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Cooperation under uncertainty: Assessing the value of risk sharing and determining the optimal risk-sharing rule for agents with pre-existing business and diverging risk attitudes

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Abstract

The allocation of risk among the cooperating parties in a shared project is an important decision. This is especially true in the case of large infrastructure investments. Existing risk allocation methods are either simplistic or do not consider the effect of the agents' pre-existing businesses. In this paper, we model and analyse the effect of risk sharing when two agents want to co-develop an energy infrastructure project in an uncertain environment. The cooperating agents have a pre-existing risky business, and the new common project has a deterministic initial cost but random revenue potential. Our analysis shows that the optimal risk-sharing rule depends not only on the agents' risk aversions but also on the volatility of the common project profit, the volatilities of the agents' pre-existing businesses and the correlation of each agent's pre-existing business with the common project. An illustrative example based on energy infrastructure is used to show the implications of the sharing rule for partners.

Keywords: Energy infrastructure investment; Risk sharing; Cooperation; Contracts; Uncertainty; Risk averse agents

1. Introduction

The selection of partners in a joint venture and the allocation of risk among them are important decisions that have a deep impact on the success of the project. However, the existing methods in the literature only consider the agent's risk aversion, leading to the least risk-averse agent taking a higher share of the risk. However, determining the best risk-sharing approach should take other factors into account such as the agent's pre-existing businesses. This paper answers this question, developing a model to determine the value of risk sharing – that is, how much value the coalition brings with respect to the project being developed by a single partner. Contrary to existing approaches, our developed value of risk sharing considers the agents' pre-existing business and their correlation to the joint venture, together with their risk attitudes. The model provides valuable insights for the most favourable design of a coalition and the risk-sharing contract in order to get the most of the benefits of cooperation.

Cooperation is even more important in infrastructure projects given their high capital intensity, which makes it necessary to form partnerships face the needs for investment in an efficient way. Specifically, the energy sector has recently experienced an increased need for cooperation which we would like to highlight, as it provides a further specific context for this need. Agents in the energy sector are increasingly seeking cooperation to cope with the competitive and complex energy landscape caused by forces such as liberalization, deregulation, renewable energy integration, and climate policies (Ligtvoet, 2013). This can be seen in several large scale joint infrastructure project

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initiatives and plans. For example, in the USA, regional transmission operators are cooperating to develop inter-regional electricity transmission lines to facilitate the integration of renewable energy sources that span across multiple regions (MIT Energy Initiative, 2011). In Europe, bordering transmission operators are cooperating to invest in cross-border transmission to facilitate electricity market integration (Brancucci Martínez-Anido, 2013). Moreover, new regulatory frameworks are being introduced to encourage cooperation in electricity markets integration (Böckers et al., 2013), renewable energy integration (EU Commission, 2006), electricity and gas infrastructure development and upgrade (Henry et al., 2014; Brancucci Martínez-Anido, 2013), energy efficiency (Nauleau et al., 2015), and CO_2 emission reduction (RCI, 2011).

The rationale for cooperation in infrastructure projects is multiple: it enables agents to minimize the effects of uncertainty by aligning their interests (Ligtvoet, 2013); provides strategic advantages such as the ability to achieve objectives faster, getting access to know-how or to markets, cost advantages, transfer or complementarity of technologies, and economies of scale (Williamson, 1979; Bronder and Pritzl, 1992; Guoa et al., 2014). However, cooperation is not always straightforward, and various uncertain factors expose parties to different kinds of risks (Lam, 1999; EU Commission, 2006). On the one hand, large-scale infrastructure projects are particularly subject to risk due to large initial costs, high irreversibility (sunk costs), and long-term durability of assets (Lam, 1999; Boatenga et al., 2015). On the other hand, cooperation involving infrastructure (and energy infrastructure in particular) is complex as multiple agents are involved with different objectives and constraints. By its own nature, cooperation is a multi-motive game. Because each party displays a rational behaviour, there are considerable costs and risks involved in the decision to join a project (Williamson, 1979; Nooteboom, 2000). The presence of endogenous uncertainty (e.g. strategic behaviour) (Berger and Hershey, 1994; Grundy, 2000) and exogenous uncertainty (e.g. technology, market, regulatory changes) often lead to a deadlock in which decision-making stagnates as parties become increasingly risk averse and are afraid to 'bet on the wrong horse' (McCarter et al., 2010; Gong et al., 2009). Therefore, with incentives on one hand and costs and risks on the other, the challenges in most infrastructure development cooperation projects are: (1) How will the associated risk and value be shared among the partners? (2) How should we structure contracts to enhance synergies at an acceptable level of risk?

In the strategic management literature, the discussion on the allocation of benefits and risks from cooperation under uncertainty is based on two perspectives: a value-creation perspective and a risk-sharing perspective. The value-creation perspective takes the view that agents cooperate to gain value and hence focuses on the allocation of value from cooperation (Folta and Miller, 2002; Holta et al., 2000). In that respect, real-options valuation is receiving increasing attention as a tool to analyse the value of cooperation, see for example (Kogut, 1991; Liu et al., 2014; Park et al., 2013). The risk-sharing perspective uses the concept of risk sharing to explain the motive for cooperation and allocation of risk among cooperative agents (see for example Allen and Lueck, 1999; Medda, 2007; Blenman and Xu, 2009).

Regarding the allocation of value from cooperation, the literature has also come a long way from deterministic cooperative game theory models of Nash (1950), Nash (1953) and Shapley (1953) to models for stochastic payoffs (Suijs et al., 1999; Savva and Scholtes, 2005). The literature on optimal risk sharing between two parties was first analysed by Borch for the specific case of insurance contracts (Borch, 1962). Later, Wilson led the research for efficient risk sharing in syndicates (Wilson, 1968) and more recently this was advanced by Pratt (Pratt, 2000). Various risk-sharing allocation techniques have been presented for infrastructure investments. (Lam et al., 2007) used qualitative risk allocation for construction projects using a fuzzy inference mechanism. Medda (2007) used a game theoretical approach to the allocation of risks in transport public-private partnerships. Other techniques applied to this problem include Artificial Neural Networks (Jin and Zhang, 2011) or fuzzy system dynamics (Nasirzadeha et al., 2014). However, all these previous works largely focus on closed contracts where the only payoff comes from the joint investment, and the effects of the agents' pre-existing businesses are ignored. Moreover, the methods used to model the uncertainty in the future performance of the common project are either deterministic or relatively simplistic, while the future revenues from most infrastructure investments are stochastic.

In this study, we deal with stochastic revenue and consider the correlation of the pre-existing businesses of cooperating agents with the common project. We use concepts from the risk-sharing literature to model a risk-sharing contract between two risk-averse agents who invest in a common project. Then, we apply cooperative game theory to analyse the synergy effects of risk sharing. A stylized case example loosely inspired by a joint venture created to develop a merchant electricity interconnector between the Netherlands and the UK, known as BritNed (BritNed, 2015) is used to illustrate the implications of this research.

This paper adds to the existent literature in two ways: we study the value of cooperation considering that the participants have pre-existing businesses that are correlated with the joint venture and that these agents can have diverging risks attitudes. We also develop the rule for optimal risk sharing –i.e. how much of the risk should be borne by each agent-. These results can be used to select among possible partners so that the value of cooperation is better and to support negotiations.

The paper is organized as follows. Section 1 introduces the work. Section 2 provides the basic model set-up and assumptions. Section 3 solves for the optimal linear contract between the two agents. Section 4 introduces uncertainty in the form of difference in contract design between cooperating parties and solves for the real option value of risk sharing. Section 5 presents computational results and analysis of optimal risk share and values of risk sharing.

2. Modelling revenue and profit

Let's take two agents ($i = 1, 2$) who intend to create a joint venture to share the development cost and future profit of an

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energy infrastructure project. Each agent has a pre-existing risky business before the possibility of investing in the common project is considered. Moreover, agents agree to share the profit risk associated with the common project. We assume that cooperating agents observe the evolution of the joint cooperative project's value and they have symmetric information. All parties have access, ex-post, to the true realized returns of the common project. All profits of the new venture will be shared between the two agents. The applicability of the proposed model is general but throughout the paper a joint project to develop a merchant transmission line is used as an illustrative case.

We assume that the future performance of the common project is uncertain and follows a stochastic process. For example, in merchant power interconnectors[1], the daily revenue is stochastic due to the random nature of congestion revenue, which depends on daily electricity demand and nodal prices (Salazar et al., 2007). There is an array of approaches (e.g., Brownian motion, mean reverting process) that can be used to model the revenue time series (Dixit and Pindyck, 1994). Geometric Brownian Motion (GBM) processes are frequently applied to model stochastic price and revenue behaviours. Salazar et al. (2007) and Fleten et al. (2011) employed a GBM process to model electricity prices for an economic analysis of merchant power interconnectors. Brandao and Saraiva (2008) and Carbonara et al. (2014) used GBM process to model revenue in infrastructure projects.

Although GBM is preferred for the purposes of price modelling, it fails to effectively model profit and cash flows as it does not allow for negative realizations. Arithmetic Brownian Motion (ABM) processes are frequently used to model economic performance measures that can become negative (e.g. profits) (Copeland and Antikarov, 2001). Since the revenue of merchant interconnector project depends on price differences between the connected markets, ABM can be used to model its dynamics over time. Moreover, if the price of each individual price region is modelled using a GBM process, the dynamics of the difference can be reasonably approximated using an ABM process (Carmona and Durrleman, 2003). Therefore, in this study, we assume that the investment-flow returns follow an ABM process.

An ABM process representation of profit $p(t)$ at any time is given by

$$p(t) = p_0 + \mu t + \sigma W(t), \tag{1}$$

where p_0 is the initial value, μ is the expected return (the drift), and σ is the volatility of profit.

To illustrate the risk-sharing rule, we consider the following cooperation scenario. The agents agree on creating the joint venture S at time $t=0$. Then, at time $t=\tau<T$, the partners decide to sign a risk-and-profit-sharing agreement based on the discounted value[2] of the common project's profit for the period $[\tau, T]$. Therefore, we are interested in the distribution of the present value of the profit of the three entities: i.e. the common project and the two pre-existing business of the agents. Mathematically, the present value of an ABM process can be reasonably approximated using a normal distribution (Ross, 1999; Cartea and González-Pedraz, 2012). Therefore, a time = $\tau < T$, the profits of the common project and the agents' pre-existing businesses are denoted as follows:

- $x_i^0(\tau)$ = the discounted value of the profit from agent i's existing business.
- $x_i^1(\tau)$ = the discounted value of the profit if either of the agents invests on the joint venture alone.
- $x(\tau)$ = the discounted value of the profit from the common project.
- $x_i(\tau)$ = the discounted value of the profit from the joint venture received by agent i.

The expressions of the distributions of the pre-existing business and the common project are shown as follows.

$$x_i^0(\tau) \sim N\left(\mu_i^0, \sigma_i^0\right) \tag{2}$$

$$x(\tau) \sim N(\mu_s, \sigma_s) \tag{3}$$

Whether the agents decide to take up the new project as a single investor or together as a joint project, it is important to define the relationship between the joint venture and their existing projects. Since the two agents have some existing risky businesses, their decision whether to invest in the shared infrastructure project or not depends on their pre-existing business and the characteristics of the new shared project. For example, if two neighbouring countries jointly invest in an electricity interconnector, the electricity prices in both countries will be affected and that in turn will affect the revenue of transmission operators and generators in each country (Parail, 2009). As a result, neighbouring countries (at least the transmission operators and generators in the high electricity price market) have the interest to keep the two electricity markets separate (Kristiansen and Rosellón, 2010; Parail, 2010). In order to take into account the influence of the new common project, we consider its correlation with the pre-existing businesses of the two agents.

The dependence between the pre-existing businesses and the common project is determined by a linear correlation coefficient ρ_i (Pastore, 1988). This correlation coefficient takes a value between 0 and 1, i.e. $-1 \le \rho_i \le 1$. If $\rho_i = 0$, then the common project and the pre-existing business are independent. If $0 < \rho_i < 1$, then the two are positively correlated and if $-1 < \rho_i < 0$, then they are negatively correlated.

The sum of two dependent normal distributions (which can each describe the present value of an ABM-cash-flow) is

[1] Merchant electricity interconnector, also called non-regulated transmission investment, is an arrangement where a third party constructs and operates electric transmission lines between unrelated electricity markets, often across borders. Interconnectors are the physical links which allow the transfer of electricity across borders.

[2] In a continuous-time game the payoffs are realized along the time of the cooperation. However, we assume that agents evaluate the worth of cooperation (i.e. their individual share) by discounting the sum of future payoffs at the time of entering into the cooperation.

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a normal distribution (Pastore, 1988). By this principle, we can define the distribution parameters of x_i^1 and $x_i(\tau)$ based on Eqs. (2) and (3).

If one of the agents carries out the investment alone[3], the total uncertain payoffs can be obtained by adding the payoff from the existing business and the payoff from the common project.

$$x_i^1(\tau) = x_i^0(\tau) + x(\tau) \tag{4}$$

Therefore, $x_i^1(\tau)$ is given as

$$x_i^1(\tau) \sim N\left(\mu_i^1, \sigma_i^1\right) \tag{5}$$

where $\mu_i^1 = \mu_i^0 + \mu_s$ and $\sigma_i^1 = \sqrt{\left(\sigma_i^0\right)^2 + \sigma_s^2 + 2\rho_i\sigma_i^0\sigma_s}$.

Similarly, if the agents cooperate the total value of each agent's payoff from engaging in the joint venture is the sum of the uncertain payoff from the existing business and a share $\varphi_i \in [0, 1]$ of the uncertain payoff from the joint venture. Here we define the risk-sharing contract to be a rule to calculate the percentage share of the equity stake in the common project. Therefore, if the agents cooperate in developing the project the cash flow depends on the contractually agreed share rule φ_i.

$$x_i(\tau) = x_i^0(\tau) + \varphi_i x(\tau) \tag{6}$$

$$x_i(\tau) \sim N(\mu_i, \sigma_i) \tag{7}$$

where $\mu_i = \mu_i^0 + \varphi_i\mu_s$ and $\sigma_i = \sqrt{\left(\sigma_i^0\right)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}$.

The probability density distribution of a normal distribution function x with mean μ and variance σ^2 is expressed as

$$f(x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{8}$$

Inserting the mean and variances of Eqs. (5) and (7) in Eq. (8) we get a probability density distribution of for $x_i^1(\tau)$ and $x_i(\tau)$.

$$f\left(x_i^1(\tau)\right) = \frac{1}{\sqrt{2\pi\left(\sigma_i^2 + \sigma_s^2 + 2\rho_i\sigma_i\sigma_s\right)}} e^{-\frac{\left(x_i^1 - (\mu_i + \mu_s)\right)^2}{2\left(\sigma_i^2 + \sigma_s^2 + 2\rho_i\sigma_i\sigma_s\right)}} \tag{9}$$

$$f(x_i(\tau)) = \frac{1}{\sqrt{2\pi\left(\sigma_i^2 + \varphi_i^2\sigma_s^2 + 2\varphi_i\rho_{is}\sigma_i\sigma_s\right)}} e^{-\frac{\left(x_i^1 - (\mu_i + \varphi_i\mu_s)\right)^2}{2\left(\sigma_i^2 + \varphi_i^2\sigma_s^2 + 2\varphi_i\rho_{is}\sigma_i\sigma_s\right)}} \tag{10}$$

The expressions in Eqs. (9) and (10) respectively show the probability distribution of profit for each agent if they invest in the common project alone and if they invest jointly. Determining the profit distributions in Eq. (9) requires only calculating the correlations (ρ_i) between the profit from the agents' pre-existing businesses and the profit from new common project, given their distribution is known. However, determining the profit distributions in Eq. (10) requires deriving the optimal risk sharing ratio (φ_i) in addition to correlation. In the next section we use utility theory to derive the optimal risk share ratio.

3. Optimal risk-sharing rule

In the previous section, we define the uncertain profit agents will receive when they engage into a shared investment. However, the value of the uncertain payoff depends on the risk preference of the agent. Without loss of generality, we assume both agents are risk averse. A risk-averse agent is reluctant to accept a bargain with an uncertain payoff compared to another bargain with a more certain, but possibly lower, expected payoff (Pratt, 2000). We model the payoff preference of agents using expected-utility functions (Schoemaker, 1982), i.e. party i prefers an uncertain payoff X over an uncertain payoff Y if $E[U_i(X)] > E[U_i(Y)]$ where U_i is a suitable utility function (Pratt, 1964). The underlying assumption is that the agents' perception of risk can be fully captured by the expected utility function, which reflects the value of the payoff share from the common project. Utility function translates each of the possible payoffs into a non-monetary measure known as utility. For tractability reasons, we consider a negative exponential utility function assuming the agents that the risk preference of each firm is governed by a constant absolute risk aversion (CARA)[4] utility function.

$$U(X) = -e^{-\gamma X}, \tag{11}$$

where $U(X)$ represents the utility function, X is the evaluation measure (such as profit or cost), γ is a constant that describes risk aversion. The degree of risk aversion that is appropriate depends, for instance, on the nature of the agent or on its asset position (Pratt, 1964). CARA means that, if we change a uncertain payoff X by adding a fixed additional amount of money to the agent's payoff in all possible outcomes of the gamble, then the certainty equivalent of the gamble should increase by this same amount. Constant risk aversion is widely used for practical decision analysis due to its convenience (Myerson, 2004). Moreover, constant risk aversion allows us to evaluate independent uncertain payoffs (i.e. P(t) and $P_i^0(t)$) separately.

For a CARA utility function shown in Eq. (11), the expected utility of Eq. (8) is given by[5]

$$EU(x) = -e^{-\gamma\left(\mu - \gamma\frac{\sigma^2}{2}\right)} \tag{12}$$

Using the same formulation $x_i(\tau)$ can be given by

$$E(U(x_i)) = -e^{-\gamma_i\left(\mu_i^0 + \varphi_i\mu_s - \gamma_i\frac{\left(\sigma_i^0\right)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}{2}\right)} \tag{13}$$

Eq. (13) shows that the expected utility of the discounted value of the joint venture for agent i is a function of her share

[3] However, for reasons of risk and other regulatory barriers, they are not willing to do it alone or not allowed by law. This is often the case for cross-border power transmission investment.

[4] The assumption of CARA utility function may seem far from reality compared to constant relative risk aversion (CRRA). However, the kind of utility function that describes the average is still controversial.

[5] See Sargent and Heller (1987) for the proof.

from the joint venture and the correlation of her existing business to the new joint venture.

For CARA utility function, $\gamma_i > 0$ implies that agents are risk averse. Therefore, for each random x_i, an agent prefers receiving the expected payoff $E[x_i]$ with certainty to receiving the random payoff x_i. Moreover, agent 1 is more risk averse than agent 2 if $\gamma_1 > \gamma_2$[6].Therefore, we can define the certainty equivalent (CE) of a random payoff x_i by $CE_i(x_i) = U_i^{-1}(E(U_i(x_i)))$, provided that the expected utility exists. Then, for all these random payoffs x_i, $E(U_i(CE_i(x_i)) \equiv U_i(CE_i(x_i)) = E(U_i(x_i))$ holds. Since the expected utilities equal one another, agent i is indifferent between the random payoff x_i and the deterministic payoff $CE_i(x_i)$. Therefore, the certainty equivalent expression of distributed x_i is given by

$$CE_i(x_i) = \mu_i^0 + \varphi_i\mu_s - \gamma_i\frac{(\sigma_i^0)^2 + \varphi_i^2\sigma_s^2 + 2\rho_i\varphi_i\sigma_i^0\sigma_s}{2} \qquad (14)$$

Individual rationality dictates that each agent will try to maximize their expected utility. Then the question becomes: what is the optimal contract for two agents to efficiently share the risks involved in a cooperative project?

To derive the optimal risk-sharing rule, we assumed that parties act cooperatively and have symmetric information about the characteristics of the venture. The returns to the venture are also verifiable ex-post, and the management of the joint venture acts to maximize the joint venture profits. It is also rational to think that both firms prefer to take up as little risk as possible while trying to increase their own gain. However, for risk-averse firms with a concave utility function, marginal gains decrease as risk taking decreases. Furthermore, this rate of reduction of marginal gains will be different for both players in view of their differing risk aversion levels. Therefore, the task for a rational firm in such situation is to optimize the amount of risk-taking in relation to the amount of gain.

The maximum total value of the joint venture will be obtained at a risk-sharing rule where the marginal value of taking up some infinitesimal fraction of the risky venture is the same for both agents (Bolton and Dewatripont, 2005). If the marginal gains were different for the two agents, it would be possible to add to the total value by taking away an infinitesimal amount of risk from the firm with the smaller marginal gain and giving it to the firm with a larger marginal gain. Therefore, the first optimality condition equates the marginal gains of the uncertain payoff of the two agents (Borch, 1962).

$$\begin{gathered}\frac{d}{d\varphi_1}CE_1(x_1) + \frac{d}{d\varphi_2}CE_2(x_2) = 0\\ \sum_{i=1,2}\varphi_i = 1\end{gathered} \qquad (15)$$

where, φ_1 is the share of agent 1 and the share of agent 2 is $1-\varphi_1$. The expression in Eq. (15) means that the risk sharing problem is given as a maximum of the sum of the certainty equivalents of the two agents.

$$x(\tau)^* = \max_{\varphi_1}[CE_1(x_1) + CE_2(x_2)] \qquad (16)$$

Inserting Eqs. (14) in (15) and rearranging, we get the optimal share of the risk φ_1^* for agent 1.

$$\varphi_1^* = \frac{\gamma_2}{\gamma_1+\gamma_2} + \rho_{2s}\frac{\gamma_2}{\gamma_1+\gamma_2}\frac{\sigma_2^0}{\sigma_s} - \rho_{1s}\frac{\gamma_1}{\gamma_1+\gamma_2}\frac{\sigma_1^0}{\sigma_s} \qquad (17)$$

With $0 < \varphi_i^* < 1$ and $\sum_{i=1,2}\varphi_i^* = 1$.

Note that the optimal risk-sharing rule does not depend on the mean rate of the returns of the pre-existing businesses (μ1 and μ2). Only the risk aversion of the two parties, the volatilities of the pre-existing businesses and the correlations of the pre-existing businesses with the joint venture affect the optimality conditions. There is no risk-sharing agreement when $\varphi_1^* = 0, \varphi_2^* = 1$, or equivalently $\frac{\gamma_1}{\gamma_2} = \frac{\sigma_s + \rho_{2s}\sigma_2}{\rho_{1s}\sigma_1}$; or $\varphi_2^* = 1, \varphi_2^* = 0$, or equivalently $\frac{\gamma_1}{\gamma_2} = \frac{\rho_{2s}\sigma_2}{\rho_{1s}\sigma_1 + \sigma_s}$. The condition that $0 < \varphi_i^* < 1$ can be equivalently expressed as $0 < \gamma_2(\sigma_s + \rho_{2s}\sigma_2) - \gamma_1\rho_{1s}\sigma_1 < (\gamma_1+\gamma_2)\sigma_s$. This condition is expressed with the parameters that represent the distribution of profit from the agents' existing businesses and the common project, and the agents' risk aversions.

Let us define the following variables that depend on risk aversion, correlation, and volatility:

$$K_1 = \frac{\gamma_2}{\gamma_1}, K_2 = \rho_{1s}\frac{\sigma_1}{\sigma_s}, \text{and } K_3 = \rho_{2s}\frac{\sigma_2}{\sigma_s}, \text{ for } \forall\gamma_1, \forall\sigma_s \neq 0$$

Then, the condition for the existence of a feasible risk sharing agreement is given as:

$$\begin{aligned}&K_1 > 0\\ &K_2 < K_1(1+K_3)\\ &K_2 > K_1K_3 - 1\end{aligned} \qquad (18)$$

An important feature of expression (17) is that it is time-invariant. This implies that after the risk-sharing contract has been agreed neither party will have an incentive for dynamic re-negotiation of their respective risk share unless these correlations and volatilities change.

3.1. The effect of correlation

In expression (17) we can see that the optimal amount of risk an agent is willing to take partly depends on the correlation of the agents' existing projects with the common project. If there is no correlation between the common project and the agents' existing businesses the optimal risk share is only a function of the agents′ risk aversions (for instance for agent 1, $\overline{\varphi}_1^* = \frac{\gamma_2}{\gamma_1+\gamma_2}$). In such case, the certainty equivalent of agent i is given by:

$$\overline{CE}_i = \mu_i^0 + \overline{\varphi}_i^*\mu_s - \gamma_i\frac{(\sigma_i^0)^2 + (\overline{\varphi}_i^*)^2\sigma_s^2}{2} \qquad (19)$$

[6] By changing the signs of the parameter γ_i, the utility function becomes convex and, as a consequence, the player will be a risk-seeker.

If the pre-existing businesses and the new common project are correlated the agents' certainty equivalents can be found by using Eq. (20).

$$CE_i = \mu_i^0 + \varphi_i^* \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + (\varphi_i^*)^2 \sigma_s^2 + 2\rho_i \varphi_i^* \sigma_i^0 \sigma_s}{2} \tag{20}$$

Then, the effect of correlation can be obtained by subtracting Eq. (19) from Eq. (20) as shown in Eq. (21).

$$CE_i - \overline{CE}_i = \mu_s(\varphi_i^* - \overline{\varphi}_i^*) - \frac{\gamma_i \sigma_s^2}{2}\left((\varphi_i^*)^2 - (\overline{\varphi}_i^*)^2\right) - \gamma_i \rho_i \varphi_i^* \sigma_i^0 \sigma_s \tag{21}$$

It can be seen that the correlation coefficient (i.e. $\rho_i > 0$ or $\rho_i < 0$) affects the value of the right-hand side of Eq. (21). Using expression (21) agents can get valuable insight, at least at exploratory stage of cooperation, about the effect of the new project to their overall expected utility.

3.2. The value of risk sharing

In this section, we derive the value of risk sharing that can be obtained from cooperation. We treat cooperation in the joint venture as an investment option that can be exercised by committing some given capital. As with any investment, cooperation in the joint venture comes with its own risks. As a result, at the conceptual stage of the cooperation agents have three options: exercise the investment in the project through cooperation, invest in the project alone or do nothing. We refer to the first one as *cooperation option*. The solo investment and the abandoning options are referred as *non-cooperation* options.

If agent i neither cooperates or invests alone (i.e. carry out only existing project), the certainty equivalent of the uncertain payoff from the existing project x_i^0 is given by

$$CE_i^0 = \mu_i^0 - \gamma_i \frac{(\sigma_i^0)^2}{2}. \tag{22}$$

If either of the agents invests alone, then the certainty equivalent of the uncertain profit x_i^1 is given by

$$CE_i^1 = \mu_i^0 + \mu_s - \gamma_i \frac{(\sigma_i^0)^2 + \sigma_s^2 + 2\rho_i \sigma_i^0 \sigma_s}{2}. \tag{23}$$

In this case, the value of risk sharing for each agent, $\mathrm{VoRs_i}$, can be obtained by comparing the utility agent i gets from the cooperation option with that of the non-cooperation options. The value of cooperation via risk sharing can be obtained by subtracting the maximum of the certainty equivalent values of the two non-cooperation options from the cooperation.

$$\mathrm{VoRs_i} = CE_i - \max(CE_i^1, CE_i^0) \tag{24}$$

Expression (24) allows us to define the condition under which partners will choose cooperation to undertake a project when there is a background risk (from their existing business) and project risk (from the common project), provided that they can also consider investing on their own. It shows the minimum of the value that the agent gets as a result of cooperation. Theoretically, the minimum $VoRs_i$ should be greater than zero for the agent to engage into cooperation. Otherwise, the agent could compare the maximum of CE^1 and CE^0 to either invest in the project alone or not invest at all. Expression (24) can also be used by individual agents to select a cooperating partner to set up a joint venture for a project. Different agents are most likely to have different background risks, resulting in an increase in the value of risk sharing. Using expression (24), agents can compare the amount of value they obtained by sharing the risk of the common project with the different kinds of prospective partners who have different background risk.

3.3. The risk-sharing zone

In expression (24), we present a model to determine the value agents get if they take an optimal share of the risk. The direct takeaway from Eq. (24) is that depending on the VoRs agents can decide whether to engage in cooperation or not. However, cooperation could be possible if one agent has a positive VoRs and can transfer a portion of the surplus to the other agent with negative VoRs. In this section, we check whether cooperation is possible via a side payment. We assume that agents agree on the cooperation at time $t=0$. Then, after uncertainty is resolved, they decide to exercise the cooperative option $t=\tau<T$ and receive an instant payoff. The core of a cooperative game is the set of payoff allocations that make both partners better off than if they were to go it alone. i.e.

$$CE_i \geq CE_i{}^1$$
$$\sum_{i=1,2} CE_\mathrm{i} = CE.$$

A payoff for either firm is in the core if

$$CE_i{}^1 \leq CE_i \leq CE. \tag{25}$$

The focus now is to define the risk-sharing-value core in which cooperation is possible. In this core, partners can agree to maximize the sum of their certainty equivalents by sharing the risky returns in proportion to their respective risk tolerances. We will focus on linear contracts, i.e. agreements involving a deterministic cash payment D_i and a share φ_i of an uncertain payoff CE at $t=\tau$. The total payoff of agent i from the joint project will be

$$CE_i = D_i + \varphi_i CE. \tag{26}$$

Linear contracts are very common in most joint-venture revenue-and-cost-sharing arrangements (Bolton and Dewatripont, 2005; Savva and Scholtes, 2005). In Eq. (17) we derived the optimal share of risk when two agents cooperate to maximize their joint certainty equivalents. However, the optimal risk-sharing rule only specifies how much risk each player will take and does not determine the optimal payoff for each agent from the cooperation. This is because the deterministic amount D_i that the two agents exchange is not constrained and is determined through negotiation.

To know the amount of D_i let us define the sharing rule in a situation where agent 1 owns the option to develop the project alone. For agent 2, there is always the alternative of not participating in the project with a zero payoff. The best sharing rule for agent 1 would be one that maximizes 1's certainty equivalent subject to the constraint that 2's certainty equivalent should not be less than zero. The best sharing rule can be achieved by sharing in the optimal proportions, to maximize the sum of the each agent's certainty equivalents, with an additional payment from agent 2 to agent 1 on the condition that 2's certainty equivalent should be equal or greater than zero. The best possible sharing rule for agent 1 would be to sell agent 2 an optimal share of the project which is φ_2^*. The maximum price of the optimal share of the investment is equal to $\varphi_2^* * CE$. Agent 1´s overall certainty equivalent is equal to $(\varphi_1^* * CE) + (\varphi_2^* * CE)$. This value is the maximum sum of certainty equivalent that the two partners can get from the project and it is allocated to agent 1.

However, agent 2 would prefer to pay less than $\varphi_2^* * CE$ for an optimal share φ_2^*. Agent 2 may try to negotiate for lower price. The negotiated price that is given from agent 2 to agent 1 for an optimal share of the project is the cash D. Although D is determined through negotiation it has minimum value that agent 1 can accept. At the minimum, D should make agent 1´s certainty equivalent better than owning 100% of the project alone. Hence, the conditions for the core of the cooperation game, subject to optimal sharing, is given as

$$CE_1 + D \geq CE_1{}^1$$
$$CE_2 \geq D$$
$$\sum_{i=1,2} \varphi_i^* = 1.$$

The first two conditions guarantee that the optimal share value, as estimated by each agent, is at least as good as going it alone and the third condition will ensure efficient risk sharing. Then, the core of the cooperation game captures the risk exchange zone. In this case, the risk exchange zone is determined by the amount of D that is exchanged between the two agents. It is given as follows:

$$CE_1{}^1 - CE_1 \leq D \leq CE_2 \tag{27}$$

It can be seen from Eq. (27) that the core of the cooperation game is non-empty as long as D is positive[7]. A non-empty core indicates that there are gains to be made by cooperating via risk sharing. In other words, the risk-sharing zone is the risk-sharing core of the contract. It can also be seen from expression (27) that the size of the risk sharing core depends on the risk aversion γ_i of the two agents in addition to the variances σ_1, σ_2 of the pre-existing businesses and the correlations ρ_1 and ρ_2 of the pre-existing businesses with the joint venture.

[7] Individual rationality is the boundary condition for having non-empty core of the cooperative game.

So far, we have seen the value that risk sharing provides for risk-averse agents seeking cooperation. We showed that for a stochastic cooperative joint venture between agents with a CARA utility function, linear contracts provide Pareto-efficient payoff allocation and allow an optimal risk-sharing rule. We assumed that agents maximize their joint welfare and under that assumption, linear contracts can provide optimal risk sharing mechanism. The optimal risk sharing contract is determined by the exchange of a negotiated cash payment from one party to another. It is dependent not only the parameters that affect the optimal risk share (i.e. risk aversion γ_i, volatilities σ_1, σ_2 of the pre-existing businesses and the correlations ρ_1 and ρ_2 of the pre-existing businesses with the joint venture), but also the agents' relative bargaining power (Choi and Triantis, 2012; Murnighan et al., 1988).

4. Illustrative example

In this section, we provide an example of our results for illustration purposes. Specifically, we present analyses of the effect of correlation on the optimal risk share and the value risk sharing for cooperating partners. A stylized joint investment on merchant electricity interconnector is used for demonstration. We provide some background that presents the need for analysing the value of risk sharing in this specific situation. However, the example should be taken only as an illustration rather than a numerically accurate case study. Fitting model parameters would require access to confidential information and interactions with the agents in order to extract accurately their risk preferences, and it would not add to the illustration intended, which considers many different possible values for the parameters.

4.1. Problem background

The current electricity infrastructure across the EU is outdated and inefficient and bottlenecks prevent efficient transmission of electricity from one part of Europe to the other and from one country to another (Norton Rose Fulbright, 2014). The lack of much new public interconnection investment has induced the European legislator to opt for merchant transmission projects (Parail, 2009). Merchant projects could be carried out by new actors as in the case of *East–West cables* and by incumbent transmission system operators (TSOs) as in the case of *BritNed* (Supponen, 2011). However, investment by new actors to connect different market regions is discouraged by the protection tendencies of incumbent TSOs on both sides of the market (Kristiansen and Rosellón, 2010). As a solution, regulators allow incumbent TSOs of both regions to invest in the interconnection as merchant project. A notable example is BritNed merchant interconnector between the UK and the Netherlands (BritNed, 2015).

There is a conflicting choice between national and company interests in cross-border transmission investments (Supponen, 2011). From the national perspective, the motivation for interconnector investment originates from a need to improve the security of supply, facilitate renewable energy integration or electricity price reduction (Kristiansen and Rosellón, 2010). For example, the major motivation for expanding the Germany-Netherland interconnector capacity is Germany's increasing share of electricity from wind which can be exported to Norway. The major motivation for constructing the NorNed cable is the security of supply, since Norway is almost entirely dependent (99%) on hydro generation, and the Nederland is predominantly thermal. BritNed has been undertaken because of security-of-supply issues and the European Commission's desire to link electricity markets. However, from a TSO perspective, the project is risky. For instance, historically the Netherlands has been a higher-priced country (especially during peak hours) relative to its neighbours. From an organizational perspective Tennet (the Dutch TSO) has an incentive to isolate the market, while the Dutch regulator's objective is to introduce renewable energies in an otherwise thermal-dominated system. On the one hand, there are national interests and associated incentives to cooperate. On the other hand, there are costs and associated risks. Therefore, TSOs need to understand the effect of cooperation: i.e. the share of risk during cooperation, the potential value of cooperation and the effect of the interconnector on their existing business. Next, a simplified Numerical analysis is presented to demonstrate these issues.

4.2. Major assumptions of the case study

The main parameter values defining the performance of the three entities and the risk aversion of the agents are shown below, in annual terms.

- Initial cost of the common project $C_s = 15$
- Distribution of revenue of the common project $\mu_s = 40$, $\sigma_s = 20$
- Distribution of revenue of the agent 1 $\mu_1 = 400$, $\sigma_1 = 100$
- Distribution of revenue of the agent 1 $\mu_2 = 250$, $\sigma_2 = 50$
- Risk aversion of agent 1 = 0.1
- Risk aversion of agent 2 = 0.3

As highlighted above, although this case study is inspired by BritNed, the situation is hypothetical, and the estimated parameter values are intended for illustration only.

4.3. Effect of correlation on the risk sharing ratio

Fig. 1 shows agent 1's optimal share of risk as a function of correlation coefficients assuming constant risk aversion. In Fig. 1a it can be seen that, for $\rho_{1s} > 0$, agent 1's share of risk decreases linearly as the correlation between its pre-existing business and the common project increases. On the other hand, for $\rho_{1s} < 0$, the optimal share of risk for agent 1 increases as its correlation increases. Fig. 1a also shows that the risk share of agent 1 depends on ρ_{2s} as well. It can be said that the risk share of agent 1 increases as the correlation of agent 2 shifts from negative to positive. However, it is important to notice that for a given correlation coefficient of agent 2, the correlation coefficient of agent 1 should be between certain value range for optimal risk sharing to exist. For example, if $\rho_{2s} = 0.5$, the optimal risk sharing between the two agents, is possible when $0.2 \leq \rho_{1s} \leq 1$ for the assumed risk aversion and volatility parameters. The optimal risk share of agent 1 steeply decreases from 90% at $\rho_{1s} = 0.2$ and $\rho_{2s} = 0.5$ to 10% at $\rho_{1s} = 1$ and $\rho_{2s} = 0.25$. In Fig. 1b it can be seen that the risk share of agent 2 linearly varies with the correlation of its pre-existing business with the common project.

In a particular case where the correlations coefficients of both agents are equal to zero agents 1 and 2 take 75% and 25% of the risk respectively. The more risk-averse agent takes a smaller share of the risk and vice versa. However, Fig. 1 shows that the agents can take a higher or lower share of the risk when the correlations of their pre-existing businesses are considered. If agent 1's pre-existing business profit is positively correlated to the projected revenue of the common project and agent 1 knows that agent 2's pre-existing business is negatively correlated to the common project revenue, then it is optimal for agent 1 to take a lower share of the risk than the one obtained at zero correlation.

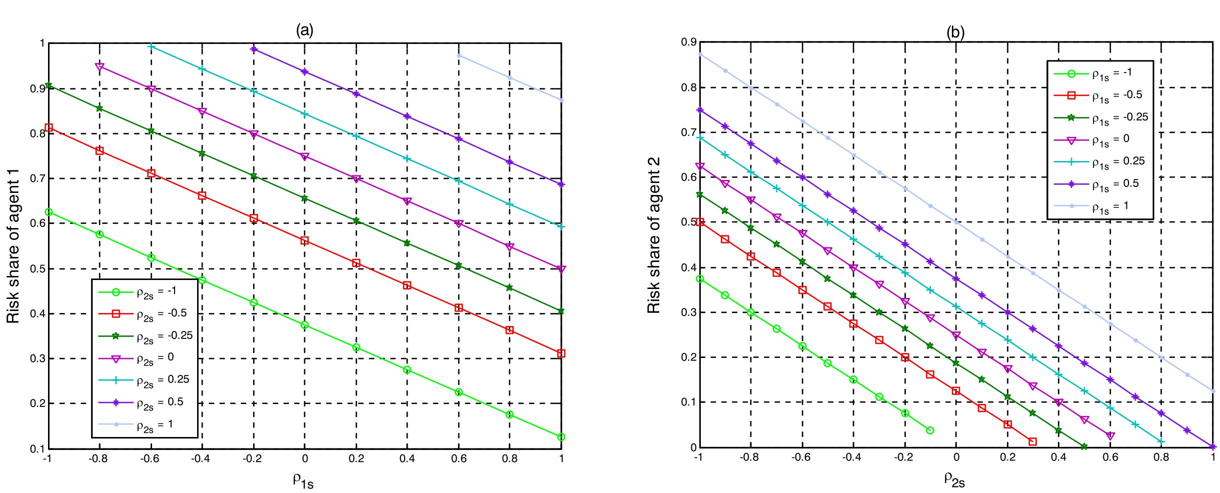

Fig. 1. Optimal risk share as function of correlation coefficients: (a) agent 1, and (b) agent 2.

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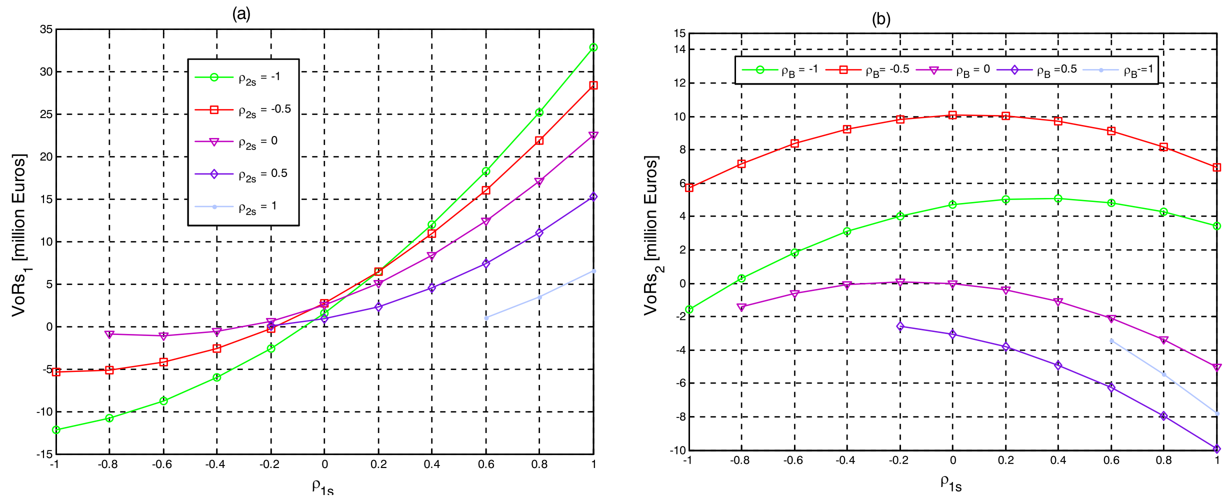

Fig. 2. Values of risk sharing as function of correlation coefficients: (a) agent 1, (b) agent 2.

Therefore, considering correlation provides a deeper insight for agents regarding their optimal share of risk in cooperative ventures. Previous approaches only considered that the share of risk taken by a partner is higher for lower risk aversion. However, we show how the optimal risk share depends greatly on the correlation of the joint venture with the agent's pre-existing businesses.

4.4. The value of cooperation via risk sharing

In the previous section, we showed that the optimal stake of risk is influenced by the correlation of the pre-existing businesses with the common project. However, the optimal risk ratio only informs how much stake of the risk each player will take and does not provide information about the value of cooperation via risk sharing. Fig. 2 shows the value of cooperation via risk sharing (VoRs) as a function of correlation coefficients. In Fig. 2a it can be seen that the value of cooperation for agent 1 is positive when her pre-existing business is positively correlated to the common project. However, the value of risk sharing depends also on the correlation coefficient of agent 2. If agent 1 has a positive correlation, the value of risk sharing increases as agent 2's correlation increases. The effect of the correlation of agent 1's business on its value of risk share can be clearly observed when the correlation coefficient of agent 2 is fixed. For example, in Fig. 2a it can be seen that for $\rho_{2s}=0.5$ the VoRs1 increases from close to zero at $\rho_{1s}=-0.2$ to 27.5 million Euros at $\rho_{1s}=1$.

Similarly, for agent 2, the value of risk sharing is influenced by the correlation of its pre-existing business with the common project, in addition to the correlation coefficient of agent 1. In Fig. 2b it can be seen that for $\rho_{1s}<0$ the value of risk sharing for agent 2 decreases as his pre-existing business is more negatively correlated to the common project. On the other hand, if $\rho_{1s}>0$, the value of cooperation for agent 2 decreases as her/his existing business is more positively correlated to the common project. If the VoRs for both agents is positive, it indicates that partners with divergent risk attitudes and correlation coefficients can gain more synergies from risk sharing in uncertain environments.

It is likely that different agents have different background risk from their pre-existing businesses. If an agent knows about the performance of the co-partner's businesses profit, then it is possible to calculate the share of risk and the value of cooperation with another agent. However, symmetry information among partners is required regarding the performance of the common project and their pre-existing businesses. If an agent has information about the pre-existing businesses of potential candidate partners, she/he can use that information to determine worthy co-investors. This is particularly important at the exploratory stage of the co-investment and during contract negotiation stages. Having a better understanding of the economic implications of committing contractual agreements, especially when the new venture has implications on the performance of the pre-existing business, could help build resilient partnerships and avoid problems.

5. Conclusions

The exploratory phase of a joint infrastructure project entails uncertainties to cooperating agents with respect to the value of the project and the optimal share of risk. Uncertainty often leads to a deadlock situation in which decision-making stagnates. To address uncertainty in such situations, an approach is required that allows the assessment of the risk and gain of cooperation for each agent. In this paper, we analyse the effect of risk sharing when two risk-averse agents co-develop an energy infrastructure project under uncertain environment. The two agents have background risks from their pre-existing businesses, and the joint project is represented by a risky cash flow. The cooperating partners are risk-averse but need not have the same risk aversion. We assume that the partners will act cooperatively to maximize their joint welfare and there is information symmetry on the common project performance. The models and numerical analyses provide valuable managerial insights.

First, agents with divergent risk attitude can gain more synergies from risk sharing in uncertain investment environments. This is in agreement with earlier work (Savva and Scholtes, 2005) and implies that cooperating with a partner with a different risk attitude can be very beneficial. As shown in Eq. (27), risk-sharing opportunities increase the risk exchange zone (i.e. the synergy set) from traditional economies of scale and scope. This could encourage uncertain agents to engage in cooperation to develop vital energy infrastructures.

Secondly, agents can structure better risk-sharing contracts. Conventionally, the risk preference of cooperating agents described with their respective risk aversion is used to allocate risk optimally. In this study, we found that the optimal share depends also on the future projection (i.e. volatility) of the new common project and the agent's pre-existing businesses. Furthermore, the optimal risk share depends on the correlations between the agents' pre-existing businesses and the new common project. These additional insights can help agents understand better the economic implications of long lasting contractual agreements and build enduring partnerships.

Last, the model can help agents to select the most suitable partner for a project. Agents can carry out an exploratory assessment of the value risk sharing with the different prospective partners. Different agents have a different background (pre-existing business) and risk attitudes, and the developed model can support the selection of a partner.

Finally, the modelling framework and the numerical analysis presented in this paper invite opportunities for future work. One area of future work could involve extending the model for multiple agents and considering the relative negotiation power of agents. Moreover, a real case study would make the model more relevant for practical deal negotiations.

Conflict of interest statement

There is no conflict of interest.

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