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Does Timing of R&D Collaborations Explains the heterogeneity of their outcomes?

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Abstract

In this paper, we investigate how firms should organize for collaboration with market-based and technology-based partners in R&D projects and how this affects projects? innovation outcome. We draw on a unique panel dataset (2002-2009) that contains data on R&D collaboration practices and project performance of 867 R&D projects of a large Global-100 manufacturing firm. We hypothesize that the way a project team organizes the timing of its R&D collaboration activities affects the performance of R&D projects. The following four dimensions of collaboration timing are examined: collaboration duration, collaboration continuity, collaboration simultaneity, and collaboration pattern. We further differentiate between market-based and technology-based partners and examine how R&D projects should organize for both types of R&D collaborations. Our results show that it is optimal for R&D projects to limit collaboration with a specific type of partner. Furthermore, collaboration needs some time to be effective, but it also cannot last too long. Next, we find that collaboration continuity plays a positive and significant role on projects? innovation performance, while collaboration simultaneity has negative effect. Moreover, it is found that collaboration with technology-based partners at the later period of the project life time is counterproductive to project innovation performance, and the project may be better off if conducting collaborations in its earliest phase.

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Abstract

There is an ever increasing trend of inter-organizational collaboration in R&D activities. While most inter-organizational R&D partnerships relate to specific R&D projects, the extant studies have been mostly analyzed R&D collaboration at the firm, not at the R&D project level. In this paper, we investigate how firms should organize for collaboration with market-based and technology-based partners in R&D projects and how this affects projects' innovation outcome. We draw on a unique panel dataset (2002-2009) that contains data on R&D collaboration practices and project performance of 867 R&D projects of a large Global-100 manufacturing firm. We hypothesize that the way a project team organizes the timing of its R&D collaboration activities affects the performance of R&D projects. The following four dimensions of collaboration timing are examined: collaboration duration, collaboration continuity, collaboration simultaneity, and collaboration pattern. We further differentiate between market-based and technology-based partners and examine how R&D projects should organize for both types of R&D collaborations. Our results show that it is optimal for R&D projects to limit collaboration with a specific type of partner. Furthermore, collaboration needs some time to be effective, but it also cannot last too long. Next, we find that collaboration continuity plays a positive and significant role on projects' innovation performance, while collaboration simultaneity has negative effect. Moreover, it is found that collaboration with technology-based partners at the later period of the project life time is counterproductive to project innovation performance, and the project may be better off if conducting collaborations (with both types of partners) in its earliest phase.

Keywords: Innovation performance, organizing R&D collaborations, timing

Introduction

Nowadays, firms' success increasingly hinges on their ability to create and share knowledge effectively and efficiently (Kogut and Zander, 1992). Due to resource limitations and fast-paced technology developments, many firms team up with partners in their R&D activities in order to improve innovation performance (Chiaroni et al., 2011; Hagedoorn et al., 2000). A number of scholars enumerate the benefits of R&D collaboration, as it helps the firm to access complementary resources, to share risks and costs, to create synergetic effects, and to respond quickly to a dynamic environment (e.g.: Shan et al., 1994; Powell et al., 1996; Gulati, 1995; Hagedoorn and Schakenraad, 1994). Yet despite these benefits, it is commonly observed that many firms face serious challenges in achieving success in their R&D collaboration activities (Lokshin et al., 2011). There is a lot of heterogeneity among firms with respect to their collaboration outcomes (Hopkins et al., 2011) — some firms are quite successful in their collaboration activities (Huston and Sakkab, 2007; Kirschbaum, 2005; Van der Meer, 2007), but others suffer from striking failures (Sivadas and Dwyer, 2000).

This performance heterogeneity among firms' R&D collaboration activities has been explained in different ways. Several authors studied collaboration partners, emphasizing the type and capabilities of the partner, collaboration portfolio, and partner selection play a decisive roles in R&D collaboration outcomes (Carayol, 2003; Laursen and Salter, 2006; Hopkins et al., 2010; Baum et al., 2000; Faems et al., 2005; Bianchi et al., 2011); other scholars investigate the relation between the focal firm and its partners, pointing out that the way to establish and to optimize the links between them affect collaboration results (Sofka and Grimpe, 2010; Caloghirou et al., 2004; Lorange and Roos, 1991; Das and Teng, 1998); still some scholars explore the characteristics of the focal firm, arguing that firm size, industry, experience, corporate strategy, capability, or innovation policy (e.g.: Van de Vrande, 2008; Tsai, 2009;

Bargegil, 2011; Asakawa et al., 2010) are important factors lead to success or failure in R&D collaboration activities. Although our understanding of the factors that lead to successful R&D collaborations has been greatly advanced during the past decades (e.g.: Hagedoorn, 1993; Powell et al., 1996), interestingly, as it is pointed out, the success rate of R&D collaborations has been stagnated over the years (Lhuillery and Pfister, 2009).

Success in R&D collaboration is not well understood because most inter-organizational R&D partnerships relate to specific R&D projects, while the majority of the extant studies have been mainly analyzing R&D collaboration at the firm, not at the R&D project level. This situation stands in sharp contrast to the real fact that R&D collaborations are activities essentially conducted in R&D projects (Pisano, 1990; Cassiman et al., 2009), each with specific resource endowments, resource demands, and may adopt a particular way of resource management. As a consequence, a number of aspects on how R&D collaborations are organized at the level of individual projects have not been examined, leaving much unsolved space for the heterogeneity in R&D collaboration outcomes.

This paper develops and tests resource-based view and resource management hypotheses for R&D collaborations at the project level. While there are many potential sources of resource and resource management for R&D projects in conducting R&D collaborations (e.g.: personnel, budget, etc.), this analysis focuses particularly on the timing of organizing R&D collaborations. More specifically, we look at the following four elements in the timing of R&D collaborations: (1) collaboration duration, (2) collaboration continuity, (3) collaboration simultaneity, and (4) collaboration pattern.

The timing of resource management plays a vital role in the resource based view of the firm. Time itself is a type of rare and valuable resource. Therefore, the capability to arrange activities and marshal resources based on the optimal timing may distinguish winners and followers, even if they are equipped with exactly the same resources. However, according to our knowledge, there is no study investigating the timing in R&D collaboration activities, especially not at the project level. Whether the timing of R&D collaboration activities also influences innovation outcomes of R&D projects is a question that remains to be answered. This question is important, as it may explain the heterogeneity of R&D collaboration outcomes of firms (and the R&D projects therein), and it also sheds new lights on the RBV and extends its application to the project level.

To examine the effect of the timing of R&D collaborations, we employ a unique dataset (2002-2009) that has annual information on the R&D collaboration practices and innovation performance of 876 research projects from a leading multi-divisional, multi-national Global 100 manufacturing company with an annual R&D budget of more than 2 billion euros. We further distinguish between two types of R&D collaboration partners—market-based partners (suppliers and customers) and technology-based partners (universities and knowledge institutes)— as each of them provides a particular type of knowledge in the collaboration process (e.g.: Deeds and Rothaermel, 1999; Faems et al., 2005). The results show that firms can indeed improve their innovation performance of R&D projects by optimizing the timing of their R&D collaboration activities. We find that *collaboration continuity*, denoting the collaborations are carried out continuously instead of in a piecewise manner, increases the success of R&D projects, while *collaboration simultaneity*, as represented by simultaneous collaborations with different types of partners all at the same time, decreases collaboration success. Next, we find that there is an optimal level of *collaboration duration* with a specific type of partner: collaboration needs some time to be effective, but it also cannot last too long. However, if we lump together both market-based partners and technology-based partners, we find that a project can be open during its entire life cycle. As for *collaboration pattern*, research projects may be better off if collaboration is conducted during the earlier period in their life cycle. More specifically, we find a strong negative effect of collaborating with technology-based partners in the later period of a project life cycle, which suggests the collaboration with technology-based partners should be arranged early in the process. In sum, the timing of R&D collaboration activities in R&D projects plays an important role in explaining R&D projects, and ultimately firms', technological success.

The remainder of the paper is organized as follows: we first provide the conceptual background of this paper. Next, we introduce our hypotheses about the different ways in which the timing of R&D collaboration activities impacts on project performance. The third section describes the data and presents the empirical findings. Finally, we discuss our results and provide suggestions for future research.

Conceptual Background and Hypotheses Development

A generally accepted theory for theorizing on the role of R&D collaboration in firms' innovation activities is the resource-based view (RBV), which is one of the most influential strategic management theories on the origins of firms' competitive advantage (Hoopes et al, 2003). The resource-based view proposes that organizations can achieve a competitive advantage by building up portfolios of valuable resources, which are rare, imperfectly tradable and hard to imitate. Firms have a mix of resources available, and the performance differences across organizations result from variances in resource portfolios and how those resources are used and arranged (Penrose, 1959; Wernerfelt, 1984; Barney, 1991; Peteraf, 1993). Through R&D collaborations, firms get access to resources of their R&D partners. As a consequence, competitive edges of organizations do not only result from the possession of own resources, but also increasingly from the way how the organizations interact with, and use resources from, their partners in R&D activities. Even when two companies may have access to the same external resources, differences in the way they manage and arrange these resources can lead to substantial differences in their innovation performance.

R&D collaborations are activities that essentially take place at the level of R&D projects, with interactions between the research teams within the focal firm and its partners. These teams interact with each other during the collaboration process, resulting in resource (in particular knowledge) transfers and accumulations (Hagedoorn, 1993; Powell et al., 1996). Therefore, organizing R&D collaboration in R&D projects is essentially an issue of organizing resources and interactions among collaborating partners.

In R&D collaborations, resource management is an important capability. How a firm organizes and manages the exchange of resources in R&D collaborations can be a difficult to imitate capability, and therefore, it can be the source of a competitive advantage (Zahay et al., 2004). The resource-based theory of the firm suggests that management capabilities relating to resource adoption and use are important drivers of firm success (Verona, 1999). Interestingly, while this concept is accepted for resources and their use in general, it is not known how firms organize for resource exchanges with partners at the micro-level (i.e. R&D projects). The purpose of this research is to improve our understanding of how the organization of R&D collaborations at the project level has an impact on the success of R&D projects and the overall performance of the firm. More specifically, we focus on the following four elements of the timing of R&D collaborations in a R&D project: collaboration duration, collaboration continuity, collaboration simultaneity, and collaboration pattern.

Collaboration Duration

R&D collaboration is an interaction process among partners. During the interaction process, the focal firm (and its R&D projects therein) both commits resources to, and receives resources from, its partners (Dyer and Singh, 1998; Madhok and Tallman, 1998). In order to establish and develop R&D relationships, each partner has to commit a certain level of resources— such as managerial attention (Cyert and March, 1963), personnel (Dodgson, 1993) and budget (Todeva and Knoke, 2005)— along the collaboration process. However, projects are at the same time constrained by the resources they can marshal, as they have a defined deadline, limited budget and personnel (Cleland & Kerzner, 1985; Pinto and Prescott, 1988). Consequently, the commitment and access to resources has to be well planned. Successful R&D collaborations are the ones which manage to access complementary resources in need (Hagedoorn, 1993), while still keep the costs and risks at a minimum level (Madhok and Tallman, 1998). In other words, *collaboration duration* may affect projects collaboration outcomes.

Successful R&D collaboration needs time. First, successful R&D collaboration requires trust among partners. Trust-building (more specifically, trust-building in the research team) is a time-consuming process. Prior studies show that higher levels of trust are associated with lower transaction costs and opportunistic behavior (Das and Teng, 1998; Gulati, 1995), which smoothens collaboration barriers (Hagedoorn et al., 2000), increases the efficiency of inter-organizational relationships (McEvily, Perrone, and Zaheer, 2003), and facilitates tacit knowledge transfers (Das and Teng, 1998). In the context of R&D projects, trust is not only inter-organizational, but also inter-personal (Abrams et al., 2003). As it is stated "… interpersonal trust is a central characteristic of relationships that promote effective knowledge creation and sharing in networks" (Abrams, Lesser and Levin, 2003, p.65). However, trust is not a commodity which can be obtained through market transactions, nor can it be developed overnight (Gulati, 1995). Instead, it calls for considerable time and resources to build up and maintained among partners (Ireland et al., 2002; Dyer and Singh, 1998) and the team members therein (Abrams et al., 2003). Thus, successful R&D collaboration needs some time to ensure trust building among partners. Second, it can be time-consuming to create relational rents in R&D collaborations. As partners become familiar with each other, they may invest additional resources in strengthening and developing their collaboration ties in the R&D project. Adopting the resource-based view, specific investments in a partnership relation create "relational advantage" (Dyer and Singh, 1998) and "social capital" (Coleman, 1988), which help the project team to generate additional advantage and relational rents because the idiosyncratic exchange relationship is rare and difficult to imitate (Penrose, 1959; Dyer and Singh, 1998). Relational rents require firms to invest in idiosyncratic assets, which takes time and is a gradual process influenced by mutual trust (Dyer and Singh, 1998). Hence, R&D collaboration can be a time-consuming process. A third aspect of the time-consuming face of R&D collaboration relates to "time compression diseconomies", which suggests that the quicker an organization develops the resource, the less effective it might be (Dierickx and Cool, 1989). Maintaining R&D activity over a particular time interval produces a larger increment to the stock of R&D know-how than maintaining twice this rate of R&D activity over half of the time interval. For example, MBA students may not accumulate the same stock of knowledge in a one-year "crash" program as in a two-year program, even if all inputs other than time are doubled (Dierickx and Cool, 1989). In terms of R&D collaboration, firms may have to wait to reap the full benefits from the collaboration (Garcia-Canal et al., 2002), and may not realize the benefits of collaboration within a limited period of time.

Despite the aforementioned benefits, however, it may also not pay off to collaborate for too long: the marginal gains of extending the collaboration period may diminish after some point of time, while the possible disadvantages of long collaborations (such as unintended knowledge spillovers and managerial complexities) may increase during further interactions with partners. Some prior studies point out that the relationship between collaboration and new product development might be characterized by diminishing marginal returns (Deeds and Hill, 1996). Early collaboration experience allows for significant learning, which may, however, diminish in further collaboration (Hoang and Rothaermel, 2005). Empirical research has documented that learning does indeed taper off, and in fact, does so fairly rapidly (Lieberman, 1984;Darr, Argote, and Epple, 1995). Besides the diminishing marginal returns in R&D collaborations, projects may also suffer, at a certain point, limitations in capacities to further absorb external knowledge. Constrained by cognitive limitations (Katz and Kahn, 1978) , the research project team may only efficiently deal with a certain amount of resources (Schilling and Hill, 1998) in its life cycle. Therefore, the additional information which is accumulated over the collaboration period may cause an information overload problem (Eppler and Mengis, 2004) or bring "noise" which may negatively influence its decisions and main innovative activities (Grabher, 2002). As Argyris (1976) pointed out, collaboration needs some specialization and could be hampered by an excess of information. Therefore, it may not be desirable to stay in collaboration throughout the project's whole life time, instead, the project may need a certain closed period to keep focused and to better digest the knowledge it absorbed. Furthermore, as the environment is continuously changing, the goals and interests of partners may also evolve over time. It can bring particular challenges for the project team to align different goals and interests of partners along the collaboration phase, failing in doing so may make the partnership vulnerable (Gulati, 1995). Additionally, the communication and coordination costs among partners can be tremendous (Malone, 1987; Becker and Murphy, 1992),bringing much complexity in managing relationships with external partners. As it is pointed out, in a fast changing environment, environmental evolution may force firms to reap the potential benefits of a collaboration from day one by accelerating collaboration development (Garcia-Canal et al., 2002).

Considering both the time-consuming and the time-efficiency face of R&D collaboration, the optimal collaboration time period should be long enough for tapping into the required external resources in need, but not too long in order to maximize the learning effect and reduce managerial complexities. Therefore, we hypothesize:

H1: There is an inverted U-shaped relation between collaboration duration and the innovation performance of R&D projects.

Collaboration Continuity

The successful "gains" of resources do not only depend on resource transfers, but also, and perhaps more importantly, on the absorption and learning capabilities of the focal organization (Cohen and Levinthal, 1990). Organization theories point out that, to ensure smooth knowledge transfers and absorption, a certain level of acquaintance among team members is needed (Katz and Allen, 1982; Brown and Eisenhardt, 1995). To create acquaintance among R&D collaboration partners, it is important to keep R&D interactions ongoing and strive for continuity in R&D interactions, since loose contacts may negatively influence knowledge exchange, particularly the transfer of tacit knowledge. Learning theories, on the other hand, contend that learning is not necessarily a constant process, but can be divided into several intervals, which, in turn, improves knowledge absorption and digestion (Duncan, 1949; Brown, 2008). In the context of R&D collaboration, discontinuous collaborations may also provide flexibilities in both learning and selecting the most desirable partner to interact with. In general, the choice between whether R&D collaborations should be organized in a continuous way, or in a piecewise manner, may affect the innovation performance of the R&D project. In this sense, *collaboration (dis)continuity* may be a second important element in collaboration timing for R&D collaboration outcomes.

There are several reasons to believe that projects would benefit from a continuous collaboration with external partners. First of all, it is costly to frequently renew or resume collaboration relationships in a R&D project. R&D collaboration is a complex process starting from partner-searching, partner engagement, relationship development, and finally to collaboration completion. Each activity requires a certain level of resource investment. In the partner-searching phase, due to information asymmetries (Aboody and Lev, 2000), it may take a considerable amount of time and resources to look for the right partner and to convince him/ her to establish a collaboration relation. Once the partner is selected and the collaboration starts, it again takes time for the project team members to get acquainted with each other before meaningful conversations take place (Katz and Allen, 1982; Brown and Eisenhardt, 1995). Even with the same partner, the collaboration needs to be resumed after some time without, or with little contact (Abrams et al., 2003). Thus, compared to continuous collaboration, it may be costly to renew, or resume, collaborations if there are several interruptions in the collaboration activities.

Second, it may be beneficial to have a consistent strategy for project development, thus switching frequently between an open and closed innovation status in the R&D project may not pay off. Prior studies find that organizations develop over time routines to execute certain operations effectively (Kelly and Amburgey, 1991), which are stored as procedural memory (Cohen and Bacdayan, 1994). Adjusting routines is a time-consuming process, and applying old routines in new context can be counter-productive (Kelly and Amburgey, 1991). In the context of R&D projects, closed (inward-looking) and open (outward-looking) innovation activities require different mindsets, behaviors, and organizational routines to be effective (Chiesa and Manzini, 1998). Managerial approaches that are better suitable for closed internal R&D activities may be detrimental for open collaborative R&D activities (Herzog and Leker, 2010). Consequently, routines and approaches that are applied successfully during the closed development period of a project may hamper innovation success if the R&D project switches to a collaborative mode (or vice versa). The situation may be aggravated if there are frequent switches between a closed and open innovation status, as the project may be slow in appropriately addressing and adapting to these changing situations. Therefore, we hypothesize:

H2a: Collaboration Continuity is beneficial for the innovation performance of R&D projects.

Despite the possible advantages of continuous collaboration in the R&D project, it may also be beneficial to organizing R&D collaborations in a piecewise way. R&D projects may benefit from discontinuities in R&D collaborations in terms of improved learning effects and reduced core knowledge leak-outs, moreover, they may enjoy higher levels of flexibility in selecting the most desirable partners along the process of project development. First, if viewing R&D collaboration as a learning process (Grant and Baden-Fuller, 2004), enjoying breaks in the collaboration process may improve learning and knowledge absorption. Just as students have breaks and holidays during a school year, having some intervals in the learning process may allow the R&D project sufficient time to digest knowledge absorbed from partners, which, in turn, improves its learning effect (Duncan, 1949; Brown, 2008). Second, discontinuous collaboration may reduce the chance of unwanted knowledge spillovers. Being continuously open in R&D projects also implies that there are continuous knowledge in- and out-flows in the R&D project during its collaboration period. External partners may be better able to tap into the knowledge base of the R&D project team when R&D collaborations and knowledge exchanges are organized continuously. In contrast, discontinuous collaborations, in which the collaboration period is cut into pieces which are not necessarily connected with each other, may prevent the R&D project from unwanted knowledge outflows. Moreover, the project may be more readily available to switch to a different partners according to its needs if collaborations are organized discontinuously, thus, avoiding being "locked-in" by the collaborating partners. Therefore, we hypothesize:

H2b: Collaboration Discontinuity is beneficial for the innovation performance of R&D projects.

Collaboration Simultaneity

Besides collaborating with a single type of partner, R&D collaboration is also a synergetic process mixing and recombining multiple types of resources (Cassiman and Veugelers, 2006). As different types of partners bringing diverse resources into the collaboration process (Ahuja, 2000; Baum et al., 2000), collaboration portfolios help to improve innovation performance (Faems et al., 2005). Prior studies show that market-based and/or technology-based partners are the most frequently involved types of partners in R&D collaborations (Deeds and Rothaermel, 1999; Faems et al., 2005), as successful innovation activities are grounded from the intertwinement of both market and technology knowledge (Tidd et al., 2000; Dougherty, 1992; Garcia and Calantone, 2002).

Simultaneous interactions among these resources may create synergetic effects, as different resources are allowed to possibly interact with each other, therefore increases the chance of novel knowledge re-combinations (Fleming and Singh, 2010). However, different types of resources may not be readily compatible, the managerial complexities may increase exponentially if they are all connected at the same time. In organizing the timing of collaborations in a collaboration portfolio, the R&D project can choose to simultaneously collaborate with different types of partners during (most of) its collaboration period, or it can organize the collaboration activities sequentially, thus mainly focus on one type of partner at one time. Since both of the approaches enable the project team access similar resources, it is a matter of questioning whether the arrangement of timing in accessing these resources affects collaboration outcomes. Hence, *collaboration simultaneity* may be the third dimension to look at when organizing timing in R&D collaboration activities.

Because innovation activities are path-dependent and follow an evolutionary trajectory (Nelson and Winter, 1982), the next step in the development process is always built on, and to a great extent influenced by, its previous steps. Adopting a "knowledge architecture" perspective[1] (Ulrich, 1995) in the collaboration process of R&D projects, a knowledge architecture is built up gradually and knowledge is added piece by piece. When collaborations are sequential, the chance of revising the previous parts is small (as the collaboration with the prior partner is already finished), and the newly added part can only be built on the existing knowledge architecture. The flexibility of trying new combinations is constrained if the cost of switching trajectories is prohibitively high. Moreover, sequential collaboration also implies that the R&D team is well aware of the knowledge architecture of the new product it is going to develop, and it can plan the optimal sequence of R&D collaborations in advance. This, however, can be challenging if the product under development is a novel endeavor. In fact, several scholars found that structured modularity in product development improves efficiencies but may be at the cost of hampering innovativeness (Sanchez and Mahoney, 1996; Lau et al., 2011). A number of well-known examples such as the "GlobalStar" project which was jointly developed by Loral Corporation and Qualcomm, and the "Iridium Satellite" project by Motorola, are noticeable examples in which a firm inappropriately engaged with different types of partners in sequence (see Business Week, 2000).

Compared to sequential collaboration, simultaneous collaboration improves communication and knowledge interaction not only between the partners and the focal firm, but also among those different types of partners themselves. As such, it enhances the possibility of coming up

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[1] Knowledge architecture is the arrangement of functional elements under the specification of the interfaces among interacting components (Ulrich, 1995, p. 420).

with something novel if different knowledge streams are simultaneously present and recombined (Fleming, 2001; Singh and Fleming, 2009). Simultaneous collaboration with different types of partners involves open generation and sharing of new ideas, resolution of problems and disagreements by means of non-routine methods and different reference frames, and responsiveness and timely feedbacks to change innovations in novel and meaningful ways (Griffin and Hauser 1996; Van de Ven 1986). Drawing from each partner's unique background and iterations through joint problem solving (Song and Parry 1997; Van de Ven 1986), the R&D team that acquires and disseminates divergent ideas and information through simultaneous collaborations is more likely to generate creative ideas and better innovations. Furthermore, as successful innovations are usually grounded in insights from both market and technology knowledge (Tidd et al., 2000 Dougherty, 1992), it can be beneficial to involve different types of partners simultaneously into the collaboration process to enable the full interaction among them. Thus, we hypothesize:

H3a: Collaboration Simultaneity has a positive effect on the innovation performance of R&D projects.

As discussed in the previous section, R&D collaborations with different types of partners also imply considerable managerial complexity in arranging multiple relations. When different types of partners are involved into the collaboration process simultaneously, the challenges of handling diverse relations can increase exponentially compared to dealing with each of them on a dyad basis. First, as each different type of partners has its distinct nature, it can be particularly challenging if managing them all at the same time. Prior studies point out that market-based partners are considered to be application-oriented, while technology-based partners, on the other hand, are claimed to lay their strength in exploration activities, instead of rushing for immediate commercial applications (Mowery, 1998). When working with both types of partners simultaneously, the research team has to deal with issues such as goal divergence

(Lorange and Roos, 1991), different working habits (Bstieler and Hemmert, 2010), as well as distinct organizational culture and thought worlds (Mowery, 1998) all at the same time, which implies considerable coordination and communication complexities among the focal firm and its partners (Gulati, 1999; Rothaermel and Deeds, 2006), and may undermine the effectiveness of R&D collaborations compared to working with different partners sequentially, on a one-to-one basis. Second, as each type of partners requires a certain level of managerial attention in the collaboration relationship, simultaneous collaboration may hamper collaboration as each partner get only a small part of the attention from the management. As managerial attention is a rare resource (Cyert and March, 1963), it can be difficult for the focal research team to assign sufficient attention to each relationship involved in simultaneous collaborations, thus it entails the risk that some relations are under-managed or even mis-managed during the collaboration process. Last but not the least, because relationships are dynamically evolving along the collaboration process, the research team needs to adjust them based on changing environments and evolving interests of each partner, which places further challenges to the R&D project if it engages in simultaneous collaboration with different types of partners all at the same time. Therefore, we hypothesize:

H3a: Collaboration Simultaneity has a negative effect on the innovation performance of R&D projects.

Collaboration Pattern

Finally, R&D projects go through several stages from the start to its end: ranging from initiation, execution, to completion (Clark and Fujimoto 1991). When the R&D project engages in R&D collaboration, collaboration activities can be carried out at each phase. The *collaboration pattern* denotes at which project stage R&D collaborations take place. As it remarks, “One important capability for firms which seek to develop innovations is the competence to involve the 'right' partners at the 'right' time in the 'right' form” (Lettl, 2006), which highlights the importance of the collaboration pattern in R&D collaboration activities. As the need to access external knowledge and collaborates with external partners varies across the course of R&D projects, the collaboration pattern is expected to play an important role on the performance of R&D projects.

So far, little is known when to include different types of partners into R&D projects. Some studies advocate early integration of external partners into the project. For example, Zahay and colleagues (2011) find that the use of several kinds of information early in the project is associated with increased success, “Thus, teams should perhaps be encouraged to make more information-gathering forays outside the confines of the firm in this early project stage” (Zahay et al., 2011, p.500). Other scholars argue that it is important to keep collaboration ongoing during the whole process of project development. It is suggested that customers may be involved in the whole process of co-developing of products (Lettl, 2006), and the integration of suppliers can occur at any point during the NPD process (Ragatz et al., 1997). Based on the SAPPHO research project, Rothwell and colleagues found that market-related information should be updated constantly during the course of R&D projects (Rothwell et al., 1974). Despite these findings, there is currently little empirical evidence on the optimal pattern of external partner involvement in R&D projects.

From a theoretical perspective, it is reasonable to conduct R&D collaboration in the early phase of the project life cycle. R&D collaboration is about knowledge accumulation (Kale and Singh, 1999; Grant and Baden-Fuller, 2004). The externally-sourced knowledge has to be synthesized with the internally-generated knowledge (Kogut and Zander, 1992; Cassiman and Veugelers, 2006). As knowledge integration is neither an automatic nor an instant process (Grant, 1996), instead, it only take place when the ingredients— the pieces of knowledge that to be combined— are readily available. Therefore, it is reasonable to keep the collaboration period in the early phase of the project to broadly prospect external knowledge, while allowing time for knowledge integration in the later phase of the project to fully synthesize all the knowledge pieces that the project has gained from both internal and external sources.

Moreover, adopting a risk reduction perspective, the risk of innovation is the highest when the uncertainty is the greatest. As the unknown resolves and the relevant knowledge architecture of the innovation emerges during the process of project development, the risk gets reduced accordingly. Therefore, innovation risk is the greatest when the project starts, and it declines as the project unfolds (Cooper et al., 2004). During the innovation process, firms collaborate with partners to collect different types of external resources, which, in turn, reduces innovation risks. Therefore, the needs of collaboration is more pronounced during the earlier period of the project where the risk is the highest. Therefore, it might be beneficial to conduct R&D collaboration in the earlier period of the project. In sum, we hypothesize:

H4: The optimal pattern to collaborate with external partners in R&D projects is early on in the project.

Data and Sample

Sample

To test our hypotheses, we use a unique longitudinal dataset on the R&D projects that are conducted by a large multi-national multi-division Global 100 manufacturing company. This company has an annual R&D budget of more than 2 billion euros and is active in a variety of industries. This dataset contains detailed information of all the R&D projects that have been initiated and executed in the company's research labs during the period 2002-2009. Each project is recorded on a yearly basis and is traced from its start to its termination. From the year 2002 onwards, every year there is detailed yearly information on R&D collaboration practices, resources and performance of the research projects. By the time of analysis, there are in total 867 research projects which are originated in/after year 2002 that have been completed. We focus on finalized projects because they give us full information on the timing of R&D collaboration activities. We have dichotomous information on the collaboration activities of R&D projects, the indicators take value "1" if there is collaboration going on with a certain type of partners (technology-based or market-based), while value "0" if otherwise. Further, this dataset includes yearly information on the number of full time equivalent researchers ("FTE"), the project leader who manages the project, the sponsoring department which initiates the research project, the starting year of each project, and the number of patents that have been generated.

Dependent Variable

Innovation Performance. We measure the innovation performance of R&D projects via the number of patents it applies for in its life cycle. Patents are a commonly used measure of the innovation performance of projects and firms. Prior research suggests that patents serve as a reliable measurement of innovation performance (Pavitt, 1985; Hall et al., 1984). Firms seek for patent protection for their innovative activities in order to secure their innovations and to appropriate returns from it. In particular, patents are good indicators of technical performance in the industries of our sample firm, as the patent propensity is high in the industries it covers. We have collected information on the full set of patents that the sample projects have applied for. Patents are applied for at national and international patent offices. Each patent is counted only once by using information on patent families. Further care is taken by carefully weeding out the projects with invalid patent applications (the ones that are abandoned or to be abandoned). In general, patents are applied for early in the innovation process, with very short time lags between R&D activities and patents applications (Hall, Griliches, and Hausman, 1984). Therefore patent applications can be used as an effective indicator to measure innovation performance of projects in our sample, as we allow for at least a two-year lag between the project start to its patent application in our sample (the latest project in our sample started in January 2009 while patent application information is collected until December 2011).

Independent Variables

Collaboration Duration. Collaboration duration is measured as the total amount of time the R&D project collaborated with external partners divided by the length of the project life time. This variable is further calculated as "general collaboration duration" (regardless of the type of partner involved), and as "specific collaboration duration" (collaboration activities with a certain type of partners), respectively. General collaboration duration indicates how much percent of time a project spent in R&D collaboration during its life cycle, no matter which type of partner it collaborated with. Specific collaboration duration measures collaboration duration with a specific type of partner.

Collaboration Continuity. Collaboration continuity is a dummy variable: "0" denotes that during the project life cycle, the collaboration activities are discontinuously organized in a piecewise manner. In the other case, when the project stays continuously in collaboration and without any breaks in the collaboration process, it takes value "1". In line with the collaboration duration measure, this variable is created separately for "general collaboration continuity", regardless of the type of partners the project engages with, and "specific collaboration continuity" takes into account of collaboration continuity with a certain type of partners.

Collaboration Simultaneity. Collaboration simultaneity measures to what extent both types of partners are involved into the collaboration process at the same time. It is measured as the amount of overlapping collaboration time with both types of partners, divided by the number of collaboration years of the R&D project. In a significant number of cases (35.05 percent), the R&D projects in our sample collaborated with both market-based and technology-based partners in the course of the project's lifetime.

Collaboration Pattern. Collaboration pattern refers to the stage of the project life cycle in which R&D collaboration activities take place. We further distinguish between two phases of the project: collaboration in the earlier phase of the project, and/ or collaboration in the later phase of the project, where we use the mid-term of the project's life time as the cutting point.

Control Variables

The analyses control for a range of other factors that may affect the innovation performance of R&D projects.

Project Resources. Project resources is an important factor that may affect the performance of R&D projects (Cooper et al., 2004). We constructed two sub-items to denote project resources:

1) *Project Staffing*: We use the number of Full Time Equivalent researchers (FTE) working on the project as the proxy of project size and internal resource endowments. This information is available on a yearly basis. For this study, we take the total FTE of the R&D project as the proxy of its resource endowment.
2) *Project Prior Technological Capabilities*: Based on the 4-digit IPC code that we collected for each of the R&D project (for details, please refer to the next section), we calculated the previous 5 years patent stock of the project in its main technology field as its prior technological capabilities. Prior studies point out that the knowledge stock of the firm depreciate along years (e.g.: Hall et al., 2005), and a 5-year stock may be a appropriate time

frame to look at for investigating the firm's technology capabilities (e.g.: Hall et al., 2005). In order to do this, we first collected the number of yearly patent applications of the firm filed at the European Patent Office in each of its active technology fields (based on 4-digit International Patent Classification (IPC)). This patent stock is calculated based on the consolidation of the yearly full list of the firm's subsidiaries, and we further take into account of mergers & acquisitions and divestments of the firm in each year. Because our sample projects are in the period of 2002-2009, from year 1997 onwards, every year the patent stock of the firm in a particular technology field (the 4-digit IPC field) is calculated, which enables us to calculate the previous 5 years patent stock of the project in its corresponding IPC field. This variable is log transformed in order to avoid very skewed distributions.

Project Technology Fields. We collect the 4-digit IPC (International Patent Classification) code for each of the project in our sample. As it is suggested, "The IPC codes, provide for the classification of patents and utility models according to the different areas of technology to which they pertain" (WIPO), thus it serve as a good indicator for identifying the technology fields of each of the R&D project. For the projects that have a patent publication number, we are able to directly link them to their corresponding IPC code as published in the EPO database; for the R&D projects that do not apply for patents, or which do not yet have a patent publication number, we did intensive text mining based on project title and project description, to match with the descriptions in patent cooperation treaty (PCT) as published in World Intellectual Property Organization website. In total, we collected 44 different IPC codes for the projects in our sample, which are then further grouped into 19 dummy variables on the technology field of the R&D project.

Corporate Research. Research projects can be initiated from two types of sponsoring units, the corporate research department, or one of the firm's business groups. On average, there are roughly half (49.89%) of R&D projects that are originated from the corporate research department. Projects that are originated from these two different sponsor units may display distinct characteristics. For instance, projects that are initiated by corporate research may be tightly related to the long term development of the firm and therefore have higher significance and strategic importance. They may get higher priority and more support from senior managers, and may be equipped with better facilities and be exposed to more innovation opportunities. These projects may also be more explorative, have higher expected returns but may take longer time to be accomplished. Projects that are initiated from different business groups, on the other hand, may be more application-oriented and usually of a short-term nature. For this analysis, we use a dummy variable—Corporate Research (0/1) to denote who has initiated the R&D projects.

Length of the Project. Project length may be another important factor influencing its innovation performance as longer projects might have had more possibilities in solving technological issues and generating patent applications.

Project Initiating Year. Finally, we control for the year in which the project started. The year may pick up changes in corporate level strategies over time that have an impact on the working and performance of R&D projects.

Method

Poisson regression is a form of a generalized linear model where the response variable is random and with non-negative integer values. As our dependent variable follows a poisson distribution, we adopt the poisson regression for the analysis. Because the standard deviation(0.705) is slightly larger than the mean(0.527), we did also negative binomial regression analysis in order to control for possible over-dispersion of the dependent variable, the hausman test suggests that poisson regression is the better approach to take. We also tried quasi maximum likelihood poisson regression as robustness check, which gives similar results.

Results

The descriptive statistics of the explanatory variables, together with the correlation table, are shown in Appendix .

The models analyzing the effects of *collaboration duration* on the innovation performance of R&D projects are in Table 1. Model 1 only includes the control variables. Positive and significant effects are found for corporate research, internal project resources, project length and project's previous 5 years patent stock. The IPC and year variables are each jointly significant (year variables omitted). Models 2 to 8 add the collaboration duration variables. There is a positive relation between the overall duration of R&D collaborations and the innovation performance of research projects (Model 2), moreover, general openness (regardless of collaborating partners) is not related to innovation performance in a curvilinear way (Model 3). Consequently, more openness during R&D projects results in better innovative performance. However, when looking into each type of collaboration partners, we find strong evidence of a curvilinear relation between the duration of R&D collaboration with a specific type of partner and the innovation performance of R&D projects (Model 5, Model 7, Model 8). Although there is no curvilinear relation between 'overall' collaboration duration and innovation performance, there is an inverted-U shape relationship between collaboration duration with technology-based partners (Duration Collab.TP) or market-based partners (Duration Collab.MP) on the one hand and the innovation performance of R&D projects on the other hand. In the case of market-based partners, we find that R&D projects should optimally be open for 78.56% of their duration and for technology-based partners 39.78% (based on estimations in model 8). Hypothesis 1 is thus only supported for collaboration with specific different types of partners. More specifically, we find that the optimal amount of time spent in collaboration with technology-based partners is less than the optimal time spent with market-based partners.

Insert Table 1 about here

The results of our models analyzing the effects of *collaboration continuity'* and *collaboration simultaneity* on the Innovation performance of R&D projects are shown as in Table 2. Because these two variables only work when the project is in collaboration with a certain partner, we therefore add them to the previously deduced regressions, the ones that are with pairs of collaboration duration variables in collaboration with technology-based, and market-based partners. The first models (Models 2, 3, 4) focus on collaboration continuity. Model 1 only contains the control variables, and shows that projects that open up for a longer period, which receive more internal resources, which are sponsored by the corporate research department, and which have a bigger patent stock, generate a higher innovation performance. Models 3 to 4 provide evidence that staying in collaboration in a continuous way pays off. Such finding is consistent regardless of which type of partner is involved in the collaboration period (Model 2, Model 3, Model 4). Therefore, hypothesis 2a is supported, while hypothesis 2b is rejected. Collaborations in R&D projects should be conducted continuously, rather than in a piecewise way.

Model 5, Model 6 add the collaboration simultaneity variable to the set of control variables. The variable “Simultaneous CI LP” in model 5 is a rough variable: it takes value “1” if there is at least one year simultaneous collaboration with both market-based, and technology-based partners. And “0” otherwise. While we do not find the effect of whether being at least once in simultaneous R&D collaboration with external partners improves or decreases innovation performance of the R&D project, we find that actually staying in collaboration simultaneously with multiple types of partners may be detrimental to innovation performance of the R&D project. The coefficient for this variable is negative and significant, confirming hypothesis 3b: simultaneous collaboration hampers innovation performance, while reject hypothesis 3a, that simultaneous collaboration with different types of partners improves the innovation performance of R&D projects. Therefore, it is desirable not to simultaneously collaborate with different types of R&D partners, but may, instead, considering conducting it in sequence.

Insert Table 2 about here

Finally, the regression results of the relationship between the *R&D collaboration pattern* and the innovation performance of R&D projects is shown in Table 3. Here, 2 pairs of mutually exclusive variables are used to indicate the collaboration patterns with different types of partners of R&D projects: Collaboration with market-based partners in the earlier/ later period of the project (Model 1), and Collaboration with technology-based partners in the earlier/ later period of the project (Model 2), We also show a model in which all these 4 variables are used simultaneously (Model 3). The results in Table 3 shows that it is beneficial to collaborate with market-based partners in the earlier phases of R&D projects (see Model 1), since the variables "Open CI in the Early Period" has a positive effect on innovation performance.

As for collaboration pattern with technology-based partners (Model 2), our results show a slightly different pattern compared to collaboration with market-based partners. We find that it is counterproductive if collaborating with technology-based partners at the end of the project. In sum, hypothesis 4 is partly supported for collaboration with both types of partners.

The results in tables 3 also show that it is counter-productive if the firm is opening projects for too long. Keeping R&D projects consistently open from the beginning to the end of the project has a negative effect on innovation performance, particularly for collaboration with technology-based partners. Altogether, these results indicate that the timing of R&D collaborations matters for the performance of R&D projects.

Insert Tables 3 about here

Discussion and Conclusion

In this study, we explore the relationship between the way how firms organize their inter-organizational collaboration activities in R&D projects and the innovation performance of these projects. More specifically, we focus on the role of timing in R&D collaborations. Based on 867 R&D projects of a Global-100 manufacturing company, we find empirical support for the assumption that the success of R&D collaborations in research projects hinges on the timing of R&D collaborations with external partners.

This study contributes to the existing literature in several ways. First, it adds a new level of analysis to the extant research on R&D collaboration and innovation performance. We start from the observation that in large companies most R&D collaboration activities are conducted in relation to specific R&D projects where researchers from partnering organizations work together in a particular sequence. Prior studies on R&D collaboration (mainly) take the firm as the unit of analysis; therefore, the way how firms organize their R&D collaborations during research projects is oftentimes neglected. On the contrary, we investigate different collaboration activities during the R&D projects, taking into account the fact that projects develop over time and that collaboration needs to be managed with the time dimension in mind. We examine how four dimensions of the timing of R&D collaborations at the R&D project level have an impact on projects' innovation performance: the duration of the collaboration, the continuity of the collaboration, the simultaneous collaboration between technology-based partners and market-based partners, and the pattern of the collaboration during the entire lifetime of the project. We find that these characteristics of collaboration activities are important to explain R&D projects' innovation performance which has been neglected in prior research. Second, the empirical evidence of our study allows us to put the current debate about the pros and cons of "open innovation" (in particular R&D collaboration activities therein) in a different light. We argue that more R&D collaboration will not necessarily improve the innovation performance of R&D projects and companies. In contrast, it is the *organization and timing of R&D collaboration* activities that may help to generate better innovation performance. Our results indicate that collaboration with external partners can indeed improve innovation performance, however, the success of R&D collaboration hinges on *when* and *how* R&D collaboration activities are organized during R&D projects life cycle. In other words, although R&D collaboration can improve the innovation performance of R&D projects (or firms with multiple research projects), merely conducting R&D collaboration without consideration its timing is no guarantee for success. Third, besides success factors that have been identified in prior research, R&D projects should take into account four dimensions of organizing R&D collaborations during research projects: collaboration duration, collaboration continuity, collaboration simultaneity, and collaboration pattern. These dimensions enrich the literature on R&D collaboration.

Furthermore, we can draw a number of managerial implications from this study. First, timing of R&D collaboration activities is crucial for the performance of R&D projects. Thus, managers should pay careful attention to *when* and *how long* they should collaborate with partners. When one makes no distinction between different partners we find that a longer openness period leads to better project performance. When we make a distinction between two types of partners (market- and technology-based), we find that a firm should not collaborate with all partners all the time. Optimal results are obtained when R&D projects collaborate 78.56% of their lifetime with market-based partners and 39.78% of their time with technology-based partners. In sum, firms reach optimal results when they work together for most of the lifetime of R&D projects. This result also gives support to the knowledge integration view: although for each particular type of partner there exists a certain optimal "closed" period, in general, the project is able to enjoy a life-long open period in its life cycle. Second, with respect to collaboration continuity, R&D projects benefit from continuous collaboration activities with technology-based partners as well as with market-based partners. Thus, when conducting collaborations, is suggested to do it continuously without interruptions in the process. Third, as for collaboration simultaneity, we find that the actual managerial complexities and coordination costs may outperform the benefits of knowledge recombination, thus, it is suggested that the project conducts with partners not all at one time, but may in some sequence. Finally, projects are performing better when collaboration with external partners takes place at the beginning of the project. This is clearly the case for collaboration with market-based partners. For technology-based partners, our results show that collaborations take place at the end of R&D projects is harmful to R&D project innovation performance, which suggests that the R&D project may need to have some closed period at the end of the project life cycle if it collaborates with technology-based partners, in order to allow sufficient time for differentiation of collaborative efforts and prevent opportunistic behavior of the partner in patent filing.

Despite the contributions and implications of this study, it has also several limitations. First, the data we rely on only describes the situation of one Global 100 manufacturing company. Although it is a large multinational company covering a wide range of technologies and industries, our findings may reflect firm-specific situations and ways how management is organizing R&D projects. It should therefore be tested whether the findings can be generalized using project-level data of projects from a larger sample of different firms. We are currently conducting research in this direction. Second, we test whether different approaches of organizing the timing of R&D collaboration activities are contingent on the type of partners that are involved into the collaboration process. However, this might be a relatively simple approach since we did not differentiate between different types of R&D projects. R&D projects serve different purposes, thus the optimal way to organize for R&D collaborations may also vary with the type of projects. For instance, projects that are more explorative in nature perhaps require longer collaboration and a stronger involvement of technology-based partners, compared to projects that are more exploitative in nature. Such improvements can be made if we can control for the technology complexity and novelty of the projects. Third, we have only indications whether or not a firm is collaborating with a particular type of partners at a particular point in time. We have no indication of how many partners are involved, and how intense the collaboration is in terms of the time and energy that different partners invest into the collaboration. Moreover, we have no idea about the identity of the partners. Therefore, we cannot investigate the moderating role of the market reputation or technological capabilities of R&D partners on project performance.

Table 1: Collaboration Duration and R&D Project Performance

VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Duration Collab.		0.191***	0.915					
		(0.0544)	(0.778)					
Duration Collab.^{2}			-0.683					
			(0.725)					
Duration Collab.MP				0.268***	1.113***			1.013**
				(0.0788)	(0.375)			(0.405)
Duration Collab.MP^2					-0.842**			-0.702*
					(0.395)			(0.395)
Duration Collab.TP						-0.0106	0.712***	0.432**
						(0.0772)	(0.214)	(0.220)
Duration Collab.TP^2							-0.721***	-0.543***
							(0.218)	(0.179)
Corporate_Research	0.257***	0.260***	0.263***	0.290***	0.279***	0.258***	0.262***	0.293***
	(0.0449)	(0.0435)	(0.0427)	(0.0476)	(0.0450)	(0.0469)	(0.0469)	(0.0489)
totalFTE	0.0406***	0.0390***	0.0396***	0.0379***	0.0374***	0.0407***	0.0413***	0.0387***
	(0.0118)	(0.0122)	(0.0115)	(0.0114)	(0.0113)	(0.0120)	(0.0117)	(0.0110)
Project_Length	0.158***	0.150***	0.120**	0.154***	0.119***	0.158***	0.129***	0.105***
	(0.0316)	(0.0307)	(0.0516)	(0.0321)	(0.0319)	(0.0332)	(0.0352)	(0.0387)
logPatentStock_5yrs	0.116***	0.113***	0.110***	0.111***	0.111***	0.116***	0.113***	0.109***
	(0.0163)	(0.0153)	(0.0148)	(0.0157)	(0.0161)	(0.0164)	(0.0160)	(0.0164)
IPC_digit_dummies	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*
Year_dummies	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*	*Included*
Constant	-2.092*	-2.199*	-2.193*	-2.188*	-2.148*	-2.088*	-2.064*	-2.105*
	(1.224)	(1.256)	(1.263)	(1.241)	(1.258)	(1.244)	(1.253)	(1.273)
Observations	867	867	867	867	867	867	867	867
Log Likelihood	-721.5	-720.2	-719.5	-719.0	-717.7	-721.5	-720.6	-716.8
lrtest		26.00***	26.00***	58.08***	61.24***	24.23***	32.64***	74.98***

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2: Collaboration Continuity, Simultaneity and R&D Project Performance

VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5
Duration Collab.MP		1.036**	1.129***		1.198***
		(0.406)	(0.352)		(0.452)
Duration Collab.MP^2		-0.730*	-0.988***		-0.800*
		(0.385)	(0.367)		(0.409)
Duration Collab.TP		0.447**		0.709***	0.711***
		(0.193)		(0.206)	(0.233)
Duration Collab.TP^2		-0.564***		-0.763**	-0.716***
		(0.155)		(0.181)	(0.188)
WeightedSimult MP& TP					-0.207**
					(0.0922)
Continuous Collab.		-0.0578			
		(0.164)			
Continuous Collab. MP			0.232***		
			(0.079)		
Continuous Collab. TP				0.207**	
				(0.090)	
Corporate_Research	0.257***	0.293***	0.278***	0.263***	0.291***
	(0.0449)	(0.0448)	(0.0453)	(0.0478)	(0.0462)
totalFTE	0.0406***	0.0394***	0.0379**	0.0406**	0.0394***
	(0.0118)	(0.0113)	(0.0115)	(0.0114)	(0.0109)
Project_Length	0.158***	0.098***	0.086**	0.094**	0.0964**
	(0.0316)	(0.0332)	(0.0350)	(0.0384)	(0.0396)
logPatentStock_5yrs	0.116***	0.109***	0.106***	0.113***	0.108***
	(0.0163)	(0.0162)	(0.0163)	(0.0162)	(0.0166)
IPC_digit_dummies	*Included*	*Included*	*Included*	*Included*	*Included*
Year dummies	*Included*	*Included*	*Included*	*Included*	*Included*
Constant	-2.092*	-2.211*	-2.165*	-2.072*	-2.131*
	(1.224)	(1.252)	(1.256)	(1.254)	(1.278)
Observations	867	867	867	867	867
Log Likelihood	-721.5	-720.2	-717.2	-720.5	-716.2
lrtest		7.84***	60.71***	21.81***	7.47***

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3: Collaboration Pattern and R&D Project Performance

VARIABLES	Model 1	Model 2	Model 3
Duration Collab.MP	0.989***		0.833**
	(0.332)		(0.331)
Duration Collab.MP^2	-0.789**		-0.597*
	(0.367)		(0.355)
Duration Collab.TP		0.462	0.276
		(0.323)	(0.337)
Duration Collab.TP^2		-0.521**	-0.415**
		(0.233)	(0.193)
Collab.MP intheEarlyPeriod	0.138*		0.068
	(0.0809)		(0.106)
Collab. MP intheLaterPeriod	-0.035		0.079
	(0.1438)		(0.200)
Collab.TP intheEarlyPeriod		0.205	0.179
		(0.145)	(0.168)
Collab.TP intheLaterPeriod		-0.3499**	-0.322**
		(0.161)	(0.146)
totalFTE	0.0367***	0.0410***	0.0381***
	(0.0116)	(0.0110)	(0.011)
Project Length	0.113**	0.171***	0.126*
	(0.0498)	(0.0443)	(0.070)
logPatentStock_5yrs	0.109***	0.109***	0.105***
	(0.0164)	(0.0169)	(0.0172)
Corporate_Research	0.277***	0.263***	0.292***
	(0.0435)	(0.0456)	(0.0475)
IPC_digit_dummies	*Included*	*Included*	*Included*
Year dummies	*Included*	*Included*	*Included*
Constant	-2.110*	-2.173*	-2.144*
	(1.263)	(1.255)	(1.264)
Observations	867	867	867
Log Likelihood	-717.2	-719.0	-715.3
lrtest	7.97***	6.23**	18.09***

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Appendix: Correlation Table

	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. TotalPatents	0,527	0,705	1,000																			
2. WeightedOI	0,537	0,453	0,177	1,000																		
3. WeightedOI2	0,493	0,461	0,135	0,981	1,000																	
4. WeightedCI	0,385	0,433	0,171	0,742	0,723	1,000																
5. WeightedCI2	0,335	0,429	0,111	0,713	0,725	0,976	1,000															
6. WeightedLP	0,388	0,441	0,126	0,755	0,745	0,383	0,360	1,000														
7. WeightedLP2	0,345	0,437	0,080	0,730	0,748	0,360	0,359	0,979	1,000													
8. LengthofthePro	1,839	1,094	0,399	0,215	0,111	0,183	0,064	0,189	0,087	1,000												
9. Corporate_Research	0,494	0,500	0,102	-0,004	0,006	-0,143	-0,139	0,066	0,074	-0,016	1,000											
10. totalFTE	4,401	4,861	0,480	0,221	0,154	0,200	0,119	0,220	0,150	0,668	0,007	1,000										
11. logPatentStock_5yrs	4,814	2,551	0,147	0,046	0,034	0,057	0,045	0,035	0,018	0,081	-0,045	0,117	1,000									
12. ContinuousOpen	0,093	0,290	0,270	0,289	0,286	0,228	0,191	0,268	0,238	0,550	0,027	0,437	0,019	1,000								
13. ContinuousCI	0,182	0,386	0,275	0,389	0,366	0,533	0,508	0,249	0,206	0,458	-0,062	0,368	0,081	0,425	1,000							
14. ContinuousLP	0,200	0,400	0,252	0,424	0,408	0,255	0,205	0,571	0,545	0,516	0,037	0,431	0,071	0,493	0,496	1,000						
15. SimultaneousCI_LP	0,325	0,469	0,222	0,512	0,465	0,652	0,575	0,660	0,587	0,363	-0,062	0,337	0,066	0,286	0,455	0,498	1,000					
16. WeightedSimultCI_LP	0,272	0,415	0,157	0,482	0,438	0,662	0,608	0,659	0,602	0,240	-0,080	0,261	0,057	0,201	0,412	0,423	0,947	1,000				
17. OpenCIintheEarlyPeriod	0,218	0,413	0,289	0,405	0,370	0,520	0,460	0,274	0,220	0,483	-0,041	0,405	0,089	0,407	0,843	0,502	0,487	0,421	1,000			
18. OpenCIintheLaterPeriod	0,098	0,298	0,287	0,213	0,166	0,289	0,229	0,135	0,085	0,615	-0,015	0,444	0,030	0,641	0,484	0,347	0,322	0,248	0,414	1,000		
19. OpenLPintheEarlyPeriod	0,239	0,427	0,282	0,443	0,410	0,270	0,209	0,554	0,490	0,526	0,030	0,434	0,095	0,434	0,499	0,874	0,502	0,412	0,546	0,296	1,000	
20. OpenLPintheLaterPeriod	0,106	0,308	0,221	0,241	0,203	0,161	0,098	0,297	0,239	0,635	0,019	0,431	0,031	0,750	0,341	0,552	0,356	0,255	0,324	0,625	0,470	1,000

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