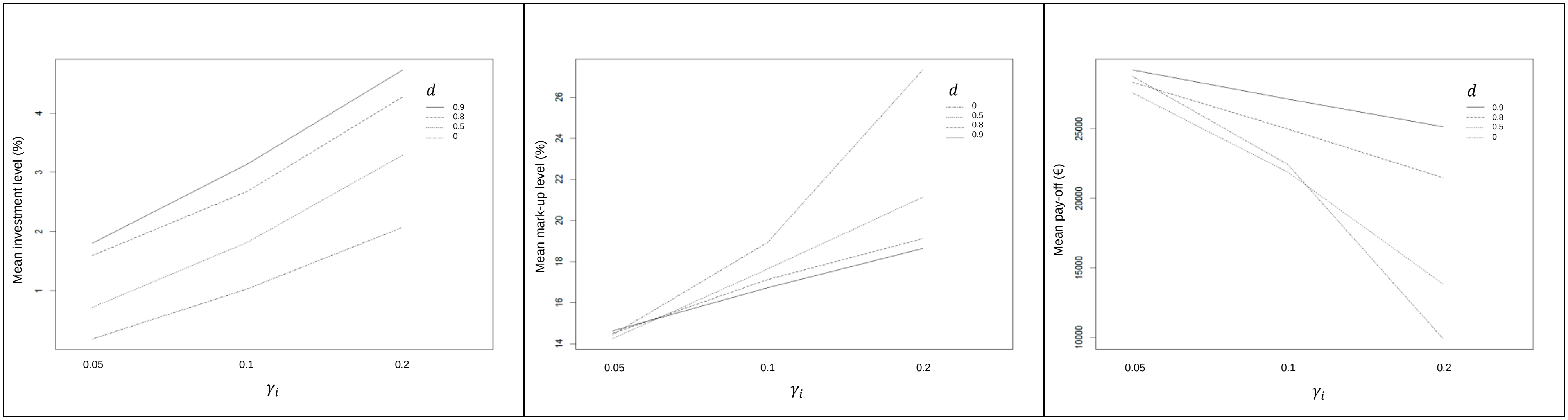


Figure 10: [strategy game algorithm] The interaction between the innovation parameter γ_i and the government compensation level d with the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which σ=5%

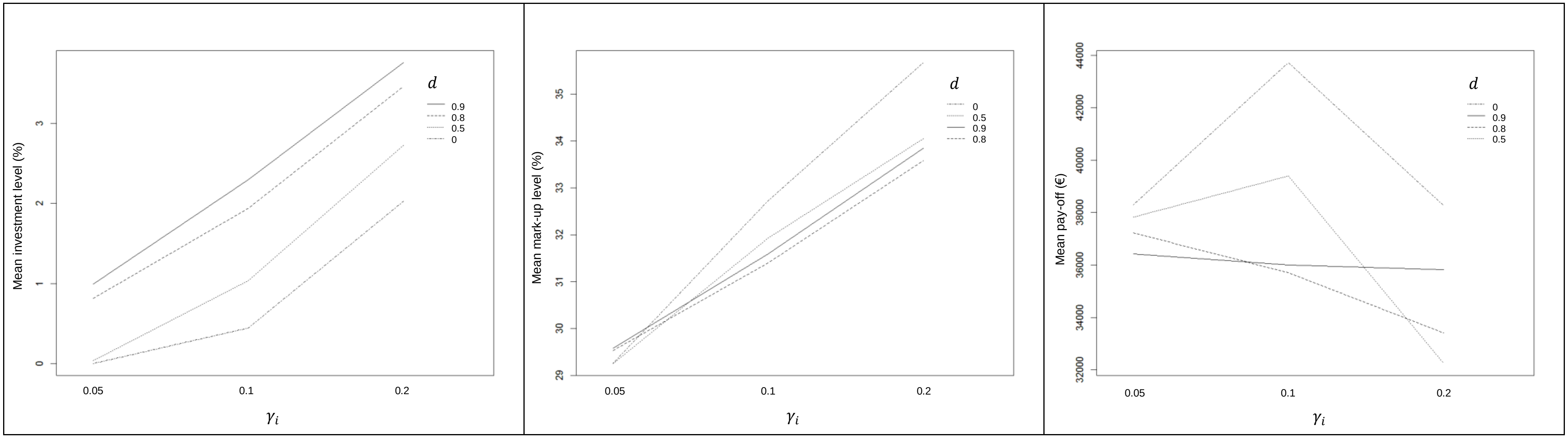


Figure 11: [strategy game algorithm] The interaction between the innovation parameter γ_i and the government compensation level d with the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which σ=15%

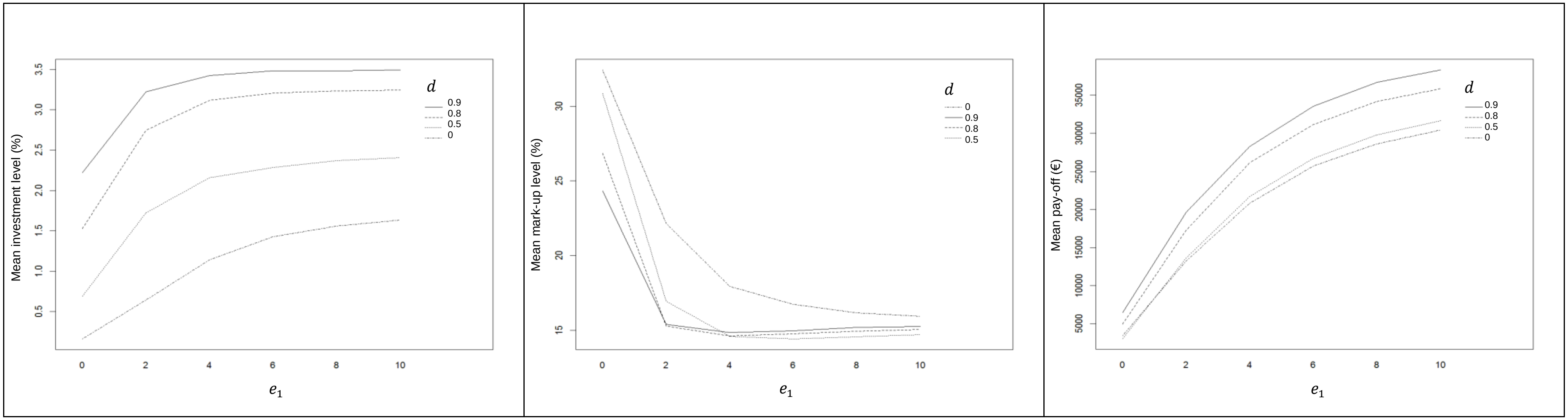


Figure 12: [strategy game algorithm] The interaction between the experience level e_1 and the government compensation level d with respect to the investment level (left), the mark-up level (middle) and the pay-off for the scenarios in which σ=5%

Respondent	Function	Region of expertise
A	Executive director of investment company	Australia and other developed countries
B	Independent PPP consultant	Czech Republic
C	Manager at Department of Treasury & Finance South Australia	South Australia
D	PPP project coordinator	Chile
E	Independent PPP consultant	South Africa
F	Construction lawyer	Australia
G	Lawyer (public law)	Belgium
H	Principal at infrastructure advisory service provider	Developing countries
I	Director at advisory firm	Belgium

Table 5: Respondents for the validation interviews

Appendix 1

ALGORITHM 1: StrategyGame(p, e)

$k_2 =$ number of strategy game iterations

```
for all $q \neq p$ do
    HomogeneousGame$(q)$
    HeterogeneousGame$(q)$
end for
for $i = 1$ to $k_2$ do
    for all $q \neq p$ do
        Select $s_q \in R_q$ randomly
    end for
    for all $x_i \in S_p$ do
        $s \leftarrow (s_1, \dots, s_{p-1}, x_i, s_{p+1}, \dots, s_P)$
        CalculatePayoff$(e, s)$
        $\pi(x_i) \leftarrow \pi(x_i) + f_p(s)$
    end for
end for
$s_p^* \leftarrow$ argmax $\{\pi(x_i), \forall i\}$
```

ALGORITHM 2: HomogeneousGame(q)

$rds =$ number of rounds

```
$e' \in \mathbb{R}^P$
$e' \leftarrow \left(e_q, e_q, \dots e_q\right)$
$s' \in \mathbb{R}^P$
$t \in \mathbb{R}^{P^r}$
for $i = 1$ to $P^{rds}$ do
    Select $t_i \in S_q$ randomly
end for
while $rds > 1$ do
    for $i = 1$ to $P^{rds-1}$ do
        $s' \leftarrow (t_{(i-1)*P+1}, \dots t_{(i-1)*P+P})$
        CalculatePayoff$(e', s')$
        $t_i \leftarrow$ argmax $\{f_p(s'), \forall p\}$
    end for
    $rds = rds - 1$
end while
$(t_1, t_2, \dots, t_P) \rightarrow R_q$
```

ALGORITHM 3: HeterogeneousGame(q)

$k_1 =$ number of iterations

$n =$number of shortlisted strategies

```
for $i = 1$ to $k_1$ do
    for all $r \neq q$ do
```

```
        Select $s_r \in S_r$ randomly
    end for
    for all $x_i \in S_q$ do
        $s \leftarrow (s_1, \dots, s_{q-1}, x_i, s_{q+1}, \dots, s_P)$
        CalculatePayoff$(e, s)$
        $\pi(x_i) \leftarrow \pi(x_i) + f_q(s)$
    end for
end for
Sort$\left(S_q, \pi(x_i)\right)$
Best $(n - P)$ strategies $\rightarrow R_q$
```

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