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NOT DELIVERING AS ONE: ASYMMETRIC OUTCOMES IN FIRM-UNIVERSITY COLLABORATIONS

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Dissertação apresentada ao Curso de Mestrado em Administração da Escola Brasileira de Administração Pública e de Empresas para obtenção do grau de Mestre em Administração.

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SUMMARY

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ABSTRACT

Extant literature examined the benefits of relational embeddedness in facilitating collaboration between organizations, as well as the necessity of firms to balance their knowledge generation into exploration and exploitation activities. However, the effects of relational embeddedness in the specific outputs of firm-university collaborations, as well as the elements that affect the exploratory nature of such outcomes remain underexplored. By examining fine grained data of more than 4.000 collaborative research and development projects by a firm and universities, 5.000 patents, and 300.000 scientific publications, it was proposed that relational embeddedness would have a positive effect on resource commitment and on joint scientific publications, but a negative effect on joint patents and exploratory outcomes resulting of such collaborations. Additionally, it was proposed that knowledge similarity would have a negative impact in exploratory endeavors made in such projects. Although some of the propositions were not supported by the data, this study revealed that relational embeddedness increases resource commitment and the production of joint scientific publications in such partnerships. At last, this study presents interesting opportunities for future research.

Keywords: Knowledge-Based View (KBV); Relational Embeddedness; Firm-University Collaboration; Research and Development (R&D).

RESUMO

A literatura existente examinou os benefícios de intensidade da relação como facilitador de colaborações entre organizações, assim como a necessidade de empresas balancearem a geração de conhecimento em ações exploratórias e de aplicação. Todavia, os efeitos da intensidade da relação nos resultados específicos das parcerias entre empresas e universidades, assim como os elementos que afetam a natureza exploratória desses resultados, permanecem subexplorados. Examinando dados detalhados de mais de 4.000 projetos de pesquisa e desenvolvimento em colaboração entre uma empresa e universidades, 5.000 patentes e 300.000 publicações científicas, foi proposto que a intensidade da relação teria um efeito positivo no investimento de recursos e na produção de artigos científicos conjuntos, porém um efeito negativo na geração de patentes conjuntas e nos empreendimentos exploratórios resultantes dessas colaborações. Adicionalmente, foi proposto que semelhança entre conhecimentos teria um efeito negativo nas iniciativas exploratórias realizadas nesses projetos. Apesar de algumas proposições não terem sido confirmadas pelos dados, esse estudo revelou que a intensidade da relação tem efeito positivo no investimento de recursos e na produção de artigos científicos conjuntos nessas parcerias. Por fim, o estudo apresenta oportunidades interessantes para pesquisas futuras.

Palavras-chave: Visão Baseada no Conhecimento; Intensidade da Relação; Colaboração entre Empresas e Universidade; Pesquisa e Desenvolvimento (P&D).

1. INTRODUCTION

Extant literature emphasizes the role of collaboration in assisting a firm's innovative activities. Private firms have increasingly relied on collaborations with partners to access external knowledge they can build upon when creating new products (Ahuja, 2000a; Powell, Koput, & Smith-Doerr, 1996). Given the importance of collaborations as an external knowledge sourcing strategy, scholars have extensively examined factors that shape the pattern of collaborative ties that a firm forms with its partners (Gulati, 1995a; Rosenkopf, Metiu, & George, 2001) and highlighted a firm's tendency to ally with partners with which it has already collaborated (Gulati & Gargiulo, 1999; Chung, Singh, & Lee, 2000). These inertial effects stemming from relational embeddedness are predicated on the notion that prior direct ties between allies help them identify subsequent collaboration opportunities, increase their awareness of each other's capabilities, and reinforce mutual trust (Gulati & Singh, 1998), factors that result in more stable partnerships (Park & Russo, 1996; Polidoro, Ahuja, & Mitchell, 2011). In contrast with research elucidating the influence of relational embeddedness on tie formation patterns and on the stability of ties formed, its effects on the outcomes of collaborative ties remain largely underexplored.

Moreover, the literature has highlighted the importance of balancing exploration and exploitation in the development of knowledge resources, which is so important that the survival of the firm in the long term depends on it (March, 1991; Levinthal & March, 1993). It is known that one of the motivations to firms enter in partnerships is to exploit an existing capability or to explore new opportunities (Koza & Lewin, 1998). Nevertheless, the effects that influence a partnership's joint outcome to be exploratory or exploitation have not received much attention from the academia yet.

To fill these voids in the literature, this study examines the context of firm-university collaborations. Universities constitute important sources of new knowledge and firms oftentimes engage in scientific activity with university-based scientists (Henderson & Cockburn, 1994; Narin, Hamilton, & Olivastro, 1997; Polidoro & Theeke, 2012). Due to the access of high quality knowledge, a firm experiences superior innovative performance by maintaining close ties to universities (Cockburn & Henderson, 1998; Zucker, Darby, & Armstrong, 2002). This study moves beyond the benefits accrued by a firm that generally collaborates with universities to focus on the specific outcomes of firm-university collaborations that are shared by a firm and its partner. Moreover, building on the duality that these collaborations entail, given that they merge the boundaries of the technological and the scientific communities, which are driven by different logics (Dasgupta & David, 1987; Gittelman & Kogut, 2003), this study distinguishes between technology related outcomes (i.e., patenting activity) and scientific outcomes (i.e., publishing activity).

Hence, this study examines the following research questions: how would relational embeddedness of a firm and a university affect the technological and scientific outcomes they jointly attain when engaging in collaborative projects? Additionally, how would relational embeddedness and knowledge similarity of a firm and a university affect the exploratory nature of the joint outcomes generated in such partnerships?

As the market is moving toward an era in which competitive advantage will be determined by knowledge rather than by access to raw materials and cheap labor (Liebeskind, 1996), the innovating activity plays a major role in firm knowledge creation and value capturing (Grant, 1996). Therefore, addressing those questions is very important in order to deepen the understanding about the factors that are important for a better technological and scientific knowledge generation, which are imperative for efficient research and development (R&D) endeavors and innovating activity in general.

The arguments are grown in existing literature about interfirm relationships demonstrating the social and technological influences on the patterns of collaborations that an organization forms, and extend those arguments to the context of firm-university collaborations. Building on prior research's evidence that relational embeddedness is conducive to collaboration, it is expected that this factor would increase a firm's propensity to collaborate with a university, and, based on that, the effects on joint collaboration outcomes and its related exploratory nature are hypothesized. Also, the inertial effects of knowledge similarity in the generation of innovation in different domains are used to predict the effects of knowledge similarity in the outcomes of firm-university collaborations.

To preview the main arguments elaborated in the theory section, it is expected that repeated collaborations with a university make a firm inclined to increase resource commitment toward subsequent collaborations with that university due to the development of trust and familiarity between partners, resulting in a firm allocating greater R&D budgets in future joint projects. Further, it is hypothesized that such repeated collaborations hinder the inventive output that a firm jointly achieves with a partnering university, while facilitating their joint scientific publishing activity, as the conflicting logics inherent to these types of partnerships would favor one type of outcome and disincentive the other. Also, relational embeddedness would have a negative effect in the production of exploratory outputs in those collaborations, since repeated partnerships would exhaust the possibilities of resource recombination. Finally, knowledge similarity, represented as technological similarity for patents and scientific similarity for academic publications, would have a negative effect in exploratory outcomes as a result of knowledge overlap between partners.

To test such predictions, it was used the context of collaborations that Petrobras, a Brazilian state-controlled and publicly-traded oil and gas corporation, formed with the top 200 Brazilian universities between 2003 and 2013, as some features of this empirical setting make it particularly suitable for this study, as explained below.

Firstly, the oil and gas sector has experienced an increase in innovation even higher than sectors that are notoriously known as innovative, such as semiconductors and pharmaceutical. To illustrate such technological innovation demand, Petrobras faced non-trivial technological challenges during the analysis period, most notably regarding the discovery and subsequent exploration of pre-salt oil reserves, which lie beneath up to 2,000 meter thick salt layers and whose depth below the sea surfaces reaches up to 7,000 meters. It is noteworthy that the exploration of pre-salt oil reserves entails significant technological challenges in numerous activities, such as reservoir characterization, oil recovery, well engineering, flow assurance, and subsea technology. To overcome the challenges it faces in exploring new technologies, the company complements its internal R&D activities by entering in partnerships with universities, which are also demanded by the local regulation.

Moreover, this setting enabled the submission of data requests to the Brazilian oil and gas regulatory agency, which resulted in access to unique, fine-grained data about firm-university collaborations. Such data comprise all collaborations between the company and universities including details about each project, such as a brief description, duration, and R&D expenditures on a yearly basis. To supplement this data, it was collected information about all patents filed by the firm and the universities of the sample, as well as all scientific articles published by (co)authors affiliated with them.

In addition to that, the Brazilian superior educational context provides many incentives to universities pursue academic publication of scientific research but much less incentive to the creation of patents and new technologies. Hence, such feature would enhance the conflicting logics between the academia and the market, which will be build upon further in order to state the propositions.

Therefore, this study advances prior research's emphasis on the benefits that firm-university collaborations provide to a firm by investigating the outcomes accruing to both firm and partnering university as well as their nature as exploratory or not. Importantly, this study intends to reveal an intriguing paradox that a firm faces when engaging in collaborations with universities: in the attempt to evade internal pressures that hinder exploration of new knowledge by relying on collaborations with universities, a firm becomes exposed to social pressures leading to collaborations that are less conducive to exploratory inventions. In contrast with prior research showing the beneficial effects of relational embeddedness in facilitating collaborations, this study aims to reveal that collaborations with old partners may defeat the purpose that could have motivated those collaborations in the first place. Further, this study sheds new light on the conflicting logics between technology and science that surround firm-university collaborations. When balancing between the creation of new inventions and the discovery of new scientific contributions, a firm that has cohesive collaborative ties with a university may tilt the balance toward greater scientific outputs at the expense of diminished inventive outputs, a finding of both theoretical and practical importance. The discussion section elaborates on these implications.

2. THEORY AND HYPOTHESES

2.1 Social aspects of interorganizational collaboration

One of the classic questions of social theory concerns how behavior and institutions are affected by social bounds (Granovetter, 1985). By challenging the utilitarian tradition presented in classical and neoclassical economic theories, which takes as granted that rational and self-interested behavior is only minimally affected by social relationships, the literature has been able to uncover many interesting effects that social relations have in the way firms behave and adopt strategies.

Organizational sociologists addressed this matter considering firm network formation as being driven by exogenous factors, such as the irregular distribution of technological resources and the social structures involved in resource dependence (Burt, 1983; Pfeffer & Salancik, 1978). Based on such view, organizations would create these social ties to address uncertainties in their environment, as well as to satisfy resource needs. As a result, they would enter in partnerships with organizations whose resources would aid them to overcome these exogenous constraints.

On the one hand, this view helped to understand the reasons that made firms enter in partnerships with other firms, and even competitors. On the other hand, such analysis did not provide enough cues about how firms decide with whom they would build those ties and how these ties shaped the formation of interfirm networks and future collaborations between partners.

In order to choose the best partner possible, firms need to be aware about the competencies, resources, necessities and reliability of potential partners, and achieve a consensus of objectives to be agreed upon the parties, which is a demanding and difficult task (Van de Ven, 1976). Especially for collaborations that involves exchange or sharing of strategic resources and activities that would result in an enduring commitment between the organizations, there are many sources of uncertainties associated with interfirm partnerships, for instance the lack of reliable information about potential partners, which increases search costs, and the risk of opportunistic behavior by the partner (Gulati, 1995b; Gulati & Singh, 1998).

To assess the adequacy of a potential collaboration that would serve the interests of both organizations is essential for the success of the partnership. However, accurate information on resources, capabilities and interests of another organization is very difficult to obtain before entering in the partnership. As a general rule, such analysis requires access to confidential and detailed information that is not publicly available, which is an especially relevant problem for organizations with different geographic origins, and would not be accessible before the arrangement is done (Gulati & Gargiulo, 1999).

Further, organizations entering alliances face significant risks of opportunistic behavior by the partner and fear of the possible costs it may incur in case such behavior happens (Kogut, 1989). An opportunistic partner may free ride the partnership by limiting its contributions and taking advantage of the relationship to have easy access to resources and information that can be used in a way that damage the other party's interests. Consequently, these behavioral matters are considered a key factor in the success of a partnership (Gulati, 1995b).

It is worth mentioning that such behavioral uncertainty feature, which is inherent to agreements in general, is so relevant that it plays a central role in Coase's theory of the firm (1937) and in the transaction-cost perspective developed by Williamson (1991).

In addition to the risks related to behavioral issues, changes in environmental conditions may affect the propensity of firms to collaborate, as it could cause changes in the organizations' needs and priorities, which may lead to alliance dissolution (Greve, Baum, Mitsuhashi, & Rowley, 2010).

Nevertheless, despite the difficulties and uncertainties regarding interorganizational collaborations, this kind of partnership has been increasing considerably in the past decades (Anand & Khanna, 2000). For this reason, scholars have extensively examined factors that shape the pattern of collaborative ties that a firm forms with its partners (Gulati, 1995a; Rosenkopf, Metiu, & George, 2001).

2.2 Collaborations and the generation of knowledge

Considering that external knowledge is crucial to innovation processes, the ability to exploit such external knowledge is thus a very important factor of organizations' innovative capabilities (Levinthal, 1997). To access external knowledge that can be used to build upon when producing innovation, organizations need improve internal competencies by investing in R&D activities and in technical qualification of its personnel (Knott, 2008). Besides that, organizations have increasingly relied on interorganizational collaborations to access external knowledge they can take advantage of when creating new products (Ahuja, 2000a; Powell, Koput & Smith-Doerr, 1996).

By entering in collaboration with other organizations, a firm increases its R&D productivity as social connections enhance the transfer of knowledge between such organizations (Reagans & McEvily, 2003). Moreover, by spanning firm boundaries, interorganizational collaborations aid the exploration of new technological domains by the firm, increasing the impact of new technology developed (Rosenkopf & Nerkar, 2001). Such result would be a direct effect of broadening the scope of search for new knowledge combinations within these collaborations (Flemming, 2001). In sum, by entering in interorganizational collaborations, firms usually increase their innovation performance (Ahuja, 2000a).

However, since these collaborations increase the porosity of firm boundaries, which generate knowledge spillover effects, there are some practical risks that managers must consider before entering in interorganizational partnerships. By coordinating the relationships among individuals, groups, and members in the collaboration, there will be voluntary and involuntary transfer of knowledge between organizations, which can lead to an imitation of resources and capabilities by the partners and other organizations that participate the network (Gittelman, 2007; Rosenkopf & Almeida, 2003; Zander & Kogut, 1995). This matter is extremely relevant for firms as to succeed in developing and maintaining knowledge-based competitive advantage, firms need to protect their knowledge from imitation, or they may not be able to keep their competitive advantage (Barney, 1991; McEvily, Eisenhardt, & Prescott, 2004). Nonetheless, it is worth mentioning that firms are not always inclined to deter imitation of its resources, since they may decrease such inclination when facing substitution threat (Polidoro & Toh, 2011).

2.3 Firm-university collaborations

Universities are also targeted as potential partners for interorganizational collaborations, as universities contribute substantially to the stock of knowledge available within any country (Mansfield, 1998). Therefore, similarly to interfirm partnerships, firm-university collaborations help a firm to gain access to superior knowledge-based resources and skills that lie outside its boundaries, which in turn helps improving its innovation performance (Gambardella 1992, Henderson & Cockburn 1994; Zucker, Darby, & Armstrong, 1998).

In order to stay close to their scholarly partners, form new alliances, and access external knowledge, private firms encourage their researchers to engage in scientific research and publish the corresponding findings in scientific journals (Cockburn & Henderson 1998; Rosenberg, 1990), as well as to collaborate with university-based scientists (Gittelman & Kogut, 2003; Narin, Hamilton, & Olivastro, 1997). The scientific publishing activity by a firm offers insights about its area of expertise and available knowledge-based resources and signals its research quality to the market (Hicks, 1995), thus adding to its credibility as a prospective partner trying to form collaborative ties with the scientific community. Moreover, scientific publications can also aid a firm's attempt to capture value from the innovations that it brings to the marketplace, as a strategic weapon in the battle for market dominance, by positioning their innovations against those of their rivals (Polidoro & Theeke, 2012).

Although scientific activities and collaborations with universities exert such positive influences on a firm's ability to access external knowledge and create competitive advantage, they are also subject to considerable levels of uncertainty. By engaging in scientific publications, firms oftentimes disclose and codify knowledge elements that could otherwise remain unrevealed to competitors. The knowledge revealed by scientific publications can serve as an indication to rivals imitate such technology (Dasgupta, 1988) or to find new applications in other domains (Henderson & Cockburn, 1996). Further, by performing firm-university collaborations, the knowledge that a firm's researchers share with their university-based partners may eventually reach other individuals with whom these scientists collaborate, increasing the porosity of a firm's boundaries and producing knowledge spillovers that can facilitate imitation by competitors, especially if they form firm-university partnerships with the same universities (Alcacer & Zhao, 2012; Gittelman, 2007). Since firms have limited possibility to use contractual terms or formal governance structures to protect its knowledge in firm-university alliances (Gulati & Singh, 1998; Kale, Singh, & Pearlmutter, 2000; Oxley & Sampson, 2004; Pisano, 1989), such collaborations are inherently subject to uncertainties regarding knowledge sharing and information disclosure, which may cause detrimental effects on the result of the collaboration.

Another very important source of uncertainty concerning firm-university collaborations is the distinct logics and objectives each of these organizations have: whereas the scientific community is mostly concerned with the stock of knowledge and is devoted to furthering its growth, the technological community is concerned with the private economic rents that can be earned from discoveries and inventions (Dasgupta & David, 1987). The difference between firms and universities logics will provide distinct and sometimes conflicting goals to the collaboration. Thus, albeit collaborations with universities can potentially enable a firm to gain access to external knowledge, to increase its innovation output and assert the merits of its innovations, they are surrounded by collaboration hazards like other types of interorganizational alliances.

2.4 Effects of relational embeddedness in collaborations

Based on the social aspects concerning collaborations elucidated herein before, prior research has shown that relational embeddedness, i.e., the existence of cohesive ties between partners, has many different effects in interorganizational collaborations.

Concerning the difficulty to obtain information regarding the partner's capabilities, resources and interests, the existence of cohesive collaborative ties between two prospective partners broadens their access to information about each other's capabilities and about opportunities for additional collaborations that would be difficult to identify outside a cohesive relationship, thus increasing the chances that they will form additional collaborative ties in the future (Gulati & Gargiulo, 1999).

About the risk of collaboration hazards, the existence of a history of collaborative ties between prospective allies enable organizations to learn about teach other's reliability and reinforces mutual trust developed around norms of equity or "knowledge-based trust" (Shapiro, Sheppard, & Cheraskin, 1992). Trust between partnering organizations refers to "a type of expectation that alleviates the fear that one's exchange partner will act opportunistically" (Bradach & Eccles, 1989, p. 104). Consequently, repeated collaborations enable the emergence of interfirm trust, which compels partners to behave loyally, thereby facilitating new collaborative relationships between organizations (Gulati, 1995a). Furthermore, the trust emanating from prior cohesive ties between two partners shapes their choice of governance structure in subsequent collaborations with each other, making them less likely to resort to hierarchical forms as a way of mitigating potential collaboration hazards (Gulati & Singh, 1998).

As a result, by facilitating collaboration between partners who have a history of cohesive ties, relational embeddedness engenders inertial pressures that make the pattern of new ties mirror the pattern of pre-existing ones, highlighting a firm's tendency to ally with partners that it has already collaborated (Chung, Singh, & Lee, 2000; Gulati & Gargiulo, 1999).

Besides, prior studies have demonstrated that the existence of cohesive ties between partners indeed increases the stability of collaboration (Park & Russo, 1996; Park & Ungson, 1997) and mitigates the hazard of unplanned alliance dissolution (Polidoro, Ahuja, & Mitchell, 2011). These studies show that relational embeddedness also contributes to alleviate tensions that could otherwise emerge during the life of interorganizational relationships.

Therefore, similar to interfirm alliances, relational embeddedness would facilitate collaborative relationships between a firm and a university it already knows well from a history of prior cohesive ties by alleviating a firm's concerns of potential collaboration hazards and providing more information about that university's resources and capabilities. Thus, in deeply embedded firm-university partnerships, relational embeddedness would mitigate the uncertainties related to the collaboration, leading to additional partnerships between those organizations and an increase in the stability of the resulting collaboration.

The question remains, though, whether relational embeddedness indeed facilitates partners' efforts to achieve collaborative outcomes that motivated the formation of a relationship in the first place and also whether relational embeddedness affect the level of financial resources invested in further collaborations with the same partner. In the sections that follow it will be examined how relational embeddedness affects the level of resources a firm commits to collaborate with a university, as well as the influence relational embeddedness exerts on the patenting output and publishing output that partners jointly attain. By doing so, this study move prior research's focus from the benefits generally accrued by a firm that maintains linkages with universities to a focus on specific firm-university collaborations and the respective outcomes.

2.5 Relational embeddedness and escalation of resource commitment in firm-university collaborations

As already mentioned, arguments of prior research suggest that relational embeddedness between a firm and a partnering university breeds familiarity and tightens their relationship, which in turn increases mutual trust and engender deeper awareness of each other's capabilities and collaborative behavior. Evidence of such effect stemming from relational embeddedness is manifested in partner's greater propensity to enter a collaborative relationship and in greater stability of the resulting relationships in the presence of a history of direct cohesive ties between them.

If indeed relational embeddedness makes a firm more confident in a partnering university, providing richer information about its capabilities, reinforcing trust, and mitigating concerns with unintended leakage of knowledge or other incidences of opportunistic behavior, then it would be expected that such effects also be manifested in the level of resources a firm commits to such relationship.

From a behavioral perspective, the increase in the confidence of the relationship would bias the perception of marginal benefits obtained with the collaboration (Camerer & Weber, 1999), which could lead to escalation of resources in future collaborations. In addition to that, the relational aspects could bias the perspective that such investment would bear future returns making partners overestimate the potential return of the partnership (Garland, Rogers, & Sandefur, 1990), collaborating to the escalation of resources in such investments.

Therefore, besides resulting in greater incidence of collaborations as prior research has demonstrated, relational embeddedness in firm-university collaborations should also result in a firm committing more resources to the collaborative ties it forms with a university. Thus, the following hypothesis is proposed:

HYPOTHESIS 1 (H1): Relational embeddedness between a firm and a university has a positive effect on the amount a firm invests in a subsequent project with that university.

2.6 Relational embeddedness, joint patenting and joint scientific publication in firm-university collaborations

The prior ties between two organizations provide channels through which partners can learn about each other's competences and how much the other is reliable. By entering in a partnership, the parties exchange many types of information, especially fine-grained information, which is more detailed, tacit and difficult to communicate through market ties, and whose valuation is based on social identities of the exchanging partners (Uzzi, 1997). Also, in embedded relationships, organizations work through problem solving and get direct feedback, which increases learning and the discovery of new combinations, as well as reduces production errors and the number of development cycles (Helper, 1990). These characteristics of the collaboration would definitively enhance combination of external knowledge with internal knowledge, generating better innovation outputs for each partner.

Nevertheless, patenting and scientific publication activities, although they share a focus on novelty, display remarkable differences. Fundamentally, patenting and scientific publishing are driven by distinct social ethos that guide technology and science. As Price (1967) puts it, inventors are assiduous readers but are not motivated to publish; scientists by contrast, are highly motivated to publish but not to read. Thus, differences between technological ethos and scientific ethos are reflected in different approaches to knowledge disclosure - whereas inventors emphasize the rents associated with private information, academia is driven by the public disclosure of discoveries, which is essential to legitimate new knowledge besides enhancing the standing of the corresponding scientist among its peers (Dasgupta & David, 1987).

It is worth stressing that patents co-owned by a firm and a university and academic publications co-authored by a firm and a university's scientists are an important outcome to analyze firm-university collaborations, as such outputs unequivocally result from a direct collaboration between them. Nonetheless, due to the conflicting logic between firms and universities, universities may not be interested in focusing their activity on joint patent outputs, since their reward system is more sharply aligned with scientific outputs. As a result of this conflicting logic, repeated partnerships with universities could be inducing a shift in the balance of the firm-university collaboration towards joint scientific publication and away from joint patenting activity, suggesting an asymmetry in the likelihood of these outputs happen in the long run, i.e., a negative impact on joint patenting and a positive impact in joint scientific publishing, as explained below.

A patent confers to its respective assignee exclusionary rights which a firm can resort to curb imitation of its patented innovation and, thus, explore with exclusivity the economic rents attached to the invention, whereas such legal recourse does not apply to a scientific publication. Note that co-invention of a patent would imply in sharing the economic benefits attached to it by the owners, which is a very relevant matter in any partnership. Considering that normally it is in the interest of firms to have economic rents from their inventions by selling or using them and such incentive is not usually in line with universities' objectives, it is possible to observe a relevant difference in the motivation to have each of these joint outcomes, as firms would prefer to not share their rights to explore economic rents of inventions, increasing their return on investment, while universities would be more interested in producing scientific outputs than patents. Also, since there are no immediate economic implications in being a co-author in scientific publications, a firm would find beneficial to have its name associated with universities in these publications, which contributes to enhancing its reputation and its attractiveness as potential partner to other organizations, among other benefits highlighted before. Due to these economic issues and conflicting logics, it would be possible to expect that relational embeddedness would lead to a negative effect in joint patenting and a positive effect in joint scientific publishing.

Furthermore, patents and scientific publications are subject to different norms in terms of who qualifies as a co-inventor of an invention or as a co-author of an academic publication. The legal requirement for an individual to be listed as co-inventor in a patent is participation in the conception of the invention at the claim level. Thus, an individual that does not participate in the ideation of an invention but rather contributes to its reduction to practice does not qualify as an inventor. Such form of contribution, however, could very well make that individual a co-author of a scientific publication. Accordingly, such flexibility makes it more likely for a university-based collaborator to become co-author of scientific publications than co-inventor of patents, which would definitively impact the joint outcomes of collaborations in an uneven way.

In addition to that, continuous embeddedness can make the social aspects of the collaboration supersede the economic ones, as feelings of commitment and companionship can be so great that may lead stronger organizations to dedicate their resources to favor the interest of the partner in detriment of their own, due to the development of trust and solidarity in the relationship (Portes & Sensenbrenner, 1993; Uzzi, 1997). Therefore, since the firm is usually the bearer of a large share of resources to be used in research activity in firm-university collaborations, it may be inclined to dedicate such resources to the university's interest, which may be less likely to result in a joint patent output, since the university's interests are more tightly attached to other types of incentives, such as scientific publication. Therefore, the social aspects and conflicting logic would be favoring more the production of joint scientific publications than the creation of joint patents.

Another issue that may impact the occurrence of joint patenting is the effect of prolonged collaborations, which generates greater familiarity, common language, and greater knowledge overlap, reducing opportunities for recombining knowledge in novel and non-obvious ways, which would hamper the creation of new patents (Levinthal, 1997). As partners collaborate repeatedly over time, they become exposed to the downside of embeddedness, which relates to poor access to non-redundant information. This issue might reduce the flow of new knowledge into the network since recurrent ties can mean that there are not many options of partners that are able to collaborate with ideas outside the knowledge stock of the organization. In these cases, the network becomes ossified and unable to contribute with different knowledge components, forcing the organization to search more narrowly among building blocks it already know, which may lead to a decline in innovative technological outputs within the partnership (Uzzi, 1997). Such fact would lead to a natural decline in joint patenting outputs within the scope of the collaboration, as patents require technological novelty in order to be filed.

In sum, norms and incentives underlying patents and scientific publications are fairly distinct from social and economic perspectives and those differences are reflected in attendant routines and incentive structures that surround innovative activities and academic research within private firms and universities.

Hence, controlling for other influences such as a firm's and a university's own patent and scientific publication outputs, as well as the technological and scientific similarity between them, the conflicting logic, social and economic aspects of the collaboration, and the increased familiarity resulting from prior collaborations would contribute to negatively impact joint patenting outcomes, but to positively affect joint scientific publication outcomes. Therefore, it was hypothesized the following:

HYPOTHESIS 2 (H2): Relational embeddedness between a firm and a university has a negative effect on the number of patents they jointly produce.

HYPOTHESIS 3 (H3): Relational embeddedness between a firm and a university has a positive effect on the number of scientific publications they jointly issue.

Note that firms would still be benefiting from the external knowledge acquired in the collaboration and would be increasing their own patent activity, as corroborated by the literature. Therefore, while firms would be profiting by having access to external knowledge, which would improve their own innovation activity and produce more inventions, universities would be improving their knowledge production and issuing more scientific publications. However, there would be an asymmetry in how these organizations reap joint rewards from collaborations, as a firm would be privately benefiting through solo patenting, but jointly benefiting from scientific publications originated in firm-university collaborations it carries out.

2.7 Relational embeddedness and exploration of new knowledge in firm-university collaborations

To develop knowledge resources and, as a result, strengthen competitive advantage, it is necessary to adapt and balance the delicate trade-off between exploration and exploitation, having in mind that the essence of exploitation is the refinement and extension of existing competences, technologies, and paradigms, whose returns are positive, proximate, and predictable, and the essence of exploration is experimentation with new alternatives, whose returns are uncertain, distant, and often negative (March, 1991). This matter is so important that the survival of the firm in the long run depends on such balance, which is very hard to specify and involves several problems of decision making and problems of myopia that may compromise the effectiveness of organizational learning (Levinthal & March, 1993).

In the alliances context, a firm can be motivated to enter in partnerships to exploit an existing capability or to explore new opportunities, which would be equally applicable to most strategic choices available to the firm (Koza & Lewin, 1998). Moreover, since the structure domain of exploration and exploitation would consider the network positions of the partners, recurrent alliances between partners can be considered as a form of exploitation and, on the other hand, alliances with new partners can be considered as a form of exploration, as firms balance their tendency to explore and exploit with respect to the nature of their alliances (Lavie & Rosenkopf, 2006).

Due to the social pressures inherent to alliance formation, relational embeddedness would be facilitating collaborations with old partners, as well as knowledge transfer between organizations (Hansen, 1999; Reagans & Zuckerman, 2001; Tsai, 2001). Therefore, these inertial pressures would make firms rely on their routines to select partners, establish the governance instruments of the collaboration, manage operations, and share resources (Kale, Dyer, & Singh, 2002). By repeating collaborations with deeply embedded partners, the benefits perceived by investing in such relationships, while providing the advantages already discussed, would not be easily applied in partnerships with other organizations, leading to a tendency to leverage these deeply embedded relationships in structure exploitation (Dyer & Singh, 1998). As a result of such embeddedness, repeated alliances would favor the exploitation of existing knowledge resources and inhibit the exploration of other domains in alliance formation (Beckman, Haunschild, & Phillips, 2004). Thus, it would be expected that such situation would harm exploratory joint outputs in these alliances, both technological, in the form of patents, and scientific, in the form of academic publications, generating a cycle that induces these alliances to have less exploratory outcomes. Considering that, it was hypothesized the following:

Hypothesis 4a (H4a): Relational embeddedness between a firm and a partnering university has a negative effect on the extent to which such collaboration results in exploratory joint patents.

Hypothesis 4b (H4b): Relational embeddedness between a firm and a partnering university has a negative effect on the extent to which such collaboration results in exploratory joint academic publications.

2.8 Knowledge similarity and exploration of new knowledge

Having in mind that patents filed and publications issued by a firm will provide signaling to prospective partners in academia about the knowledge the firm has, as mentioned before, such firm would be likely to attract partners that wish to build on the same underlying technological and scientific paradigms (Gittelman, 2007; Hicks, 1995). By building on pre-existing resources and accumulating exploitation experience, a firm would reinforce its established routines within those domains, increasing inertia and leading to path dependency, favoring the exploitation of pre-existing knowledge and hampering the exploration of novel possibilities, which causes a suboptimal equilibrium between these two types of knowledge development (March, 1991).

Hence, although knowledge similarity is conducive to the formation of firm-university collaboration linkages, the resulting knowledge proximity hinders a firm's ability to engage in distant search, which is more conducive to exploration (Levinthal, 1997). Therefore, knowledge proximity between a firm and a partnering university would favor the exploitation of existing resources and would, on the other hand, have a negative effect on exploratory actions. Considering that the knowledge involved in patent creation is more related to technological features and the knowledge related to academic publications is more related to scientific features, it was hypothesized the following:

Hypothesis 5a (H5a): Technological similarity between a firm and a partnering university has a negative effect on the extent to which such collaboration results in exploratory joint patents.

Hypothesis 5b (H5b): Scientific similarity between a firm and a partnering university has a negative effect on the extent to which such collaboration results in exploratory joint academic publications.

3. DATA AND METHODS

3.1 Empirical setting

To test these propositions, it was used a unique dataset containing fine-grained data regarding all R&D projects carried out in collaboration with universities by Petrobras, the biggest Brazilian oil and gas firm, the world's largest publicly traded oil corporation that produces liquid hydrocarbons, and the world's fourth largest producer of oil and gas, with a production of 2.9 million barrels per day[1].

The oil and gas sector was chosen to test the propositions due to its technology intensive nature. It is worth mentioning that the innovation in such sector has recently increased more than in typical innovation-driven contexts, such as semiconductors and pharmaceuticals[2]. Therefore, the major relevance of innovation in this industry is unambiguous. As a result, so is the necessity to leverage R&D gains, which can be achieved, for instance, by having access to external knowledge in collaborations with universities.

An important event that illustrates the technological intensity of the oil and gas sector was the discovery of Brazilian pre-salt oil reserves in 2006, which generated the necessity to leverage existing technical solutions to face the new risks and challenges presented by this novel type of oil and gas exploitation. The first major challenge of this achievement was the characterization of the oil and gas reserve, which began in 2004 when Petrobras drilled to search for oil in Santos Basin. As geological characteristics of the pre-salt, such as uneven surface of the top of the salt layer, internal variations within the salt layers, and the limited vertical resolution in the reservoir, among others, raised difficulties about quality of seismic data, Petrobras' specialists had to keep "betting" that there would be oil there until they finally had the confirmation in 2006, when drilling had already reached a depth of 7,600 meters from the water line. After that, other spots were found and other challenges were presented to make the exploitation of such oil fields feasible, like the development of new techniques of oil recovery, which could adjust to the new environment presented in the pre-salt, and the improvement of cost effective wells to drill in deepwater reservoirs, which would

[1] According to the firm's website. Retrieved from: <http://www.petrobras.com.br/en/news/>.
[2] U.S. Patent and Trademark Office. Electronic Information Products Division - PTMT. Patent Counts by Class by Year Jan 1977 - Dec 2014. Retrieved from: <http://www.uspto.gov/web/offices/ac/ido/oeip/taf/cbcby.htm>.

require special equipment and skilled people to improve the learning curve and reduce well construction duration[3].

These needs required an improvement of various types of materials, equipment and techniques able to deal with pre-salt environmental conditions, such as high pressures in the reservoirs, the contaminants in the fluids produced, temperature of the water, acidity of the oil extracted etc. As a result, many enhancements have been made on existing materials, equipment and techniques in order to make the exploitation of these oil reserves technically and economically viable, such as new pipeline support buoys, which enabled the use of rigid steel pipelines at greater water depths, development of flexible risers specifically designed for pre-salt environment, new technology for drilling wells, among several other types of solutions that required a substantial degree of innovation.

In addition to these technical challenges specifically related to oil extraction, logistical challenges also demanded attention from firms. The location of the basins posed many difficulties to the supply of materials and equipment, transport of people, positioning of pipeline laying vessels and drilling rigs, as well as the existence of terminals for oil export through crude carriers. Moreover, Brazil has a local content public policy that places several restrictions to which suppliers Petrobras can use to carry out its activity, imposing even more challenges for the economic and technical feasibility of such exploitation (Estrella et al. 2011).

Due to these reasons, there was a significant shift in the R&D and capital investments made by firms following this discovery of pre-salt oil (Hults, Thurber, & Victor, 2012). Therefore, to achieve such results and keep developing solutions to the new challenges arising, Petrobras and the other firms of the sector continued to invest significant amounts of resources in R&D in the last decades.

Furthermore, to increase innovation in the sector, the Brazilian oil and gas regulatory agency imposed a public policy obligating organizations of the oil and gas sector to invest a small percentage of the gross revenues obtained in the exploitation of highly profitable or highly productive oil wells in R&D activities, which in part must be carried out with domestic universities. This public policy started in 1998, shortly after the regulatory agency was

[3] According to firm’s website. Retrieved from: <http://www.petrobras.com/en/energy-and-technology/sources-of-energy/pre-salt/>.

created. However, even though there is a minimum investment required in the terms demanded by the public policy, organizations have no limits to invest in internal projects and projects with other organizations, such as suppliers, service providers, and even universities. Note that noncompliance of the minimum mandatory investment may cause the regulatory agency to impose a fine, which is applied each year noncompliance is verified, as organizations must file timely reports of their R&D activities to the regulator. In sum, since firm-university collaborations would necessarily happen in this environment due to such mandatory investment policy imposed by the oil and gas regulation, this feature of the empirical setting makes it very favorable to study firm-university collaborations, as such phenomenon will happen in abundance.

Another interesting feature of this setting is the incentives that the Brazilian public policy of postgraduate education grants for scientific and technological production in universities. This public policy is managed by the Brazilian Ministry of Education and Culture (MEC) and the Coordination of Personnel Training in Superior Education (CAPES), a public foundation created by such Ministry. CAPES is responsible for the evaluation of postgraduate courses, the development of scientific production, investments in the formation of high level resources in the country and abroad, the promotion of international scientific collaboration, and the training of human resources.

Therefore, with the purpose of certifying the quality of postgraduate courses and orientating actions for further development of the educational system, CAPES receives yearly information from all postgraduate courses in Brazil and makes a triennial detailed evaluation. This evaluation is normally divided in five scopes: (i) proposal of the course; (ii) faculty; (iii) student body; (iv) intellectual production; and (v) social insertion, which altogether constitutes a grade. The criteria “intellectual production” is usually the one of the most important for the grade and consists of the number of publications per faculty, their participation in scientific events, the technical production and other relevant productions defined by CAPES.

To illustrate the difference in importance of scientific publications and patent production in the Brazilian academia by using the criteria applied to engineering schools in the most recent available period (triennium from 2010 to 2012)[4], it is possible to observe that patent production is responsible for a very small part of the final grade attributed to the criteria "intellectual production". In a general way, scientific publication was responsible for 80% of that grade and patent production, together with many other types of production (such as participation in technical committees, technical services performed, publication of books and technical manuals, among other types of production), was responsible for the other 20%. Even though how these criteria are evaluated varies according to the course's area, usually the scientific production is one of the most important, especially the number of publications per faculty and their participation in scientific events, whose relevance is also defined by CAPES and representatives of the academia.

In addition to that, by comparing the evolution of the standards along the trienniums, it is evident that CAPES has been hardening the criteria for scoring in these scopes, as their objective is to increase the quality of the postgraduate courses in Brazil. One example of this measure was the increase of scoring standards of scientific production and events, demanding additional publications and participation in more relevant journals and events to achieve the same score obtained in previous trienniums. This pressure certainly increased the incentives for universities to carry out more research activity and to increase their participation in scientific channels, as it became harder to increase or even maintain their grade. Note that in order to enforce the compliance of the established target CAPES can apply sanctions that range from the reduction of financial resources designated to the program to its disaccreditation. Consequently, it is noteworthy that Brazilian academia values much more scientific publication than patent production, collaborating to the conflicting logics issue present in firm-university partnerships, as aforesaid.

3.2 Data sources and data collection

In order to collect data about R&D projects that occurred in the sector, it was filed a request, similar to an U.S. Freedom of Information Act request, to the National Petroleum Agency (ANP), the Brazilian regulatory agency of the oil and gas sector. Such request was based on the Federal Law n. 12,527/2011 (*Lei de Acesso à Informação*), in effect since May 2012, that regulates the constitutional right to access public information. By the terms provided in this law, anyone - individuals and legal entities - can file a request to receive public information

[4] CAPES. Area documentation of the triennium from 2010 to 2012. Retrieved from: <http://www.capes.gov.br/avaliacao/instrumentos-de-apoio/documentos-de-area>.

from the government. Such law is applicable to direct public administration (such as governmental bodies), to indirect public administration (such as public foundations, public companies and mixed capital corporations, such as Petrobras), and to entities that receive public funds. Thus, following such request, it was obtained data on all R&D projects carried out by Petrobras in collaboration with 165 universities and research institutes from 1993 to 2013, which sum 4,490 projects in total.

A distinct feature of this dataset is that it includes fine-grained, project-level data about each collaborative R&D project, including a description of the project, as well as the associated yearly R&D expenditures. This data was determinant to test predictions about influences on the outcomes of the collaborations instead of prior research's emphasis on the formation of collaborative ties. Table 1 provides a brief description of a few collaborative R&D projects in the sample.

Table 1. Examples of R&D projects carried out by Petrobras and universities

Description	**Partner university**	**Duration**	**Total investment in US$**
Development of support system for dry completion risers to explore oil in the pre salt layer	Federal University of Rio de Janeiro (UFRJ)	1 year	$ 40,054
Experimental analysis and analysis of set up and construction	University of São Paulo (USP)	2 years	$ 211,957
Fast development of software components for virtual reality applications	Pontifical Catholic University of Rio de Janeiro (PUC-RIO)	1 year	$ 211,251
Development of a portable system for the inspection of failures in pipelines and plates	State University of Campinas (UNICAMP)	3 years	$ 449,607
Study of nanoscale and microscale particles issued in the exhaustion of engines fueled by diesel and diesel mixtures/biodiesel	Federal University of Bahia (UFBA)	5 years	$ 150,238

To avoid the selection bias implicit in examining collaboration outcomes by observing only firm-university collaborative ties that were indeed formed, the sample was composed not only by collaborations between Petrobras and Brazilian universities but also by data of collaborations at hazard of being formed. Accordingly, besides data of universities that collaborated with Petrobras, it was collected data of universities that hypothetically could have formed a partnership but actually have not done so. It was identified the top 200 Brazilian universities according to the ranking provided by Webometrics[5], regardless of whether or not those universities conducted joint projects with the focal company. For each of these universities, it was gathered data of all patents they filed and all articles they published in scientific journals, as explained below.

It was conducted a detailed data collection effort with the goal of identifying all patents filed by the focal firm and the universities of the sample in the Brazilian Industrial Property National Institute (INPI), the governmental body responsible for analyzing and granting patents, during the analysis period. Note that public databases maintained by INPI do not provide search functions typical of the database maintained by the U.S. Patent and Trademark Office – that is, the INPI database does not enable identification of, for example, of all patents filed in a particular technological class, or of all patents that cite a given patent as prior art. These limitations notwithstanding, it was collected data of all patents filed by Petrobras, a total of 1,439 patents filed between 1974 and 2013, and all patents filed by the top 200 Brazilian universities, a total of 7,064 patents in the period between 1919 and 2013. Moreover, the Web of Science database was used to collect data of all academic publications involving a co-author affiliated with Petrobras, totaling 2,019 scientific publications for the period of 1973 to 2013. Also, it was collected data of all academic publications involving a co-author affiliated with all universities in the sample, totaling 344,487 scientific publications for the period of 1966 to 2013. This data was filtered to fit the period of analysis, which ranged from 2003 to 2013, resulting in 712 patents filed by Petrobras, 4,743 patents filed by the top 200 Brazilian universities, 1,323 scientific publications issued by Petrobras, and 312,131 scientific publications issued by the universities in such period.

The final sample comprised 2,000 university-year observations, referring to the collaborations between Petrobras and 200 universities observed between 2004 and 2013, the year 2003 being

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[5] Webometrics. Retrieved from: <http://www.webometrics.info/en/Latin_America/Brazil>.

used to predict outcomes in 2004. In the following section it is provided more details about the variables used to test the propositions.

3.3 Dependent variables

R&D projects expenditure (H1)

To calculate the amount of resource commitment by Petrobras in each R&D project conducted in collaboration with a university, it was calculated the average expenditure per project per year in each university. It was created a variable with the logarithm of those R&D expenditures in order to reduce skewness.

Joint patenting (H2)

This variable is represented by the number of patents that the focal firm and a university have filed in a year as co-owners (that is, both organizations figure as owners in the patent record).

Joint publishing (H3)

Similarly to the previous variable, this variable is represented by the number of scientific publications co-authored by the focal firm and a university (that is, if there was at least one researcher affiliated with the focal company and at least one researcher affiliated with the focal university co-authoring the publication) that were issued in a year.

Joint exploratory patents (H4a and H5a)

To classify a patent jointly owned by Petrobras and a university as exploratory, it was necessary to observe the whole historical record of Petrobras patents, which began in 1974, and identify which joint patents were the first to be included in a certain primary technological classification, as per International Patent Classification (IPC) code. When a joint patent was the first one to integrate an IPC code, considering all patents filed by Petrobras in its history, it was considered as exploratory. Thus, the variable was the count of how many of these exploratory joint patents could be observed in a university in a year.

Joint exploratory publications (H4b and H5b)

To classify a co-authored scientific publication by Petrobras and a university as exploratory, it was used the Science Citation Index Expanded (SCIE) of Web of Science to observe the thematic areas of the top 10 journals in which Petrobras most published, jointly or solo. Based on the seven thematic areas in which those journals were included by Web of Science, such as engineering, chemistry, energy, geosciences, environmental, among others, all joint publications were classified as within journals of one of these seven categories and within journals not in one of these seven categories. The joint publications not in journals of these seven categories were considered as exploratory. Therefore, the variable was the count of how many of these exploratory joint publications could be observed in a university in a year.

3.4 Independent variables

Relational embeddedness (H1, H2, H3, H4a and H4b)

This variable represents the level of embeddedness of the relationship between the focal firm and a university (dyad) by indicating the number of collaborations that were ongoing in a year. It was operationalized as the number of collaborative R&D projects ongoing between Petrobras and the university in a year. Such variable was based on the same used by Gulati and Gargiulo (1999). However, since the dataset used in this study has the information about when the project started and when the project ended, it was not necessary to estimate the duration of the partnership as was made in their study, since it could be directly observed. Some robustness tests were conducted considering alternate ways to calculate relational embeddedness, such as by using exactly the same method used by Gulati and Gargiulo (1999) and measures taking into account the whole history of collaborations between Petrobras and the partner university. Please refer to the robustness tests section for more details.

Technological similarity (H5a)

In order to estimate the knowledge similarity related to technology production, it was used the number of university patents whose primary technological classification, as per IPC code, was in one of the primary classifications that all Petrobras patents were classified into, divided by the number of total patents owned by the university. This proportion would provide a measure of how closely these organizations would be in technological knowledge and production.

Scientific similarity (H5b)

To estimate the knowledge similarity related to scientific production, it was used the number of publications that a university had in one of the top 50 journals in which Petrobras most published divided by the number of total publications that such university had. This proportion would provide a measure of how closely these organizations would be in scientific knowledge and production.

3.5 Control variables

The analysis control for various other sources of heterogeneity across projects that could significantly impact its results, as explained herein below.

As the geographic distance between the focal firm and the universities could significantly impact the likelihood of the alliance formation (McEvily, Eisenhardt & Prescott, 2004), it was included a dummy variable for geographic collocation of the university, being 1 if it was located in the State of Rio de Janeiro (where Petrobras' headquarter and research center are located) and to 0 otherwise. Hence, it was possible to control for the effects of geographic proximity on the collaborations formed.

To address the concern that larger universities often have access to more resources and personnel to carry out its activities, resulting in more technical capabilities (Griliches, 1990), which may both encourage more collaborations and lead to more patents and more scientific publications, models included a variable with the number of patents filed by a university in a given year and the number of scientific articles published in that year. These controls also capture the extent to which a university is likely to encourage inventive activities. Similarly, models account for the number of patents filed by Petrobras in a given year, as well as the number of scientific articles listing its researchers as coauthors.

As control variable for universities, the model included a dummy variable to separate if the university was public or private, as it is a relevant difference in the Brazilian context. In addition, a variable controlling for the number of faculty the university had each year was included, based on the census data provided by INEP, which is a governmental body linked to MEC and responsible for performing research and evaluations of the Brazilian education system. As some data was missing in the census (around 300 observations), the gaps were filled by using interpolation of data in the statistics software used for the analysis.

Additionally, as Petrobras' financial result could impact their inclination to start collaborative projects with universities, as well as the amount of resources it can allocate to those projects, which may in turn affect collaborations outcomes, a variable controlling for Petrobras' net income each year was included by collecting data from the financial statements published in the U.S. Securities Exchange Comission's 20-F reports.

Another potential influence is that stemming from records of patents and scientific publications, which may both provide signals of technological expertise, thereby facilitating the formation of collaborative ties between prospective partners with similar expertise (Ahuja, 2000a; Anton & Yao, 2003; Hicks, 1995) and affect the success of the resulting collaborative projects. Therefore, the variables Technological similarity and Scientific similarity, described in the previous section, were included as control variables in H1, H2, H3, H4a and H4b.

Further, since the amount of resources committed to the projects could impact the result of the collaboration, the tests controlled for R&D projects expenditure in the models used to test H2, H3, H4a, H4b, H5a and H5b.

3.6 Estimation

In order to fit the panel data into the regression models used in hypotheses testing, it was utilized random-effects models using generalized least squares (GLS) estimator, which produces a matrix-weighted average of the between and within results at university level. This methodology also accounts for additional time-variant heterogeneities across universities that may affect their propensity to form collaborative ties with the focal firm, as well as the outcomes of those collaborations. Thus, the models will predict the dependent variable related to each hypothesis, namely R&D projects expenditure in H1, Joint patenting in H2, Joint publishing in H3, Joint exploratory patents in H4a and H5a, and Joint exploratory publications in H4b and H5b, for Petrobras (*i*), university *j* in the year *t*, lagging independent and control variables by one year to ensure temporal precedence.

The regression equation used to the tests made in H1, H2, H3, H4a and H4b is stated as follow:

$$Dependent\_variable_{ijt} = \beta_0 + \beta_1 Relational\_embeddedness_{ijt-1} + \beta_k \text{Controls}_{ijt-1} + \varepsilon$$

For H5a and H5b, the independent variables are Technological similarity and Scientific similarity, respectively, represented as Knowledge similarity in the regression equation used to test the hypotheses, as indicated below:

$$Dependent\_variable_{ijt} = \beta_0 + \beta_1 Knowledge\_similarity_{ijt-1} + \beta_k \text{Controls}_{ijt-1} + \varepsilon$$

To provide robustness to the results, some supplementary tests were conducted, as will be described in the results section.

4. RESULTS

Table 2 reports summary statistics and correlations between the variables used in the models. Figure 1 shows the patenting activity and the scientific publication activity of Petrobras during the analysis period, indicating a decrease in patenting activity and an increase in publication activity. Figure 2, in turn, presents similar information for the universities of the sample, showing a regular increase in both patenting and publishing activities. Figure 3 shows that the number of joint scientific publications has been increasing more rapidly than the number of joint patents and the amount of resources applied in R&D projects with universities has been growing.

Initially, Table 3 reports the results of Model 1 regression, used to test H1. The prediction was that relational embeddedness would be positively and significantly related to the amount of resources the firm would apply to collaborative projects with that university. A simple regression with the same variables was carried out to calculate the variance inflation factor (VIF) of the model, whose mean VIF was 1.72 and the higher value was 3.14 for university publications per year. Such analysis shows that multicolinearity would not present a problem to the results shown by the model. In line with this prediction, the coefficient of "Relational embeddedness" was significantly positive (β=0.0346; $p<0.001$), showing that the more embedded is the relationship between Petrobras and the university the more resources will be allocated to the R&D projects with that university. This finding supports H1.

Table 2. Descriptive statistics and pair-wise correlations

Variables	Mean	S.D.	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16
01. R&D projects expenditure	2.9	5.2	1.00															
02. Joint patenting	0.0	0.3	0.18	1.00														
03. Joint publishing	0.5	2.6	0.35	0.53	1.00													
04. Joint exploratory patents	0.0	0.2	0.16	0.80	0.44	1.00												
05. Joint exploratory publications	0.3	1.3	0.35	0.58	0.96	0.47	1.00											
06. Relational embeddedness	5.1	23.2	0.40	0.60	0.90	0.46	0.90	1.00										
07. Technological similarity	0.0	0.1	0.13	0.07	0.08	0.10	0.08	0.10	1.00									
08. Scientific similarity	0.0	0.0	0.31	0.07	0.13	0.06	0.12	0.14	0.08	1.00								
09. University patents	2.7	9.1	0.39	0.21	0.42	0.17	0.40	0.41	0.12	0.12	1.00							
10. University scientific publications	185.8	697.5	0.37	0.26	0.46	0.18	0.47	0.45	0.08	0.09	0.75	1.00						
11. Petrobras' patents	64.7	15.9	0.02	0.04	-0.05	0.00	-0.04	-0.03	0.00	-0.02	-0.08	-0.06	1.00					
12. Petrobras' scientific publications	120.3	41.9	0.06	0.06	0.07	0.01	0.06	0.06	0.01	0.01	0.11	0.09	-0.52	1.00				
13. Petrobras' net income	13,168.6	4,589.0	0.08	0.02	0.05	0.04	0.05	0.06	-0.01	0.01	0.07	0.07	-0.35	0.68	1.00			
14. Geographic collocation	0.1	0.3	0.09	0.10	0.24	0.09	0.26	0.24	-0.01	0.01	-0.03	0.01	0.00	0.00	0.00	1.00		
15. Public/private university	0.5	0.5	0.33	0.09	0.14	0.07	0.14	0.14	0.08	0.08	0.19	0.20	0.00	0.00	0.00	-0.09	1.00	
16. Number of faculty	656.9	766.6	0.46	0.27	0.46	0.22	0.47	0.46	0.11	0.14	0.55	0.68	0.10	-0.13	-0.11	0.08	0.17	1.00

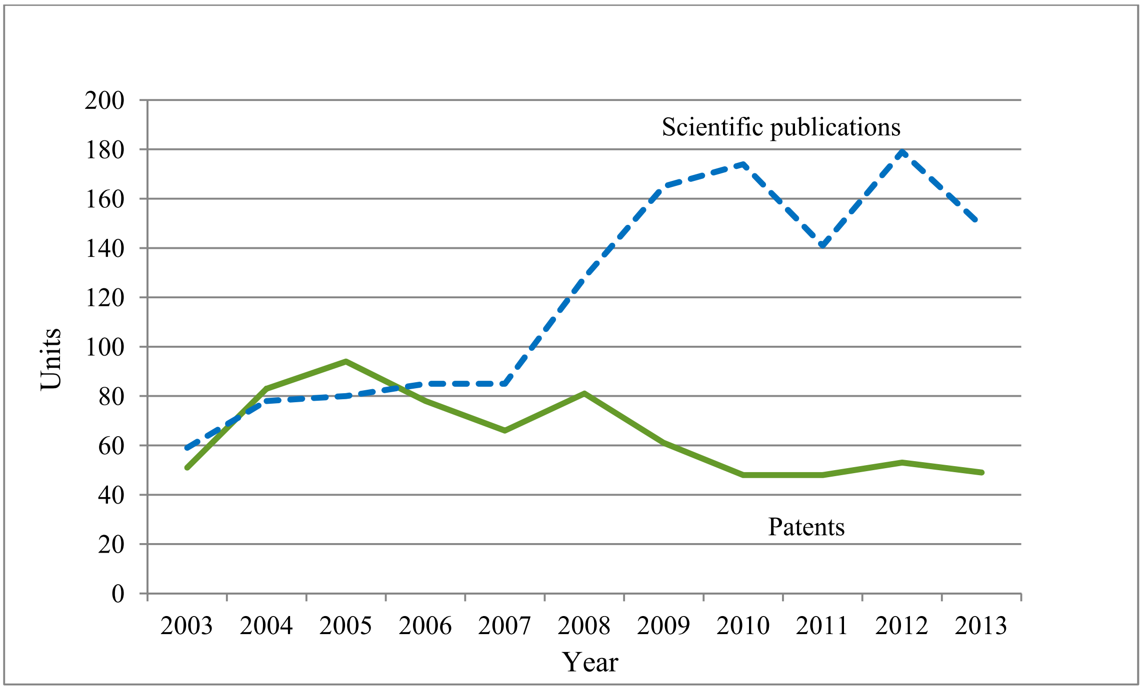

Figure 1. Petrobras' patent and scientific activity

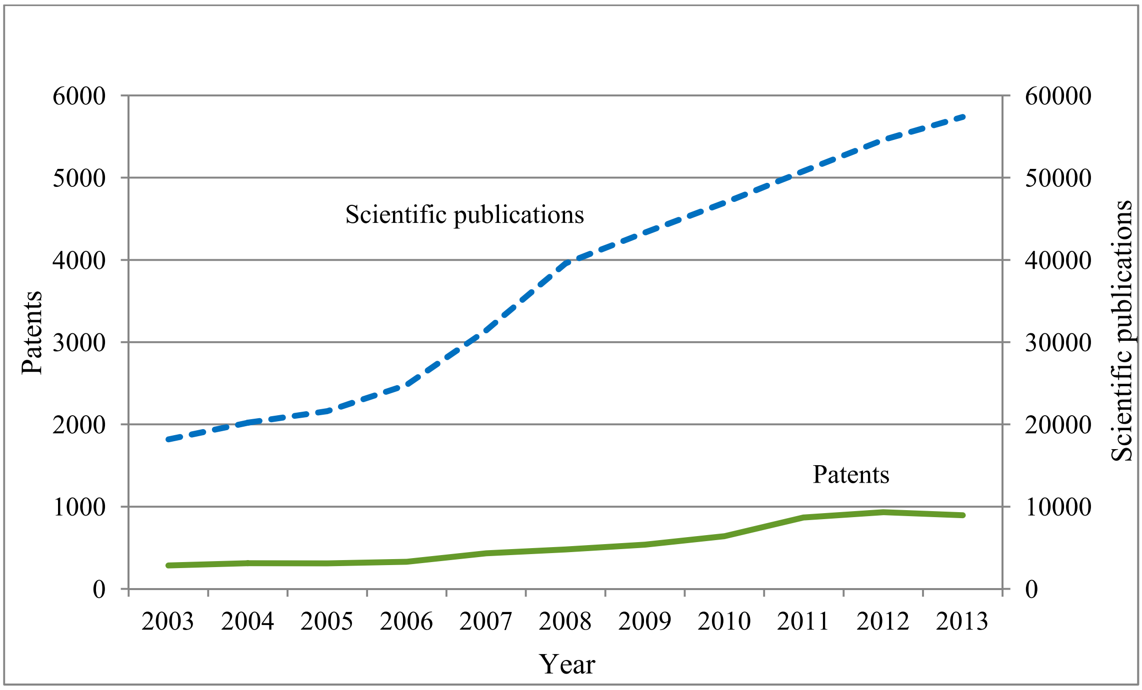

Figure 2. Universities' patent and scientific activity

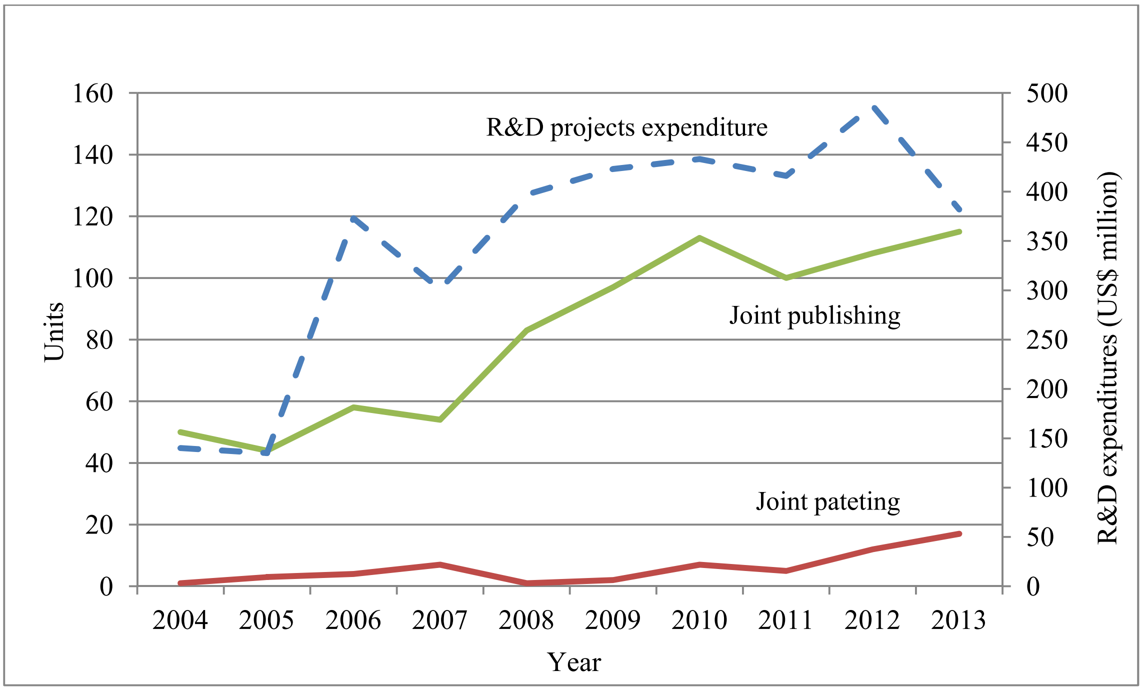

Figure 3. Joint outcomes and R&D projects expenditure.

Table 3. Random-effects estimate of effect of relational embeddedness on R&D projects expenditure (n=2000)

	Model 1		
	Coef.		S.E.
Relational embeddedness	0.0346	•••	(0.0080)
Controls			
Technological similarity	-1.3722	†	(0.7539)
Scientific similarity	5.9375	•	(2.4476)
University patents	0.0247		(0.0166)
University scientific publications	0.0005	†	(0.0003)
Petrobras' patents	0.0079	†	(0.0043)
Petrobras' scientific publications	0.0017		(0.0021)
Petrobras' net income	0.0001	•••	(0.0000)
Geographic collocation	1.1747	†	(0.7101)
Public/private university	2.9235	•••	(0.4425)
Number of faculty	0.0003		(0.0002)
Constant	-1.2229	•	(0.5600)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.

Table 4 presents Model 2, used to test H2, which predicted that the more embedded the relationship between the firm and a university, the lower would be their joint patent output. A simple regression with the same variables was carried out to calculate the VIF, whose mean was 1.75 and the higher value was 3.15. Nevertheless, the results did not support such prediction, as the coefficient of "Relational embeddedness" was significantly positive (β=0.0077; $p<0.01$), showing that the more embedded is the relationship between Petrobras and the university, the more likely such collaboration will results in joint patenting, which would be the opposite of the predicted effect. Therefore, such result does not support H2.

Table 4. Random-effects estimate of effect of relational embeddedness on joint patenting (n=2000)

	Model 2		
	Coef.		S.E.
Relational embeddedness	0.0077	•••	(0.0003)
Controls			
Technological similarity	0.0529		(0.0616)
Scientific similarity	0.0007		(0.1641)
R&D projects expenditure	-0.0041	••	(0.0013)
University patents	-0.0017	†	(0.0009)
University scientific publications	0.0000		(0.0000)
Petrobras' patents	-0.0001	†	(0.0004)
Petrobras' scientific publications	0.0005	••	(0.0002)
Petrobras' net income	0.0000	†	(0.0000)
Geographic collocation	-0.0420	•	(0.0168)
Public/private university	0.0134		(0.0107)
Number of faculty	0.0000		(0.0000)
Constant	-0.0161		(0.0384)

† $p< 0.10$; • $p< 0.05$; •• $p< 0.01$; ••• $p< 0.001$; standard errors in parentheses; two-tailed test for all variables.

Further, Table 5 reports the results of Model 3 regression, used to test H3, which predicted that relational embeddedness would be positively and significantly related to the amount of joint scientific publications produced in repeated collaborations between the firm and a university that had a deeply embedded relationship with it. A simple regression with the same variables was carried out to calculate the VIF, whose mean was 1.75 and the higher value was 3.15. In line with this prediction, the coefficient of "Relational embeddedness" was significantly positive (β=0.0907; p<0.001), showing that the more embedded is the relationship between Petrobras and the university, the more co-authored publications would be jointly issued by them. Such finding supports H3.

Table 5. Random-effects estimate of effect of relational embeddedness on joint publishing (n=2000)

	Model 3		
	Coef.		S.E.
Relational embeddedness	0.0907	•••	(0.0022)
Controls			
Technological similarity	0.2360		(0.2765)
Scientific similarity	0.0281		(0.8636)
R&D projects expenditure	-0.0148	•	(0.0073)
University patents	0.0043	†	(0.0055)
University scientific publications	0.0002	•	(0.0001)
Petrobras' patents	-0.0026		(0.0016)
Petrobras' scientific publications	0.0015	†	(0.0008)
Petrobras' net income	0.0000		(0.0000)
Geographic collocation	0.5183	••	(0.1579)
Public/private university	0.1527		(0.0993)
Number of faculty	0.0001	•	(0.0001)
Constant	-0.1158		(0.1818)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.

Table 6 reports the results of Model 4a and Model 4b, used to test H4a and H4b, respectively. Whereas H4a predicted that relational embeddedness would be negatively related to the production of joint exploratory patents, H4b predicted that relational embeddedness would be negatively related to the production of joint exploratory scientific publications. A simple regression with the same variables was carried out to calculate the VIF of the two models, whose mean was 1.75 and the higher value was 3.15 for both of them. Nevertheless, neither prediction were supported by the models, as the coefficient of relational embeddedness was significantly positive for joint exploratory patents (β=0.038; p<0.001) and for joint exploratory scientific publications (β=0.0490; p<0.001).

Table 6. Random-effects estimate of effect of relational embeddedness on joint exploratory patents and publications (n=2000)

	Model 4a Joint exploratory patents			Model 4b Joint exploratory publications		
	Coef.		S.E.	Coef.		S.E.
Relational embeddedness	0.0038	•••	(0.0002)	0.0490	•••	(0.0011)
Controls						
Technological similarity	0.1343	••	(0.0436)	0.0894		(0.1464)
Scientific similarity	-0.0250		(0.1163)	-0.0437		(0.4554)
R&D projects expenditure	-0.0016	†	(0.0009)	-0.0109	••	(0.0038)
University patents	0.0000		(0.0006)	-0.0073	•	(0.0029)
University scientific publications	0.0000	†	(0.0000)	0.0002	•••	(0.0000)
Petrobras' patents	0.0000		(0.0003)	-0.0012		(0.0009)
Petrobras' scientific publications	-0.0001		(0.0001)	0.0007	†	(0.0004)
Petrobras' net income	0.0000	†	(0.0000)	0.0000		(0.0000)
Geographic collocation	-0.0153		(0.0119)	0.2826	•••	(0.0811)
Public/private university	0.0071		(0.0076)	0.0653		(0.0510)
Number of faculty	0.0000		(0.0000)	0.0001	•	(0.0000)
Constant	-0.0188		(0.0272)	-0.0598		(0.0957)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.

Moreover, Table 7 reports the results of Model 5a, used to test H5a, whose prediction was that Technological similarity would be negatively related to the creation of joint exploratory patents. A simple regression with the same variables was carried out to calculate the VIF, whose mean was 1.74 and the higher value was 3.12. At first, the results were not supported by the model, since the effect of Technological similarity on joint exploratory patents was significantly positive (β=0.1459; p<0.01). However, by running an additional model, also stated in Table 7, with the independent variable squared, it was possible to observe that such effect is curvilinear, as the effect of Technological similarity was significant and positive (β=0.3761; p<0.01), but the effect of Technological similarity squared was significant (at the limit of five percent) and negative (β=-0.2875; p=0.05). Consequently, although H5a was not supported by the results, there are indications that a curvilinear effect would be applicable in such relationship, which will be further explored in the discussion section.

Table 7. Random-effects estimate of effect of technological similarity on joint exploratory patents (n=2000)

	Model 5a		Model 5a (2)	
	Coef.	S.E.	Coef.	S.E.
Technological similarity	0.1459 ••	(0.0460)	0.3761 ••	(0.1281)
Technological similarity squared			-0.2875 •	(0.1496)
Controls				
Scientific similarity	-0.0049	(0.1370)	-0.0080	(0.1366)
R&D projects expenditure	0.0017	(0.0011)	0.0016	(0.0011)
University patents	0.0003	(0.0008)	0.0000	(0.0008)
University scientific publications	0.0000	(0.0000)	0.0000	(0.0000)
Petrobras' patents	0.0000	(0.0003)	0.0000	(0.0003)
Petrobras' scientific publications	-0.0001	(0.0001)	-0.0001	(0.0001)
Petrobras' net income	0.0000 •	(0.0000)	0.0000 •	(0.0000)
Geographic collocation	0.0425 •	(0.0187)	0.0418 •	(0.0184)
Public/private university	0.0082	(0.0122)	0.0072	(0.0120)
Number of faculty	0.0000 ••	(0.0000)	0.0000 ••	(0.0000)
Constant	-0.0367	(0.0290)	-0.0371	(0.0290)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.

At last, Table 8 reports the results of Model 5b, used to test H5b, whose prediction was that that Scientific similarity would be negatively related to the creation of joint exploratory patents. A simple regression with the same variables was carried out to calculate the VIF, whose mean was 1.74 and the higher value was 3.12. Nonetheless, the results were not supported by the model, since the effect of Scientific similarity on joint exploratory patents was not significant (β=0.0460; p=0.93). By running an additional model, also reported in Table 8, with the independent variable squared, it was possible to observe that the effect of Technological similarity remained non significant (β=0.3352; p=0.74), as well as the effect of

Technological similarity squared (β=-0.9507; p=0.73). Therefore, H5b was not corroborated by the data.

Table 8. Random-effects estimate of effect of scientific similarity on joint exploratory publications (n=2000)

	Model 5b			Model 5b (2)		
	Coef.		S.E.	Coef.		S.E.
Scientific similarity	0.0460		(0.5290)	0.3353		(1.0032)
Scientific similarity squared				-0.9507		(2.8002)
Controls						
Technological similarity	0.0293		(0.1606)	0.0273		(0.1607)
R&D projects expenditure	0.0132	••	(0.0046)	0.0131	••	(0.0046)
University patents	-0.0054		(0.0037)	-0.0054		(0.0037)
University scientific publications	0.0008	•••	(0.0001)	0.0008	•••	(0.0001)
Petrobras' patents	-0.0011		(0.0009)	-0.0011		(0.0009)
Petrobras' scientific publications	0.0006		(0.0005)	0.0006		(0.0005)
Petrobras' net income	0.0000		(0.0000)	0.0000		(0.0000)
Geographic collocation	1.1142	•••	(0.2305)	1.1133	•••	(0.2306)
Public/private university	0.1727		(0.1460)	0.1711		(0.1462)
Number of faculty	0.0001	•	(0.0000)	0.0001	□	(0.0000)
Constant	-0.1987		(0.1472)	-0.1982		(0.1472)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.

The results of all models using only with control variables are presented in the annexes.

4.1 Robustness tests

Several robustness tests were carried out to verify the consistence of the results reported herein before.

Initially, in order to address temporal heterogeneity issues, it was not possible to use year dummies, as such variables presented multicollinearity problems with many variables of interest. Thus, this matter was addressed in two different ways. Firstly, by introducing a linear time variable to control for the number of years elapsed since the start of the analysis period.

This variable had a value of one for the first year of analysis and was added one for each passing year. The hypotheses testing with this additional control had fully robust results. Secondly, additional models were run accounting for year random-effects instead of university random-effects. Results were fully robust too. This supplemental analysis increases confidence that the results reported were not driven by temporal heterogeneities.

Additionally, the same hypotheses were tested exchanging the control variables of Petrobras and universities count of patents and publications by this same count net of the joint outcomes. Results were fully robust.

Also, the same hypotheses were tested adding as control variable the joint outcomes of the partnership, which are the dependent variables for H2 and H3. Results were robust.

Moreover, some more restrictive and some less restrictive approaches to classify patents and publications as exploratory were used in the testing. In the case of patents, a similar variable was built, but, instead of using the patent's primary class to identify which technological classes would represent Petrobras' technological expertise, it was used the first three digits of the patent's primary class IPC code, which represents the most comprehensive classification possible to that patent. Hence, the joint patents that were the first to be created in that three-digit category were considered as exploratory in order to test the predictions. Results were fully robust by using this alternative method for patents. In addition, another dependent variable was built by using the first four digits of the patent's primary class IPC code, which represent a less comprehensive category of technological class than the one with three digits, but more comprehensive than using the primary class. Results were also fully robust.

A similar exploration of results was carried out by using different criteria to select the areas of interest for academic publication. Besides using the top 10 journals in which Petrobras most published, which resulted in seven thematic areas, as per Web of Science SCIE classification, it was also used the thematic areas of the top five journals in which Petrobas most published (resulting in five thematic areas) and the journals in which Petrobras had more than 10 publications (resulting in 14 thematic areas), which is the same as the top 19 journals in which Petrobras most published. Results using these variables as dependent variables were fully robust.

In addition, some alternate measures of relational embeddedness were used to evaluate the robustness of the results for the hypotheses that had such variable as independent variable (H1, H2, H3, H4a and H4b). Firstly, a variable was created by using the exact same terms used by Gulati and Gargiulo (1999, p. 1463), that is, “the number of alliances dyad members had entered with each other in the previous five years”. Results were fully robust. Secondly, it was created a variable representing the accumulated number of projects that Petrobras and the university started in each year, considering the whole history of collaborations between them, as per available data. Hence, this variable had in year 2003 the total number of projects that these partners had started in all previous years added with the number of projects they started in such year. In 2004, the variable would be number presented in 2003 added with the number of projects started in 2004, and so on for the following years. Results using such variable were fully robust, except in H1, whose result was marginally significant (β=0.0041; p=0.087). At last, similarly to the previous variable, it was created a variable representing the accumulated number of projects that Petrobras and the university concluded in each year, considering the whole history of collaborations between them. Results were fully robust, apart from H1, whose result was not significant (β=0.0009; p=0.80). It is worth stressing that the database had information about collaborative projects between Petrobras and universities since 1993.

Furthermore, in order to facilitate the interpretation of results, some supplemental analyses were carried out, which will be discussed in the next section.

5. DISCUSSION

This study proposed that relational embeddedness in firm-university partnerships besides facilitating the formation of future alliances with cohesive partners would also increase the amount of resource commitment to future collaborations and the production of joint scientific publication as outcomes of such collaborations. On the other hand, relational embeddedness would hinder the production of jointly owned patents, due to the conflicting logics inherent to firm-university partnerships, and would also inhibit the possibility that the outcomes of these collaborations would result in exploratory attempts to develop new knowledge, due to inertial effects present in repeated collaborations. In addition, this study proposed that knowledge similarity between a firm and a partnering university would make it more difficult to have exploratory joint outcomes as a result of these collaborations, since this knowledge overlap would make partners inclined to exploit pre-existing knowledge instead of exploring opportunities outside existing knowledge. Whereas some of these propositions were supported by the data, others were not.

The results showed substantial evidence that relational embeddedness is leading to an increment of financial resource allocation in future partnerships with deeply embedded partners, since the model displayed a positive and significant effect between these variables. Therefore, future firm-university collaborations would benefit from the generation of interorganizational trust and reduction of cost to search for another partner which would lead the firm to allocate more resources to such partnerships, besides the already known effects of relational embeddedness, such as the increase of frequency of those collaborations.

Regarding the prediction that relational embeddedness would have a negative effect in joint patenting outcomes and a positive effect in joint scientific publishing outcomes, due to the conflicting logic inherent to firm-university collaborations, such proposition was supported only in relation to the joint scientific publishing. The results displayed a positive and significant effect of relational embeddedness for both types of outcomes, suggesting that relational embeddedness would lead to an increase in the number of joint patents and in the number of joint scientific publications. Although such result is not totally in line with the predictions, there are reasons to suspect that the predictions regarding joint patents would not be totally reliable. Firstly, the variable joint patenting resulted in only 34 nonzero observations in the dataset, having as maximum value six joint patents in a university-year.

Since it would have a low frequency in comparison to the total number of observations and a low variance, this issue could be making it harder for the statistical model to predict the variables affecting it. However, this issue would not be applicable to joint scientific publication, as such variable had a much larger number of nonzero observations, which was 323, and a maximum value of 49 joint publications in a university-year. Thus, the predictions regarding a positive effect of relational embeddedness in joint publishing outcomes would be more reliable. Nonetheless, there are reasons to suspect that the dataset would not be able to evaluate with precision the variables effecting joint patenting, a fact that would jeopardize the empirical conclusion, but not the theoretical foundation of the proposition, suggesting that this matter should be tested in a different way or with another dataset.

About the predictions expecting a negative effect of relational embeddedness on outcomes with exploratory nature and a negative effect of knowledge similarity on these types of outcomes, the results were also not supported in the way they were predicted. However, different reasons would be jeopardizing such results.

Some supplemental models were run to test the effects of relational embeddedness in the joint outcomes of exploitation type instead of exploration type. The same concept used to create the variable regarding exploratory joint outcomes was inverted to build a variable regarding exploitation outcomes, i.e. if the joint outcome did not fit on the classification used for exploration, it was considered as exploitation. The results achieved by these alternate models, one testing the effect of relational embeddedness on joint patents of exploitation type and other testing the effect of relational embeddedness on joint scientific publications of exploitation type showed a significant and positive effect for both cases ($\beta=0.0018$; $p<0.001$; and $\beta=0.0446$; $p<0.001$, respectively). Such result would suggest that relational embeddedness would have a very similar effect in exploration and in exploitation, which would be theoretically unfeasible. Thus, there should be an endogenous variable affecting these relationships - and, in fact, there is.

By observing the description of the R&D projects presented in Table 1, it is possible to note that such projects have very different scopes. For instance, the R&D project Petrobras carried out with UFRJ seems to be closely related to its core business, whereas the R&D project carried out with PUC seems to be distant from the oil and gas field. This evidence suggests that the scope of the R&D project would have a relevant impact on the outcome generated in those collaborations, a matter that was not addressed by the dataset used. Hence, there is a possibility that Petrobras is avoiding embedded relationships when they want to explore areas of knowledge outside its specialization, causing an omitted variable bias issue in the tests carried out. As a result, in order to properly test the predictions proposed in this study, it would be necessary to obtain more fine grained data about the scope of each project and develop a way to classify them into exploration and exploitation purposes. Note that the description of the R&D projects is frequently dubious or contains technical terms that make it difficult to interpret the actual scope of the project (for instance, see the description of the project carried out with USP in Table 1). Consequently, such analysis was outside the scope of this study, as it would require access to sufficient information to classify the projects into those categories in a reliable way, and such information was not available.

Regarding the analysis predicting a negative effect of knowledge similarity on the joint outcomes of the collaboration, the results were also not supported by the data, as the coefficient was positive and significant for joint exploratory patents and not significant for joint scientific publications. Thus, a supplemental test was made by using the dependent variables for exploitation outcomes, in the same terms used to evaluate the effect of relational embeddedness. Nevertheless, these supplemental tests did not achieve a significant coefficient predicting joint exploratory patens or joint exploratory publications.

Therefore, it is important to stress that there are no well established ways to measure exploration and exploitation characteristics of patents and scientific publications. Thus, the criteria adopted to do the analysis, although reasonable and robust, may not be adequate to test the propositions and could be misleading the results accomplished. Hence, although the theoretical ground for the proposition was consistent, there was little support on the empirical tests. It is worth mentioning, however, that the effect of technological similarity seemed to have an inverted U shaped effect in exploratory patents, as the effect of the independent variable was positive and the effect of the independent variable squared was negative. Such result would suggest that there is an optimal level of technological similarity for the production of joint patents of exploratory nature. Therefore, when the technological similarity level is low to medium, this would make the partners profit from having a common ground to start exchanging resources and knowledge, but without limiting their ability to explore other areas, as they would also have a significant amount of non-similar resources. Nevertheless, when technological similarity is medium to high, the intense overlap of existing knowledge and resources would be limiting the ability of partners to think outside the box and develop new knowledge resources in areas away from pre-existing knowledge, as they would not have much to exchange outside the common domains, which was the effect predicted in the hypothesis proposed. Still, it is important to have in mind the limitations of the dataset regarding joint patent outcomes when interpreting the reliability of these results.

Finally, it is worth mentioning that the results of all supplemental analyses are presented in the annexes.

5.1 Theoretical implications

Existing literature demonstrates the benefits stemming from relational embeddedness between partnering organizations, such as facilitating the exchange of information about organizational competences and trustworthiness, enhancing mutual trust, and mitigating the risk of partnership dissolution, as well as favoring the formation of future alliances with the same organization. Also, the literature has emphasized that firm-university collaborations favor the creation of competitive advantage by enhancing a firm's innovative performance and its capacity to absorb external knowledge by tapping into knowledge resources available in the scientific community.

This study adds value to this knowledge by showing that relational embeddedness between two partners not only increases the chances that they will form an additional collaborative relationship, as prior research has demonstrated, but also that it leads to an escalation of resource commitment to the embedded relationships. Thus, it is expected that deeply embedded relationships would not only lead to more partnerships executed by also to a higher financial resource commitment by the firm.

Interestingly, though, such escalation of commitment would not be necessarily in line with facilitating all joint outcomes perceived from those partnerships. This occurs because relational embeddedness in firm-university collaboration could have different effects on the types of outcomes obtained from the partnerships, since conflicting logics, social inertia, increasing familiarity and legal requisites for authorship impact different collaboration outcomes differently. Therefore, this study suggested that relational embeddedness would increase the issuance of publications co-authored by the firm and the university while reduce the creation of joint patents, although such insight was only partially observed in the empirical setting.

Although this study was not successful in showing empirically that relational embeddedness would lead to a reduction in the exploratory outcomes that could arise from firm-university partnerships, it has brought some interesting insights about how such proposition should be operationalized in order to be properly tested in future research, besides bringing the theoretical foundation to the existence of such effect. The same could be said about the effects of knowledge similarity in the exploratory outcomes that could happen in firm-university partnerships.

If all predictions made in this study are true, then relational embeddedness in firm-university partnerships would generate asymmetric rewards to each partnering organization. Over time, as a firm repeatedly collaborates with the same group of universities, a focus on joint scientific production would supersede a focus on joint technological production. The decrease in the number of joint patents, though, would not necessarily mean that the firm is in no way benefiting from repeated collaborations to gain access to external knowledge that supports its innovative efforts, as the firm would still be reaping those rewards in inventions that are exclusively created by its own researchers without the participation of university-based researchers. In addition to that, the social, technological and scientific aspects that influence such projects' results would negatively impact the exploration of new knowledge as such aspects would make partners concentrate their inventive efforts into innovations that are not too distant from already possessed knowledge. This matter could harm the firm's ability to conduct research and innovate in different fields, compromising the effectiveness of the R&D investments, which would be especially dangerous in a scenario that a disruptive innovation is taking place in the market. Consequently, there would be a trade-off between having R&D partnerships with deeply embedded universities, as the social aspect would provide some benefits, but at expense of other effects that could be undesirable in the knowledge generation.

A final contribution of this study is to open doors to future research in the field, as such study has addressed many relevant and intriguing issues of firm-university collaboration and knowledge generation that lead to significant insights that could be explored, as will be described in the future research section.

5.2 Public policy and business policy implications

This study brings interesting potential implications for public policy. As firms and universities could be benefiting asymmetrically from those collaborations when related to joint patent outputs, there could be a negative implication to universities that share specific interest in the production of technology. To the extent that private firms manage to insulate their inventive efforts from the relationships that occur during the course of collaboration with external university affiliated researchers, they may succeed in drawing on otherwise public knowledge to privately reap the benefits embodied in inventions. Hence, public policies encouraging the use of private funds to support university research could thus result in an asymmetry between universities and private partners in their abilities to secure intellectual property rights over the outputs of their innovation activities.

Nonetheless, it is very important to have in mind that these collaborations supply universities with resources that would not be available otherwise. These resources refer not only to the funds that private firms allocate to collaborative projects with universities, but also to access to real-world problems that firms face, as well as to their facilities. The access to these resources may provide setting to university-based scientists test their ideas, thus facilitating the process of scientific discovery. Therefore, would be important to evaluate all benefits that universities have when entering in firm-universities collaborations and not focus only on the joint patent outcome that such partnership would lead.

Another relevant matter for public policies would be that repeated collaborations between private firms and universities, although they may facilitate scientific publications as this study shows, could be shaping the areas that university-based scientists emphasize in their research projects. At the same time that cohesive ties in those collaborations may result in a focus on publishing superseding a focus on patenting, it is possible that it may also lead university researchers to pay greater attention to the technological problems faced by the partnering firms in detriment of other research programs that, although less immediate, might have a stronger impact on the scientific community at large, or could be of national interest. This possibility of scientific capture through repeated interactions with private partners is but a conjecture, but one worthy of future investigations due to its relevance in public policy elaboration.

Moreover, this study also alerts managers in firms seeking collaborations with universities the necessity to balance the conflicting logics underlying these collaborations, as the balance between technology and scientific production may eventually tilt toward the latter. Hence, when forming these alliances, firms should focus on their specific needs and be prepared to absorb external knowledge to complement their own to develop new solutions to their problems. Also, how the benefits of the innovations are going to be shared, from a legal perspective, should be addressed carefully in these collaborations, especially because this subject has been thoroughly discussed in the public audiences of forthcoming regulation about R&D investments in the Brazilian oil and gas sector[6].

5.3 Limitations and opportunities for future research

The main limitation of this study is that it encompasses data from only one firm. On the other hand, an important merit of the setting used was the possibility to access fine-grained data about firm-university collaborations. Although the focal company is a large player in the oil and gas industry, the opportunity remains for future research to investigate firm-university collaborations in other settings, thereby enhancing the generalization of the findings.

Also, the findings hinge on the accuracy of the data used in the analysis. As explained before, the data used for this study was obtained through a Freedom of Information Act request and regard all R&D projects that Petrobras conduced with universities that were reported to the sector's regulator. In order to confirm the accuracy of the data, a meeting was held with the Petrobras' manager of relationships with the academic community in March, 2015, and he stated that such list would encompass all R&D projects carried out in collaboration with universities and research institutes, but not all R&D projects carried out by Petrobras, since this list obviously does not encompass internal R&D projects or other collaborative projects with competitors, suppliers, and other firms that they were not obliged to report to the regulator. This further enhances confidence that the data used indeed reflect all collaborations between the focal company and universities thereby dispelling concerns that such data might be incomplete or somehow biased.

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[6] ANP. Minutes from the public audience held in Feb 2015 discussing the new rules about the R&D investment clause. Retrieved from:
<http://www.anp.gov.br/?pg=75865&m=&t1=&t2=&t3=&t4=&ar=&ps=&1435517444293>.

Additionally, due to lack of available information, it was not possible to classify the R&D projects carried out by Petrobras and the partner universities into exploration and exploitation categories. Thus, a potential concern of endogeneity remains as Petrobras could be intentionally avoiding embedded relationships when seeking to develop knowledge in areas which it does not have expertise. So, it would be necessary to control for this matter to address such endogeneity concern. Therefore, future research could build on this issue and obtain more fine-grained data about those projects and, by classifying them into exploratory and exploitation, it would be possible to evaluate if the firm is selecting specific types of partners when developing different types of knowledge resources. Such possibility is intriguing and could very well lead to an important contribution to the theory.

Moreover, the ways used to classify the patents and scientific publication into exploration and exploitation categories could be harming the results achieved in the statistical tests. However, there are no well established ways to classify patents and scientific publications into those categories. Hence, a concern remains if the methodology used compromised the results obtained in the empirical tests regarding this subject, which could be address by future studies by the development of a different way the classify patents and academic publications in the referred categories. If such deed is achieved, it would represent a potential contribution to research method as well as to theory.

This study presented a broad concept of geographical collocation of the firm and the universities. However, future research could put more emphasis on the geographical collocation of the firms' branches and universities and their interaction with the areas in which knowledge is being generated, such as technological hubs. There are many studies pointing out the relevance of geographical proximity in the occurrence of partnerships and knowledge generation. Expanding this analysis to a more detailed approach on geographical collocation could bring valuable insights to the theory.

Another interesting point to expand the analysis would be to evaluate the strategic changes that Petrobras carried out during the years, as many significant events, such as the discovery of pre-salt oil, should have caused a shift in the R&D strategy of the firm. Analyzing the impact of those shifts in the types of outcomes produced and the partnerships made would provide some interesting insights about firm behavior.

A further promising avenue for future research would be to contrast the joint benefits that a firm accrues due to its partnering with universities with the benefits that each collaborating party privately obtains in the partnership. By comparing these benefits it should be possible to observe in which conditions each party would benefit more than the other from the partnership, which would have some relevant practical implications.

Besides building on the limitations of this study, future research could explore how the network position of the firm and the university would be impacting the knowledge development of the firm. An interesting feature that could be explored in future research would be the use of measures for weak and strong ties and other measures of network distance and proximity. These elements are an important part of the network in which firms and universities are included and could lead to further theory development.

Shifting the analysis from the firm-university to the individual level, i.e., firms' and universities' scientists and inventors, could bring a novel perspective on the subject. Given the complexity of the relationships involved in knowledge generation, a more micro analysis carried out by future research could uncover new insights about the mechanisms underlying firm university collaboration.

In addition to that, shifting the focus of the analysis to the universities instead of the firms would represent a potential contribution to understand the dynamics of the relationships between firms and universities. For instance, future research could evaluate how universities compete for firm resources when firms are seeking partnerships. Also, the way universities interact with each other in knowledge resources development could bring many interesting issues for upcoming research, as the logics underlying university activity could impact many of the well known theories about organizational behavior and would be worth investigating.

6. CONCLUSION

Extant literature highlighted the relevance of the social aspects involved in interorganizational cooperation as well as how collaborations between firms and universities are used by organizations to access resources outside their boundaries and improve their knowledge generation and absorption. Moreover, the literature has thoroughly investigated and discussed the benefits of relational embeddedness in facilitating collaboration between organizations. Also, prior studies have stressed that organizations need to balance their knowledge generation into exploration and exploitation activities in order to remain competitive in the long run, and have investigated the role of interorganizational alliances in the exploration of other knowledge domains.

This study advances existing knowledge about the benefits that firms derive from firm-university collaboration by examining the outcomes of these collaborations that are jointly attained by the partners. Such examination was based on fine-grained data about all collaborative R&D projects carried out by Petrobras and Brazilian universities in the Brazilian oil and gas sector, as well as their patent production and their scientific publication.

In contrast with existing literature, this study defended that repeated collaborations with old partners may shift the focus of the collaboration to generate more joint scientific publication at expense of less inventive outputs. Additionally, this study proposed that social pressures and knowledge similarity would favor the exploitation of pre-existing knowledge instead of the exploration of novel domains in deeply embedded collaborations, which would be a relevant matter, as firms usually engage in external collaborations with universities when they seek knowledge outside their own domains. But, the study was not able to demonstrate these propositions empirically due to limitations in the available data.

Nevertheless, this study was able to demonstrate empirically that relational embeddedness positively affects the level financial resources committed to projects carried out with deeply embedded universities, showing that the more embedded is the relationships between a firm and a university, more financial resources will be invested in future collaborative projects with such institution. Several robustness tests confirmed the reliability of such finding.

Moreover, the empirical tests showed that relational embeddedness would increase the number of joint scientific publications as outcomes of these collaborations. This would provide partial support to the predictions made about the effect of relational embeddedness in the types of joint outcomes achieved in firm-university collaboration, suggesting a potential shift in the balance of the firm-university collaboration towards joint scientific publication.

As a result, this study brings new insights about the conflicting logics between technology and science that surround firm-university collaborations and the way each partner profit from it, which have significant theoretical and practical implications. Another significant contribution of this study was the revelation of many intriguing issues and possibilities that could be further explored by future research in the field.

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8. ANNEXES

8.1 Models used for hypothesis testing with control variables only

Models used for hypothesis testing with control variables only

	Model 1			Model 2		
	Coef.		S.E.	Coef.		S.E.
Controls						
R&D projects expenditure				0.0026		(0.0017)
Technological similarity	-1.4434	†	(0.7563)	0.0630		(0.0670)
Scientific similarity	6.1586	•	(2.4560)	0.0228		(0.2067)
University patents	0.0294	†	(0.0166)	-0.0018		(0.0013)
University scientific publications	0.0009	••	(0.0003)	0.0001	•••	(0.0000)
Petrobras' patents	0.0083	†	(0.0044)	-0.0003		(0.0004)
Petrobras' scientific publications	0.0020		(0.0021)	0.0005		(0.0002)
Petrobras' net income	0.0001	•••	(0.0000)	0.0000		(0.0000)
Geographic collocation	1.7820	•	(0.7033)	0.0745	•	(0.0340)
Public/private university	3.0315	•••	(0.4463)	0.0113		(0.0220)
Number of faculty	0.0004	†	(0.0002)	0.0001	•••	(0.0000)
Constant	-1.4232	•	(0.5613)	-0.0508		(0.0433)

† $p < 0.10$; • $p < 0.05$; •• $p < 0.01$; ••• $p < 0.001$; standard errors in parentheses; two-tailed test for all variables.

Models used for hypothesis testing with control variables only

	Model 3			Model 4a		
	Coef.		S.E.	Coef.		S.E.
Controls						
R&D projects expenditure	0.0293	•••	(0.0082)	0.0017		(0.0011)
Technological similarity	0.0797		(0.2871)	0.1459	••	(0.0460)
Scientific similarity	-0.0880		(0.9476)	-0.0049		(0.1370)
University patents	0.0047		(0.0066)	0.0003		(0.0008)
University scientific publications	0.0012	•••	(0.0001)	0.0000		(0.0000)
Petrobras' patents	-0.0024		(0.0017)	0.0000		(0.0003)
Petrobras' scientific publications	0.0014	†	(0.0008)	-0.0001		(0.0001)
Petrobras' net income	0.0000		(0.0000)	0.0000	•	(0.0000)
Geographic collocation	2.0820	•••	(0.4561)	0.0425	•	(0.0187)
Public/private university	0.4220		(0.2885)	0.0082		(0.0122)
Number of faculty	0.0001		(0.0001)	0.0000	••	(0.0000)
Constant	-0.3335		(0.2795)	-0.0367		(0.0290)

† $p < 0.10$; • $p < 0.05$; •• $p < 0.01$; ••• $p < 0.001$; standard errors in parentheses; two-tailed test for all variables.

Models used for hypothesis testing with control variables only

	Model 4b			Model 5a		
	Coef.		S.E.	Coef.		S.E.
Controls						
R&D projects expenditure	0.0132	••	(0.0046)	0.0018	†	(0.0011)
Technological similarity	0.0293		(0.1606)			
Scientific similarity	0.0460		(0.5290)	0.0162		(0.1372)
University patents	-0.0054		(0.0037)	0.0004		(0.0008)
University scientific publications	0.0008	•••	(0.0001)	0.0000		(0.0000)
Petrobras' patents	-0.0011		(0.0009)	0.0000		(0.0003)
Petrobras' scientific publications	0.0006		(0.0005)	-0.0001		(0.0001)
Petrobras' net income	0.0000		(0.0000)	0.0000	•	(0.0000)
Geographic collocation	1.1142	•••	(0.2305)	0.0422	•	(0.0188)
Public/private university	0.1727		(0.1460)	0.0093		(0.0122)
Number of faculty	0.0001	•	(0.0000)	0.0000	••	(0.0000)
Constant	-0.1987		(0.1472)	-0.0372		(0.0291)

† $p < 0.10$; • $p < 0.05$; •• $p < 0.01$; ••• $p < 0.001$; standard errors in parentheses; two-tailed test for all variables.

Models used for hypothesis testing with control variables only

	Model 5b		
	Coef.		S.E.
Controls			
R&D projects expenditure	0.0132	••	(0.0046)
Technological similarity	0.0300		(0.1604)
Scientific similarity			
University patents	-0.0054		(0.0037)
University scientific publications	0.0008	•••	(0.0001)
Petrobras' patents	-0.0011		(0.0009)
Petrobras' scientific publications	0.0006		(0.0005)
Petrobras' net income	0.0000		(0.0000)
Geographic collocation	1.1142	•••	(0.2302)
Public/private university	0.1728		(0.1458)
Number of faculty	0.0001	•	(0.0000)
Constant	-0.1984		(0.1470)

† $p < 0.10$; • $p < 0.05$; •• $p < 0.01$; ••• $p < 0.001$; standard errors in parentheses; two-tailed test for all variables.

8.2 Supplemental analyses

Exploring alternative explanations for H4a and H4b

	Model 4a (2) Exploitation Patents			Model 4b (2) Exploitation Publications		
	Coef.		S.E.	Coef.		S.E.
Relational embeddedness	0.0018	•••	0.0001	0.0446	•••	0.0013
Controls						
Technological similarity	-0.0147		0.0141	0.1200		0.2001
Scientific similarity	-0.0321		0.0377	0.2556		0.6048
R&D projects expenditure	-0.0015	•••	0.0003	-0.0082	†	0.0050
University patents	-0.0010	•••	0.0002	0.0126	••	0.0037
University scientific publications	0.0000		0.0000	-0.0001		0.0001
Petrobras' patents	0.0000		0.0001	-0.0012		0.0012
Petrobras' scientific publications	0.0000		0.0000	0.0008		0.0006
Petrobras' net income	0.0000		0.0000	0.0000		0.0000
Geographic collocation	-0.0038		0.0039	0.1863	•	0.0908
Public/private university	0.0003		0.0025	0.0764		0.0573
Number of faculty	0.0000	†	0.0000	0.0001		0.0000
Constant	-0.0010		0.0088	-0.0629		0.1274

† $p < 0.10$; • $p < 0.05$; •• $p < 0.01$; ••• $p < 0.001$; standard errors in parentheses; two-tailed test for all variables.

Exploring alternative explanations for H5a

	Model 5a (3) Exploitation Patents			Model 5a (4) Exploitation Patents		
	Coef.		S.E.	Coef.		S.E.
Technological similarity	-0.0083		(0.0155)	-0.0384		(0.0435)
Technological similarity squared				0.0375		(0.0507)
Controls						
Scientific similarity	-0.0272		(0.0478)	-0.0267		(0.0478)
R&D projects expenditure	0.0003		(0.0004)	0.0003		(0.0004)
University patents	-0.0011	•••	(0.0003)	-0.0011	•••	(0.0003)
University scientific publications	0.0000	•	(0.0000)	0.0000	•	(0.0000)
Petrobras' patents	-0.0001		(0.0001)	-0.0001		(0.0001)
Petrobras' scientific publications	0.0000		(0.0000)	0.0000		(0.0000)
Petrobras' net income	0.0000		(0.0000)	0.0000		(0.0000)
Geographic collocation	0.0224	••	(0.0078)	0.0225	••	(0.0078)
Public/private university	-0.0002		(0.0051)	-0.0001		(0.0051)
Number of faculty	0.0000	•••	(0.0000)	0.0000	•••	(0.0000)
Constant	-0.0124		(0.0100)	-0.0123		(0.0100)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.

Exploring alternative explanations for H5b

	Model 5b (3) Exploitation Publications			Model 5b (4) Exploitation Publications		
	Coef.		S.E.	Coef.		S.E.
Scientific similarity	-0.0173		(0.6527)	0.7879		(1.2360)
Scientific similarity squared				-2.6584		(3.4635)
Controls						
Technological similarity	0.0678		(0.1992)	0.0619		(0.1994)
R&D projects expenditure	0.0181	••	(0.0056)	0.0177	••	(0.0056)
University patents	0.0120	••	(0.0045)	0.0118	••	(0.0045)
University scientific publications	0.0003	•••	(0.0001)	0.0003	•••	(0.0001)
Petrobras' patents	-0.0014		(0.0012)	-0.0014		(0.0012)
Petrobras' scientific publications	0.0008		(0.0006)	0.0008		(0.0006)
Petrobras' net income	0.0000		(0.0000)	0.0000		(0.0000)
Geographic collocation	0.9508	•••	(0.2307)	0.9484	•••	(0.2310)
Public/private university	0.2166	•	(0.1466)	0.2126		(0.1469)
Number of faculty	0.0001		(0.0001)	0.0001		(0.0001)
Constant	-0.1648		(0.1634)	-0.1633		(0.1635)

† p< 0.10; • p< 0.05; •• p< 0.01; ••• p< 0.001; standard errors in parentheses; two-tailed test for all variables.