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The design of vertical R&D collaborations

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No. 2009/06

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Patrick Herbst and Uwe Walz





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A handwritten signature in black ink, appearing to read "Krahenen".

Prof. Dr. Jan Pieter Krahenen

A handwritten signature in black ink, appearing to read "Volker Wieland".

Prof. Volker Wieland, Ph.D.



CFS Working Paper No. 2009/06

The Design of Vertical R&D Collaborations

Patrick Herbst¹ and Uwe Walz²

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Abstract:

Suppliers play a major role in innovation processes. We analyze ownership allocations and the choice of R&D technology in vertical R&D cooperations. Given incomplete contracts on the R&D outcome, there is a tradeoff between R&D specifically designed towards a manufacturer (increasing investment productivity) and a general technology (hold-up reduction). We find that the market solution yields the specific technology in too few cases. More intense product market competition shifts optimal ownership towards the supplier. The use of exit clauses increases the gains from the collaboration.

JEL Classification: L22, L24, O31, O32

Keywords: Managing Innovations, Vertical R&D, R&D Collaboration, Rent-Seeking.

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1 Introduction

Input suppliers play a major role in the innovation process of many industries (see e.g., Clark (1987) for the automobile industry and Pisano (1991) for the biotechnology industry). Given their specific expertise, input supplying firms can build on a stock of knowledge. This enables them to step beyond the existing technological frontier by developing new and better products which are used in the final production processes of their customers. Often, however, the research and development (R&D) activity of the input supplier is complemented by collaborative R&D efforts of the manufacturer. Neither a pure market transaction (full-scale outsourcing) nor a fully integrative approach appear efficient. Rather we observe in very many instances vertical R&D cooperations between suppliers and buyers. Jorde and Teece (1990) stress that a significant number of industries, most notably in Europe and Japan, are characterized by (vertical) R&D collaborations. Harabi (1998) reports for German firms that in the majority of all cases R&D takes place in cooperation between the supplier and the buyer.¹

The main objective of this paper is to analyze the functioning and determinants of vertical R&D collaborations and relate them to competition in output markets. Our main research questions thereby are: How should firms organize vertical R&D cooperations (in terms of technology and allocation of property rights)? How does the intensity of competition in output markets affect the organizational design of vertical R&D collaborations?

We investigate these questions in an incomplete contracting framework in which due to the uncertainties associated with the innovative process it is not feasible to write a contract on a newly developed input nor on the supplier's knowledge. The innovation process leading to mass production of the new input consists of three phases: An initial research phase, a subsequent development phase in which collaborative efforts are undertaken by the manufacturing firm as well, and a production phase which requires the production expertise of the supplying firm. There are two major contracting decisions to be made. The first concerns ownership of the output of the research process (such as a patent or a prototype) which can be assigned to either party of the cooperation. Ownership

¹In his sample of 3112 innovative German firms the overall percentage of firms reporting vertical R&D cooperations is 84%. This number is even higher (99%) when only companies with a formal R&D department are taken into account.

in our model is on intellectual property but not on the knowledge embedded in the new input. The second contracting decision concerns the specificity of the R&D technology. Choosing a specific R&D technology increases the value of the new input for the manufacturing firm while at the same time increasing the lock-in of the supplier. In order to increase ex-post bargaining power, the supplier will engage in inventing-around activities to be able to sell the new input to other manufacturers.

Realizing the full value of the new technology requires, besides the patent, the expertise of the supplying firm. Therefore, ownership of the patent by the manufacturing firm allows only to appropriate parts of the rents (by using the expertise of an alternative supplier). In case of the supplying firm owning the patent, full value realization is secured. When deciding on the allocation of ownership, however, both the impact on value appropriation as well as the effect on value creation (i.e. on investment incentives) have to be taken into account.

Taking the choice of ownership and R&D specificity together allows us to investigate in detail various degrees of R&D collaboration between a supplier and a manufacturer. We are not only able to look into the effects of technological factors but also of product market characteristics which affect the choice of the R&D collaboration regime. The focus of our analysis is on later stages of the innovation process rather than on the initial research phase and its related hold-up problems.

To illustrate our set-up more specifically, consider the relationship between a supplier of fuel-injection systems and a car manufacturer. Given the accumulated expertise of the specialized supplier which develops a wide range of injection systems with economies of scope it is efficient to undertake R&D with respect to the development of the new system in an arm's length manner. At the same time, the value of the new system can be improved with collaborative R&D whereby the car manufacturer also contributes his knowledge. The more narrowly the R&D efforts are designed towards the particular needs of the manufacturer the more valuable the new input is. However, designing R&D efforts closely towards the needs of the customer limits the applicability of the new input to other potential car manufacturers. As this reduces his bargaining power, the supplier might think about simultaneously exploring techniques which allow him to sell the new technology to a competing manufacturer (i.e., to invest in inventing-around

activities). In this case, product market competition lowers the added value of the fuel-injection system to the initial manufacturer. This induced incentive for investments in inventing-around activities lowers the case for narrowly defined R&D processes and opens up the question to which extent the manufacturer should invest in collaborative R&D in the first place.

We find that the market solution is characterized by an excessive choice of the general technology: The two firms opt for the general technology in order to avoid excessive investment into inventing-around even though the specific technology would be optimal in a first-best view. Furthermore, we analyze the effect of a more intense product market competition which makes the exclusive supply to the manufacturer more attractive. If the degree of product market competition increases, the contract is structured to minimize excessive inventing-around by either choosing a general technology or allocating ownership of the patent to the supplier. In addition, our analysis reveals that the value of the supplier's expertise in the ex-post production process also affects the ex-ante choice of technology and ownership. As this expertise becomes more important, the threat of the buyer to take the new design to another supplier becomes less credible. This makes ownership by the manufacturer as well as the specific R&D technology more attractive. We also consider contracts with options on ownership by allowing for exit clauses. For example, the supplier might be entitled to terminate the R&D cooperation by acquiring the patent. Choosing an appropriate price for the patent may improve the firms' investment incentives and lead to the choice of the specific technology more often.

The paper is organized as follows. In the subsequent chapter we relate our analysis to the literature. In chapter three we outline the basic model. The subsequent fourth chapter solves the model and analyzes the optimal (contractual and technological) choices. We thereby restrict the analysis to the case of ex-post exclusivity of the innovation. In chapter five we consider the impact of allowing changes in ownership due to option contracts or renegotiation. Chapter six considers the case of non-exclusive use of the innovation ex-post. The seventh chapter concludes.

2 Relationship to Literature

Our paper is related to four different branches of the literature. First, and foremost, there is a growing literature dealing with innovation management issues on the basis of incomplete contracting arguments. The papers most closely to ours are Aghion and Tirole (1994) and Rosenkranz and Schmitz (2003). Aghion and Tirole (1994) investigate the management of innovation of mature firms in vertical relationships. Their analysis rests on the notion that the allocation of ownership affects incentives for a research unit. We distinguish ourselves mainly from their paper by focusing on vertical R&D cooperations between independent organizations which requires collaborative R&D efforts of both organizations rather than on pure make or buy decisions. Furthermore, while Aghion and Tirole (1994) only allow for the use of the innovation with one user or with various independent users, the effect of product market competition is an important part of our analysis. In a dynamic incomplete contracting approach, Rosenkranz and Schmitz (2003) look into organizational issues of horizontal R&D cooperation. By focusing on horizontal rather than vertical R&D cooperation their approach addresses a quite different set of questions than ours. Bias and Perotti (2008) and Baccara and Razin (2004) are part of a larger literature which rather than looking at the organization of the innovation process in mature firms as a whole focus on creation of new ideas in organizations and the problem of information leakages. By doing this they very much address the problem of the creation of new start-up firms and contrast the advantages of entrepreneurial spirit with the creation of new ideas in established organizations.

Second, Anand and Galetovic (2000) are akin to our approach by stressing weak property rights and hold-up in R&D. However, they consider the financing of R&D (venture capital financing vs. financing in a corporation) rather than looking into the design of the R&D process itself. Thereby, they form part of a second related branch of the literature which considers the interaction of the design of the innovation process and its financing. Similarly Fulghieri and Sevilir (2003) address this interaction by investigating the competition between two upstream firms with one downstream firm for the provision of a newly designed input. Their approach is somewhat complementary to ours by looking at the reverse type of vertical competition and by focusing on the financial aspects of the innovation

process rather than on the organizational implications.

Third, our analysis is based on the incomplete contracting literature. We thereby rely on the notion of contracting at will as put forward by Hart and Moore (1988). We consider this notion which assumes that the levels of trade can not be observed by courts most applicable for our analysis of providing and trading a newly designed input. This new input incorporates features that are difficult to understand and overlook by a third party (courts). We thereby abstract from the idea of performance-based contracting and on ex-ante option contracts on the pricing of the newly designed input as proposed in Nöldeke and Schmidt (1995). We do, however, consider options on ownership. While such option contracts may improve the outcome of the R&D cooperation, they do not as in Nöldeke and Schmidt (1998) lead to the first-best result. This is due to the simultaneity of the agents' investment decisions as well as the fact that in our set-up neither party can be induced via sole ownership to invest efficiently. This latter effect stems from our notion of weak ownership which implies that the manufacturing firm cannot appropriate the full value of the patent even if he is the sole owner. In addition, we allow for investments in the outside option of the ex-post bargaining game making it unfeasible to achieve first-best even with option contracts. Therefore, our analysis is related to Edlin and Hermalin (2000) who show that options on ownership do not achieve the first-best in cases in which the option contract expires before the agent's final decision is undertaken. Our paper is also akin to Schmitz and Sliwka (2001) who allow for the endogeneity of the specificity of the technology. In contrast to our approach they focus on the joint determination of ownership and specificity against the background of a standard hold-up problem of the supplier (applicable to the research phase) while we specifically focus on later stages of the innovation process and analyze collaborative R&D efforts of both parties. One of the main driving forces of our analysis, namely the possibility to change ex-post the degree of specificity of the ex-ante chosen technology via inventing-around activities is absent in Schmitz and Sliwka (2001).

Fourth, there exists a substantial literature investigating competition and research joint ventures. This literature (see e.g., Amir and Wooders (2000), D'Aspremont and Jacquemin (1988), and De Fraja (1993)) is, however, almost entirely concerned with horizontal R&D joint ventures. There are only very few

addressing vertical R&D joint ventures. These exceptions (see Inkmann (1999) and Harhoff (1996)) focus on R&D spillovers and their effect on strategic R&D. They hence neglect organizational issues concerning vertical R&D cooperations. In that respect, our paper is also somewhat related to Inderst and Wey (2003) who consider technology choice and product market competition in vertically structured oligopolies, leaving, however, the organizational issues completely aside.

3 The Model

3.1 The Innovation Process

We consider the organization of innovative activities between a supplier (firm S) and a manufacturer (firm M). Innovative activities result in new or improved inputs into M's final product. Thereby, successful innovations increase the value of M's final product. Firm S is a specialized supplier with an accumulated stock of expertise in the field. The supplier has to incur an investment in order to initiate the R&D process. Since we aim to focus our analysis on the interaction of firms M and S in later stages of the innovation process we choose a fixed-investment approach for the investment in the research phase. For matters of notational simplicity we normalize these investment costs to zero. Furthermore, without loss of generality we assume a deterministic relationship between R&D input and the value of the R&D outcome.

Due to the high degree of uncertainty it is not feasible to write ex-ante a contract which describes the crucial characteristics of the new input in a verifiable manner. This is akin to the notion that there are many potential outcomes and it is prohibitively expensive ex-ante to describe which should be implemented but costless to do so ex-post (given that both firms are active in the R&D process) and the two firms cannot commit not to renegotiate (see Hart and Moore (1999)). Due to contractual incompleteness ownership rights matter. Ownership gives the right to determine on the implementation of the outcome of the research process. We refer to this outcome in the following as patent.² In an extension we allow for the renegotiation of this right in later stages.

²Alternatively, one could interpret it as a physical prototype which emerges from the innovative process.

In the process of transforming the patent into a new input, collaborative development efforts of the manufacturer come into play. In this development phase, the efforts of firm M improve the quality of the new input by fitting it to the needs of the final product (e.g., by bringing in the engineering capabilities of firm M into the development process in the form of joint development teams of firms S and M). These collaborative efforts by M are particularly productive if the technology is specifically designed towards its own needs. With a general technology, collaborative investments by firm M are less productive. Simultaneously with M's collaborative development efforts, the supplier may engage in inventing-around activities. In case of success these inventing-around activities allow the supplier to create a new modified input which can potentially be sold to M's competitor, firm C.

In a subsequent post-development phase the special production expertise of the supplier is required in order to implement the new input into the mass production process of firm S. Hence, our notion is that the value creation process stems from two sources: The new input (consisting of the patent and collaborative development efforts) and the expertise of firm S, which is required in the subsequent production process. The expertise of the supplier at this post-development stage (e.g., consisting of the human capital of employees of S) is not contractible in any stage of our analysis and depicts the notion of non-alienability of human capital as stressed e.g., in Hart and Moore (1994). Figure 1 summarizes and illustrates the overall structure of the innovation process.

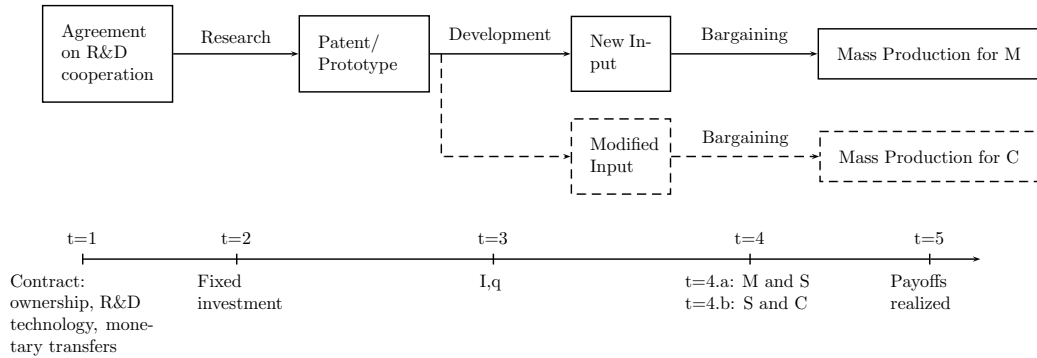


Figure 1: The structure of the R&D process

We endogenize the choice of ownership over the patent and distinguish be-

tween the case in which S owns the patent (S-ownership) and the situation in which M holds the ownership rights over the patent (M-ownership). In the former case, firm S possesses both sources of value creation and can potentially withhold the new input. Under M-ownership, M can take the patent to another supplier but, since he only owns the patent while lacking the production expertise of S, he can only extract the fraction $a \in (0, 1)$ of total value. Hence, we depict the alienability of S's expertise with the parameter a . The larger the (in-)alienability of S's expertise the (smaller) larger is a .

3.2 Design and Usage of the New Input

In the following we distinguish between the ex-post usage of the innovative product (allowing either for an exclusive use only in M's production or a non-exclusive use by supplying the product to M as well as C) and the ex-ante design of the R&D technology being either specific (leading to a higher productivity of M's investment) or general. Using the newly developed input ex-post exclusively in M's production creates a value of Y_M^X . If, in contrast, the innovation is also embodied in an input supplied to C, the value of the new input for M reduces to Y_M ($Y_M^X > Y_M$) while adding Y_C in value to C's product. We refer to $\Delta \equiv Y_M^X - Y_M$ as the intensity of product market competition between M and C.

The value of the new input can be improved if firm M also contributes to research and development by investing $0.5I^2$. The effectiveness of this contribution depends on the choice of the R&D technology. If a specific R&D technology designed towards M's needs is chosen the value of the new input for M is augmented by σI with $\sigma > 1$ measuring the exogenous degree of specificity of R&D with respect to M's needs. With a general R&D technology, M's effort leads to an increase in value by I .

We denote the value of the new input for M including M's investment in the case of exclusive use and specifically-designed R&D technologies by $V_{M,\sigma}^X = Y_M^X + \sigma I$. In the case of non-exclusive use of the specific technology we have $V_{M,\sigma} = Y_M + \sigma I$. We use corresponding notation to describe the value of the new input in the case of a general R&D technology. With exclusive use we have $V_{M,0}^X = Y_M^X + I$ while with non-exclusive use the value of the new input amounts to $V_{M,0} = Y_M + I$. Since M's investments are directed towards its own product only, the value of the new input for C is not influenced by this investment

(i.e., $V_C = Y_C$). Note that independent of the R&D technology chosen ex-ante, Δ measures the pure competition effect and remains unaffected by the R&D technology choice or the choice of M's investment in R&D.

Choosing a specifically-designed R&D technology has a potential downside as it limits the possibility to sell the new input to firm C. In order to be able to do so, S has to engage in inventing-around activities. Given that ex-ante a specific R&D technology has been chosen, investing $0.5cq^2$ opens up with probability q the possibility for S to sell the new input ex-post to C as well. This implies that if ex-ante a specific R&D technology has been chosen ex-post it might be feasible to sell the new input to the competitor as well. The parameter $c > 0$ measures the cost of inventing-around activities. In case of no or unsuccessful inventing-around activities, however, S remains locked into the relationship with M. If a general R&D technology is ex-ante selected the new input can be sold to C without any further costs.

3.3 Sequence of Decisions

The sequence of decision-making is as follows (see also figure 1). In a first stage ($t=1$) the two parties (M and S) agree about undertaking research (or not, in this case the game ends). In addition, the parties agree on the allocation of ownership as well as on the R&D technology chosen (i.e., specific or general technology). The design of the technology is fixed thereafter. Furthermore, monetary transfers might be agreed on.³

With a positive agreement, the R&D project will be started with the R&D investment by firm S. In order to facilitate the analysis we assume that the R&D expenditures (which are normalized to zero) are contractible at stage 1 thereby allowing us to neglect the individual incentives of R&D investing in stage 2 later on. Given our chosen set-up (zero R&D costs and non-cooperative decisions on collaborative R&D) this is for ease of exposition rather than having an impact on our results.

In stage three, the two parties invest in collaborative R&D (firm M) and inventing-around activities (firm S) simultaneously. In the subsequent stage

³These monetary transfers reflect different degrees of ex-ante bargaining power, but do not affect our allocative results. Since we do not impose any further assumptions on ex-ante bargaining power, these monetary transfers can be neglected in the analysis.

($t=4$), bargaining starts. We assume that in a first step, one-shot bargaining between M and S with randomly chosen proposer will take place. We use this simple modeling approach to approximate the equal division of the surplus. With a specific R&D technology chosen and unsuccessful inventing-around, bargaining takes place between M and S only, leading either to a contract entailing exclusive usage of the new product or no delivery. If a non-specific R&D technology has been used or if inventing-around has been successful, the proposing party offers a contract entailing the usage of the input (exclusive or non-exclusive) as well as its price. The other party may accept or decline this offer. In case of an acceptance of an exclusive offer, bargaining ends. Otherwise, S may approach C and the two firms engage also in a random-proposer, one-shot bargaining process. In the final stage of the game ($t=5$) cash flows are realized.

We solve this game in the following by looking at the bargaining stage first, before then turning to an analysis of the choice over inventing-around and collaborative research. Finally, we analyze the design of the cooperation in the first stage of the game.

4 Exclusive Use of the New Input

To simplify the analysis, we consider the case in which

$$\Delta \geq \frac{Y_C}{2} \quad (1)$$

is fulfilled. Section 6 considers the reverse case. Hence, we first focus on the case in which ex-post the technology will be used exclusively by firm M rather than being sold to competitor C as well (see our later analysis for this to be indeed the case). The crucial question with respect to the cooperation's organization in this case therefore is: Anticipating the ex-post exclusive use of the technology are there reasons for choosing a general technology ex-ante? Additionally, we assume

$$c > \frac{V_C + 2\Delta}{4}. \quad (2)$$

This technical assumption ensures inner solutions in the investment stage.

4.1 Bargaining Stage

We solve the model by backward induction, starting with the bargaining process as the final stage. The key aspect in the bargaining process is the alternative use of the new product by S and M. In case the parties initially chose the specific technology and S did not pursue any (or did not succeed in) inventing-around, S is unable to apply the new product at M's competitor C. In this case, bargaining takes place only between the two initial parties M and S. Conversely, if inventing-around was successful or the general technology was chosen initially, then S may sell the new input to both M and C. This leads to the three-party, sequential bargaining process. In either bargaining structure, ownership affects M's valuation of the new input in its alternative use: In case of M-ownership, M may realize a fraction a of the final value (which again depends on S's ability to sell also to C). Additionally, in the three-party bargaining process, M and S may choose to offer contracts conditional on exclusive or non-exclusive use.

In the following, we denote ownership and technology by subscripts (M or S gives ownership, 0 and σ denote the general and the specific technology, respectively). We find for the result of the bargaining process:

Lemma 1

Let $a_i \in \{a_S = 0, a_M = a\}$, and $\hat{\sigma} \in \{0, \sigma\}$.

1. For the case of the two-party bargaining process, the expected payoffs are

$$\pi_M = (1 + a_i) \frac{V_M^X(\hat{\sigma})}{2} \quad (3)$$

$$\pi_S = (1 - a_i) \frac{V_M^X(\hat{\sigma})}{2} \quad (4)$$

2. Three-party bargaining results in exclusive use of the good. The expected payoffs of the bargaining process are,

$$\pi_M = \frac{V_M^X(\hat{\sigma})}{2} + a_i \frac{V_M(\hat{\sigma})}{2} - \frac{V_C}{4} \quad (5)$$

$$\pi_S = \frac{V_M^X(\hat{\sigma})}{2} - a_i \frac{V_M(\hat{\sigma})}{2} + \frac{V_C}{4} \quad (6)$$

Proof: See the appendix.

The outcome of the two-party bargaining illustrates the role of M's alternatives: The two parties equally share the joint surplus which is equal to the value

of the exclusive use of the good minus M's ability to realize this value on its own (zero in case of S-ownership, proportion a in case of M-ownership). The more pronounced the alienability of the supplier's expertise (i.e., the larger is a) the better is M's bargaining position in case of M-ownership and the larger the share of surplus M is capturing. In the case of three-party bargaining, M and S also share the jointly created surplus which is maximized by choosing exclusive use as the value for C is low enough. However, S now realizes part of the new input's value for C as he can use non-exclusivity as a threat in bargaining with M. M still retains his alternative of producing without S, but is only able to realize the non-exclusivity value due to S's ability to sell to C.

4.2 Development Stage

We next consider the development stage with the choice of M's collaborative development efforts and the inventing-around activities of firm S. Investments by M are always productive, as they directly increase the value generated by the new input. The inventing-around investment by S is a pure rent-seeking activity: Successful inventing-around allows S to bypass the initially specific technology and to offer the new input to C. As this enables S to demand more in the bargaining process with M, inventing-around simply transfers rents from M to S.

Lemma 2

1. *The optimal investment levels for M are: $I_{S,0} = \frac{1}{2}$, $I_{M,0} = \frac{1+a}{2}$, $I_{S,\sigma} = \frac{\sigma}{2}$ and $I_{M,\sigma} = \frac{\sigma(1+a)}{2}$. For given ownership, M's investment levels are always higher under specific technology than under general technology; for given technology, M's investment levels are always higher under M-ownership.*
2. *Choice of the general technology always leads to zero inventing-around ($q_{S,0} = q_{M,0} = 0$)*
3. *Choice of the specific technology leads to inventing-around of $q_{S,\sigma} = \frac{V_C}{4c}$ or $q_{M,\sigma} = \frac{V_C}{4c} + a\frac{\Delta}{2c}$ with $q_{S,\sigma} < q_{M,\sigma}$.*

Proof: See the appendix.

The investment levels for M highlight the importance of technology and outside options offered by ownership: Investment levels are highest for M-ownership

and the specific technology and lowest for S-ownership and general technology. This is quite intuitive not least against the background of our discussion of the outcome of the bargaining stage. As owner, M captures a larger share of the total surplus, especially if the degree of alienability is high (large a). Hence, in this case, the larger is a the larger the incentives of M to invest in cooperative R&D. With a more specific technology, investment in cooperative R&D is more productive leading to stronger incentives to invest.

For S, inventing-around is only necessary in case of the specific technology where it improves his bargaining position as he can threaten to sell to C. Finally, M-ownership additionally increases S's incentive to invent around as it reduces M's outside value by its exclusivity value $a\Delta$. Hence, under M-ownership, an increase in either the value of the new input to C or in its exclusivity value increases the costly inventing-around activity (relative to the level under S-ownership).

4.3 Contracting Stage

In the initial contracting stage, M and S have to specify the R&D technology as well as ownership of the final input. Absent any constraints on side-payments, the two parties will choose the ownership/technology combination that maximizes the expected joint payoff. The choice of ownership and technology will take place such that M's investment incentives are as little distorted as feasible while minimizing at the same time the incentives to invest in inventing-around activities.

Proposition 1

1. *The combination of S-ownership with general technology is never optimal.*
2. *M and S are indifferent between choosing S-ownership with specific technology, M-ownership with specific technology and M-ownership and general technology if*

$$\frac{\Delta(V_C + a\Delta)}{(2 - a)\sigma^2} = c = \frac{V_C^2}{4(3(\sigma^2 - 1) - 2a + a^2)} \quad (7)$$

Proof: See the appendix.

The optimal ownership/technology choice involves trading off the value enhancing effects of the specific technology and M-ownership with the efficiency loss

due to inventing-around. Given that M-ownership always improves M's investment and that the general technology requires no inventing-around, it is never optimal to combine S-ownership with the general technology. Or, put differently, it is always optimal to transfer some (bargaining) power to M, be it in terms of ownership and/or by choice of a technology that is specific to M. Additionally, there can be combinations of the exogenous parameters, such that all remaining three combinations yield the same joint payoff. This yields the following comparative static results.

Corollary 1

Let (7) be fulfilled. Then a marginal increase (decrease) in

1. *a results in M and S choosing M-ownership and the general technology (M-ownership/specific technology)*
2. *σ results in M and S choosing M-ownership and the specific technology (M-ownership/general technology)*
3. *V_C results in M and S choosing M-ownership and the general technology (M-ownership/specific technology)*
4. *Δ results in M and S choosing either S-ownership and the specific technology or M-ownership and general technology (M-ownership/specific technology)*

Proof: See the appendix.

Table 1 presents the optimal ownership/technology choices for parameter changes at indifference, both pairwise and overall. In order to illustrate the

Change in	$M, \sigma / S, \sigma$	$M, \sigma / M, 0$	$M, 0 / S, \sigma$	$M, \sigma / M, 0 / S, \sigma$
$a \uparrow (\downarrow)$	$S, \sigma \uparrow$	$M, 0 \uparrow$	$M, 0 \uparrow$	$M, 0 \uparrow (M, \sigma \uparrow)$
$\sigma \uparrow (\downarrow)$	$M, \sigma \uparrow$	$M, \sigma \uparrow$	$S, \sigma \uparrow$	$M, \sigma \uparrow (M, 0 \uparrow)$
$V_C \uparrow (\downarrow)$	$S, \sigma \uparrow$	$M, 0 \uparrow$	$M, 0 \uparrow$	$M, 0 \uparrow (M, \sigma \uparrow)$
$\Delta \uparrow (\downarrow)$	$S, \sigma \uparrow$	$M, 0 \uparrow$	no change	$S, \sigma / M, 0 \uparrow (M, \sigma \uparrow)$

Table 1: Optimal ownership and technology – comparative static results

trade-offs of the model more clearly, it is helpful to consider only variations in two parameters at the same time. Figures 2 to 4 show how optimal ownership

and technology depend on the extent of market competition (captured by Δ) and one other parameter.⁴

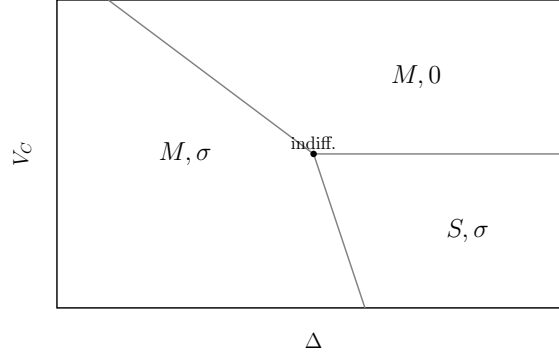


Figure 2: Optimal choices depending on V_C and Δ

Figure 2 illustrates the effect of changes in the new input's value for the two manufacturers. The first conclusion to be drawn is that the market solution may fail to ensure that the specific technology is chosen when it would be efficient. As $\Delta \geq V_C/2$ is assumed to hold, implying that ex-post bargaining will result in exclusive use of the new product (see Lemma 1), choice of the general technology would be inefficient if investments were contractible. However, the cost of rent-seeking by inventing-around are excessively high for sufficiently high values of V_C and Δ , such that the apparently inefficient general technology is chosen.

Additionally, figure 2 shows that – for low values of V_C – an increase in competition leads to a transfer of ownership from M to S. By switching from M-ownership to S-ownership the contracting parties try to reduce the degree of inventing-around. For higher values of Δ , i.e., higher product market competition, the decrease in rent-seeking by switching from M-ownership to S-ownership is more pronounced while the difference in M's investments between the two ownership structures remains unaffected. Furthermore, a reduction in the degree of product market competition (decreasing Δ) makes investments in the specific technology more profitable.

Figure 3 illustrates the role of the alienability of S's expertise, captured by a . High inalienability of the supplier's production expertise (low values of a) make ownership relatively less important for M's investment incentives. Rather,

⁴In the figures, we choose parameters such that there exists an indifference point.

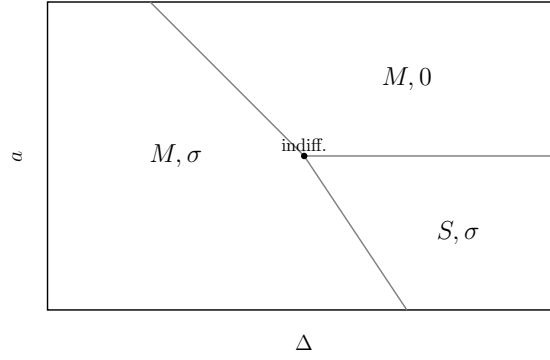


Figure 3: Optimal choices depending on a and Δ

the choice of the specific technology is the main driver of investment. It is consequently chosen more often. Additionally, given the specific technology was chosen, lower values of a also reduce the gains in terms of low inventing-around under S-ownership. As a result, M-ownership is also chosen more often. For sufficiently high values of a , ownership already provides strong investment incentives and the general technology is chosen to avoid costly inventing-around.

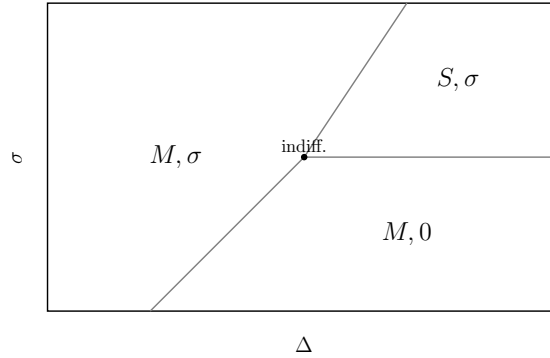


Figure 4: Optimal choices depending on σ and Δ

The technology parameter σ in figure 4 measures the benefits of choosing the specific technology (in terms of productivity enhancement). Intuitively, a low productivity gain due to specificity makes choice of the general technology more likely as costs of inventing-around are avoided. Increasing σ makes the specific technology more profitable, but then requires balancing investment and rent-seeking incentives. For intermediate values, this requires giving ownership

to S. However, for even higher levels of the gains from specificity, M's investment incentives are more strongly affected by the choice of ownership (while inventing-around is not affected by σ). Hence, M-ownership combined with the specific-technology choice is optimal when specificity yields high productivity gains.

We summarize our main findings in

Proposition 2

1. *The market solution exhibits too little specificity (in too many cases a general technology is chosen).*
2. *The more intense product market competition, the more often S becomes the owner.*
3. *Technologies with pronounced inalienability lead to choice of specific technologies and allocation of ownership towards firm M.*

5 Interim Changes in Ownership

In the following we extend the previous analysis by looking at two cases which might lead to changes in ownership during the course of the R&D cooperation. First, we investigate the consequences of introducing option contracts on ownership. Second, we allow for the possibility of renegotiation.

5.1 Option Contracts

In a first step, we look into the possibility of ownership allocated via option contracts. Specifically, ownership is allocated ex-ante to one firm and can be re-allocated on the basis of an option contract with a pre-specified strike price at $t = 4$, before the start of the bargaining process. This kind of option contract can be implemented by giving one firm an exit right: With one firm holding a call, this firm can, by paying the pre-specified fee (the strike price), terminate the contract and appropriate ownership of the patent. Equivalently, a put right allows the firm to terminate the initial contract and entitles it to a payment in

exchange for relinquishing all ownership.⁵ We show in the following that while improving the efficiency of the outcome, these option contracts do not change our basic mechanisms and results qualitatively.⁶

Option contracts only affect our previous analysis if the optimal exercise depends on the outcome of the inventing-around process. If options are always or never exercised our earlier analysis applies because strike prices are fixed transfers not affecting incentives to invest in cooperative R&D or in inventing-around. A direct consequence of this is that option contracts only matter if combined with the specific technology.

Although there are four potential cases of allocating option contracts, only the allocation of the exit right to either S or M matters. In the following, we focus on the case of S holding the exit right (the case of M holding the exit right is discussed thereafter). An exit right for S implies a put right under initial S-ownership or a call right under initial M-ownership. We consider both cases which are structurally identical but lay out the analysis by focusing on the latter case in detail. Let P denote the agreed strike price defined as a payment from S to M. Then the payoff structure including the call option payoff is as given in table 2.

Inventing-around successful		... not successful	
Base payoff	Option payoff	Base payoff	Option payoff
$\pi_M = \frac{1}{2}(Y_M^X + aY_M + (1+a)\sigma I - V_C/2)$	$-\frac{a}{2}(Y_M + \sigma I) + P$	$\pi_M = \frac{1}{2}(1+a)(Y_M^X + \sigma I)$	$-\frac{a}{2}(Y_M^X + \sigma I) + P$
$\pi_S = \frac{1}{2}(Y_M^X - aY_M + (1-a)\sigma I + V_C/2)$	$+\frac{a}{2}(Y_M + \sigma I) - P$	$\pi_S = \frac{1}{2}(1-a)(Y_M^X + \sigma I)$	$+\frac{a}{2}(Y_M^X + \sigma I) - P$

Table 2: Payoff structure with option contracts

With a low (high) strike price, S will exercise the call in either (neither) case and equilibrium investments will be as under S-ownership (M-ownership). For intermediate levels of the strike price, S will only exercise the call in case of failed inventing-around. For this case, the expected payoffs of the two firms can be

⁵Similar exit rights/options are frequently used in the venture capital industry and allow one party (typically the venture capitalist) to terminate the cooperation. See, for example, Chemla, Habib, and Ljungqvist (2007) or Bienz and Walz (2008)).

⁶Our analysis of option contracts with one innovation thereby significantly differs from the one of Aghion and Tirole (1994) who consider split ownership in the case of multiple innovations.

expressed as:

$$E[\pi_M] = \frac{q}{2}(Y_M^X + aY_M + (1+a)\sigma I - \frac{V_C}{2}) + \frac{1-q}{2}(Y_M^X + \sigma I + 2P) - \frac{I^2}{2}, \quad (8)$$

and

$$E[\pi_S] = \frac{q}{2}(Y_M^X - aY_M + (1-a)\sigma I + \frac{V_C}{2}) + \frac{1-q}{2}(Y_M^X + \sigma I - 2P) - \frac{cq^2}{2}. \quad (9)$$

However, these objective functions only apply if the asymmetric exercise is optimal after the investment decisions have been realized. This puts a restriction on the combination of the option strike price and M's investments. Specifically, the strike P must be in the range $P \in [0.5a(Y_M + \sigma I), 0.5a(Y_M^X + \sigma I)]$, which itself depends on the investment I . Hence, the choice of investments and the applied objective functions need to be consistent in equilibrium.

Lemma 3

Consider choice of the specific technology and an exit right for S (i.e., either M-ownership and a call option for S or S-ownership and a put option for S) at price P (defined as a transfer to the initial owner).

1. *Equilibrium investments I and q are continuous in P ;*
2. *M's equilibrium investment I is strictly increasing in P for $P \in [P_1, P_4]$ and constant else ($I = I_{S,\sigma}$ for $P < P_1$ and $I = I_{M,\sigma}$ for $P > P_4$);*
3. *S's equilibrium level of inventing-around q is strictly increasing in P for $P \in [P_2, P_3]$ and constant else ($q = q_{S,\sigma}$ for $P < P_2$ and $q = q_{M,\sigma}$ for $P > P_3$);*

where

$$\begin{aligned} P_1 &\equiv \frac{a}{2} \left(Y_M + \frac{\sigma^2}{2} \right), & P_2 &\equiv \frac{a}{2} \left(Y_M + \frac{\sigma^2}{2} (1 + a \frac{V_C}{4c}) \right), \\ P_3 &\equiv \frac{a}{2} \left(Y_M^X + \frac{\sigma^2}{2} (1 + a \frac{V_C + 2a\Delta}{4c}) \right), & P_4 &\equiv \frac{a}{2} \left(Y_M^X + \frac{(1+a)\sigma^2}{2} \right), \end{aligned}$$

and $P_1 < P_2 < P_3 < P_4$.

Proof: See the appendix.

Including an option for S in the contract allows the two firms to increase the set of attainable investment levels by varying the strike price. For intermediate

levels ($P \in [P_2, P_3]$), both firm's investments increase in the strike and lie between the extreme levels under M-ownership or S-ownership. An increase in the strike in case of asymmetric exercise raises S's return from inventing-around as ownership (by exercising the call) after inventing-around failed is more costly. Hence, M is also more likely to remain owner which increases its own investment return. Thus, the two types of investment affect each other for intermediate strike prices.

The most important effect of including an option for S occurs at levels of the strike price which are close to but still above the level where S always exercises its call, $P \in [P_1, P_2]$. At these strike prices, the two firms can realize higher investments by M without increasing S's level of inventing-around. This improvement is achievable because by raising its investment from the S-ownership level, M can offset the negative payoff that would arise when S exercises the call. Simultaneously, this behavior leaves S indifferent with respect to the exercise and thus leaves the incentives for inventing-around unaltered.

Given that there is generally too little investment by M in cooperative R&D, an option contract can improve the overall outcome of the R&D cooperation. This is particularly the case if S-ownership is not too inferior: As an exit option for S improves the investment relative to S-ownership, the option contract is more likely to yield the most preferable outcome. Generally, the optimal strike price will be equal to or higher than P_2 but below P_3 : P_2 will only be optimal if choice of S-ownership and the specific technology is the (weakly) preferred contract design initially; setting the strike price above P_3 will always be inferior to M-ownership as the latter yields the same level of inventing-around but higher investments by M. Moreover, as it is always combined with the specific technology, this technology will be implementable more often than without an option contract.

Proposition 3

Allowing for option contracts on ownership by giving S an exit right (weakly) improves the return from the R&D cooperation and shifts the choice of technological design in favor of the specific technology.

Despite (weakly) improving the outcome of the R&D allocation, option contracts on ownership are not able to achieve first-best. There is still a positive level of inventing-around, i.e. investments in unproductive and costly activities.

Even permitting for sequentiality of moves as in Nöldeke and Schmidt (1998) would not lead to first-best results with options on ownership because of the fact that we allow only for partial ownership of M on the full value of the patent (reflected in $a < 1$, which implies that M cannot be induced to invest optimally even with M ownership). Furthermore, we analyze in contrast to Nöldeke and Schmidt (1998) a situation in which one of the parties may change its outside option via its investment (S may open up the possibility of a non-exclusive use of the new technology via its inventing-around activities).

Finally, instead of giving S an exit right, an option contract may allocate this right to M. This kind of contract will also enable the firms to realize investments at levels between those under M-ownership and S-ownership. However, there is no unambiguous improvement over either of the pure ownership cases. In case of S holding the exit right, M could adjust its investment I to counter an undesirable option exercise by S. If M holds the option, the interaction between its investment and the subsequent exercise is more complex. By choosing different levels of its investment, M may commit to different exercise strategies for given strike prices. This gives rise to multiplicity of equilibria and issues of equilibrium selection. However, the general mechanisms and trade-offs remain intact.

5.2 Renegotiation

Allowing for renegotiation before the investment decisions in $t = 3$ does not change matters at all. All variables are not yet contractible making renegotiation pointless. Neither renegotiation of ownership (which yields the same result as in the absence of renegotiation) nor of monetary transfers change anything compared to the initial stage since the contracting environment has not changed yet.

The same is true with respect to renegotiating ownership after stage 3 when investments in cooperative R&D have been realized. This is due to the fact that bargaining leads to an outcome which maximizes the joint payoffs of firms S and M irrespective of ownership. Hence, renegotiation does not have any impact on the outcome realized and the distribution of profits, thereby leaving the results of the overall game unchanged.

6 Non-exclusive Use of the New Input

We now review the result of our analysis when the assumption about the strength of the competitive effect is reversed. Hence, we change the parameter restriction of the base model by allowing for parameter constellations which lead to non-exclusive use of the technology in the three-party bargaining process. Specifically, let

$$\Delta < \frac{V_C}{2} \quad (10)$$

in the following. Similarly, let

$$c > \frac{V_C}{2} \quad (11)$$

in order to focus on inner solutions in investment decisions.

In the bargaining stage, the new parameter assumption only matters in case of three-party bargaining. The jointly created surplus that is now shared between M and S is now maximized by choosing a non-exclusive use of the new input.⁷ Although this affects the expected payoffs of the two firms, it does not alter M's investment incentives as the marginal value of his investments does not depend on exclusivity. However, S's incentives are altered under non-exclusivity ex-post. In contrast to the base model, inventing-around is now a (partly) productive activity in case the specific technology was chosen: Opening up the possibility of a sale to C increases the rents created by the new input. Hence, some degree of inventing-around is value-enhancing. Nevertheless, even in this case inventing-around is excessive: It not only enables the two firms to increase the joint surplus, but also improves S's bargaining position by creating an outside option.

Overall, we get the following results:

Proposition 4

1. *Successful inventing-around results in non-exclusive use of the new input.*
2. *The combination of S-ownership with general technology is never optimal.*

⁷The payoffs accruing to C in the bargaining process do not matter for the cooperation and are therefore disregarded here.

3. *M and S are indifferent between choosing S-ownership with specific technology, M-ownership with specific technology and M-ownership and general technology if*

$$\frac{\Delta(2+a)}{(2-a)\sigma^2} = c = \frac{(V_C - 2\Delta)^2 - \Delta^2}{2a - a^2 + 4(V_C - 2\Delta) - 3(\sigma^2 - 1)} \quad (12)$$

Proof: See the appendix.

The result is very similar to the base model: It is never optimal to give all (bargaining) power to S, because that would reduce M's investment incentives too much, while inventing-around can always be avoided by the choice of technology. Even more important, the market solution again leads to too little specificity in this setting as well. Despite the fact that ex-post non-exclusivity maximizes the joint surplus, it can be efficient to choose a specific technology in order to raise M's investment productivity. Non-exclusivity may then still be realized by S's inventing-around. However, since this inventing-around is excessive under the specific technology, the general technology is chosen too frequently by the firms. Finally, the following corollary shows that the general structure of our earlier comparative static results for optimal contract choices remain valid under ex-post non-exclusivity.

Corollary 2

Let (12) be fulfilled. Then a marginal increase (decrease) in

- *a results in M and S choosing M-ownership and the general technology (M-ownership/specific technology)*
- *σ results in M and S choosing M-ownership and the specific technology (M-ownership/general technology)*
- *V_C results in M and S choosing M-ownership and the general technology (M or S-ownership/specific technology)*
- *Δ results in M and S choosing S-ownership and the specific technology (M-ownership/general technology)*

Proof: See the appendix.

7 Conclusion

A major source for the innovative development of firms are the innovative efforts of their suppliers which lead to technological enhancements of the final product. At the very same time these innovative efforts of the supplier are often undertaken at least to some degree collaboratively with the buyer. These joint R&D processes allow the combination of both parties' stock of knowledge. Obviously, given the problems associated with contracting on the output of R&D this leaves room for potential exploitation of one side by the other and hence to inefficiency. Against this setting, this paper explores the design and structure of vertical R&D collaborations which we observe in many instances.

Using an incomplete contracting framework, our model aims to capture important issues related to vertical R&D cooperation while still being simple enough to detect clear-cut mechanisms. Our analysis yields the following empirically testable hypotheses for R&D collaborations:

- H1: The more intense product market competition, the more often the supplier becomes the owner of the innovation.
- H2: The more important the supplier's production expertise, the more often the manufacturer becomes the owner of the innovation.
- H3: Option contracts/exit rights increase the returns to R&D cooperations. Therefore, the lower the costs of contracting on contingent ownership (a) the more often option contracts should be used, and (b) the more R&D cooperations should be observed.

Putting these hypotheses to the data is obviously an interesting next step.

While we believe that the model incorporates crucial feature of vertical R&D collaborations, obviously, our model abstracts from a number of aspects. First and most notably we concentrate on fixed-investment projects only. Thereby, we neglect potential hold-up problems associated with ex-ante investment decisions. Endogenizing the size of the ex-ante investment clearly aggravates the contractual problems associated with vertical R&D cooperations but leaves our main mechanisms in place. Second, we have neglected the repeated interaction between the supplier and the buyer as a mechanism to mitigate contractual problems. This is, given the focus of our analysis, clearly an important aspect. But even if one

accepts the validity of repeated interaction, it is unlikely to eliminate all contractual problems, which leaves enough room for the mechanisms stressed in the paper. Consequently, our model provides a starting point for analyzing vertical R&D collaborations more closely.

A Appendix

A.1 Proof of Lemma 1

Part 1. In the two-party bargaining process, exclusive use is the only available option with $a_i V_M^X$ as M's payoff in case of disagreement and zero alternative payoff for S.⁸ In the random proposer bargaining, the proposer offers this disagreement payoff to the other party (who accepts the proposal) and pockets the difference between V_M^X and the offer. With equal probability of being the proposer, this yields the expected payoffs given in (3) and (4).

Part 2. In the three-party bargaining process, the disagreement payoff of M depends not only on ownership (via a_i) but also on the final use of the new input (V_M^X versus V_M). Similarly, S also receives some payoff from bargaining with C in case bargaining with M breaks down or results in non-exclusive use. Given zero disagreement payoffs for both S and C in their bargaining, the expected (potential) payoff for S is $V_C/2$.

In the M-S bargaining process, the proposer not only offers the responder some payoff but combines this payoff with the final use of the new input. Hence, the proposer chooses between two potential offers – under non-exclusivity or exclusivity, taking into account the corresponding disagreement payoffs. Consider the optimal offers for S: In case of disagreement, M may always realize $a_i V_M$ because S is then free to sell the new input to C. Thus, S offers this to M and receives:

$$\pi_S(S \text{ proposer}) = \begin{cases} V_M^X - a_i V_M & \text{under exclusivity} \\ (1 - a_i)V_M + \frac{V_C}{2} & \text{under non-exclusivity} \end{cases} \quad (13)$$

For $\Delta \geq \frac{V_C}{2}$, see (1), exclusivity yields a (weakly) higher payoff.

Next, let M be the proposer. In case bargaining breaks down or yields non-exclusivity, S receives $V_C/2$. This has to be offered in order to induce S to accept an exclusivity agreement. The payoff structure for M is then

$$\pi_M(M \text{ proposer}) = \begin{cases} V_M^X - \frac{V_C}{2} & \text{under exclusivity} \\ V_M & \text{under non-exclusivity} \end{cases} \quad (14)$$

⁸For the sake of brevity, we omit denoting V_M^X and V_M as functions of σ .

Again, for $\Delta \geq \frac{V_C}{2}$, exclusivity yields a (weakly) higher payoff. Combination of these proposer payoffs and disagreement payoffs (for the receiver) yields the expected payoffs and the final use of the new input as specified in the lemma. ■

A.2 Proof of Lemma 2

Using the results of lemma 1, we can specify the expected payoffs depending on the final use of the good (exclusivity/non-exclusivity), ownership (determining the value of a_i), and the technology (specific/general). Note that for general technology, bargaining always takes place between the three parties, while it is only possible with probability q (successful inventing-around) for the specific technology.

$$E[\pi_M] = \begin{cases} \frac{1}{2}(Y_M^X + I) - \frac{V_C}{4} - \frac{1}{2}I^2 & \text{for } S, 0 \\ \frac{1}{2}(Y_M^X + I) + \frac{a}{2}(Y_M + I) - \frac{V_C}{4} - \frac{1}{2}I^2 & \text{for } M, 0 \\ \frac{1}{2}(Y_M^X + \sigma I) - q\frac{V_C}{4} - \frac{1}{2}I^2 & \text{for } S, \sigma \\ \frac{1+a}{2}(Y_M^X + \sigma I) - q(\frac{V_C}{4} + \frac{a}{2}\Delta) - \frac{1}{2}I^2 & \text{for } M, \sigma \end{cases} \quad (15)$$

$$E[\pi_S] = \begin{cases} \frac{1}{2}(Y_M^X + I) + \frac{V_C}{4} - \frac{c}{2}q^2 & \text{for } S, 0 \\ \frac{1}{2}(Y_M^X + I) - \frac{a}{2}(Y_M + I) + \frac{V_C}{4} - \frac{c}{2}q^2 & \text{for } M, 0 \\ \frac{1}{2}(Y_M^X + \sigma I) + q\frac{V_C}{4} - \frac{c}{2}q^2 & \text{for } S, \sigma \\ \frac{1-a}{2}(Y_M^X + \sigma I) + q(\frac{V_C}{4} + \frac{a}{2}\Delta) - \frac{c}{2}q^2 & \text{for } M, \sigma \end{cases} \quad (16)$$

The optimal levels of investment and inventing-around and their relative magnitudes follow then directly. (2) ensures interior solutions for inventing-around. ■

A.3 Proof of Proposition 1

Inserting the optimal levels of investment and inventing-around of lemma 2 into the payoff functions (15) and (16) yields the following structure of joint surplus $TS \equiv E[\pi_S + \pi_M]$:

$$TS = \begin{cases} Y_M^X + \frac{3}{8} & \text{for } S, 0 \\ Y_M^X + \frac{3+2a-a^2}{8} & \text{for } M, 0 \\ Y_M^X + \frac{3\sigma^2}{8} - \frac{V_C^2}{32c} & \text{for } S, \sigma \\ Y_M^X + \frac{(3+2a-a^2)\sigma^2}{8} - \frac{(V_C+2a\Delta)^2}{32c} & \text{for } M, \sigma \end{cases} \quad (17)$$

Part 1. $TS_{S,0}$ is always smaller than $TS_{M,0}$ for $a \in (0, 1)$.

Part 2. (7) follows from solving $TS_{S,\sigma} = TS_{M,\sigma}$ and $TS_{S,\sigma} = TS_{M,0}$ with respect to c . ■

A.4 Proof of Corollary 1

The pairwise differences in joint surplus are

$$TS_{S,\sigma} - TS_{M,\sigma} = \frac{a}{8c} (a(V_C\Delta + a\Delta^2) - c\sigma^2(2a - a^2)) \quad (18)$$

$$TS_{M,0} - TS_{M,\sigma} = \frac{1}{32c} ((V_C + 2a\Delta)^2 - 4c(\sigma^2 - 1)(3 + 2a - a^2)) \quad (19)$$

$$TS_{M,0} - TS_{S,\sigma} = \frac{1}{32c} (V_C^2 - 4c(3(\sigma^2 - 1) - 2a + a^2)) \quad (20)$$

The pairwise comparative static effects can then be confirmed directly (when evaluated using the indifference condition), where the signs are immediately visible with one exception:

$$\begin{aligned} \frac{d(TS_{M,0} - TS_{M,\sigma})}{da} &= \frac{1}{32c} (4\Delta(V_C + 2a\Delta) - 4c(\sigma^2 - 1)(2 - 2a)) \quad (21) \\ &= \frac{12\Delta V_C - 2V_C^2 + 2a(\Delta^2(12 + 4a) + V_C^2 + 2a\Delta V_C)}{32c(3 + 2a - a^2)} \quad (22) \\ &> 0 \end{aligned}$$

where we used the indifference condition $c = \frac{(V_C + 2a\Delta)^2}{4(\sigma^2 - 1)(3 + 2a - a^2)}$ and the condition $\Delta \geq V_C/2$. Finally, combination of all three pairwise comparisons yields the overall changes at indifference between all three ownership/technology structures (see also table 1). ■

A.5 Proof of Lemma 3

We will first derive and characterize the equilibrium in case of initial M-ownership and a call for S. Afterwards, we will show how initial S-ownership and a put for S yield the same equilibrium conditions.

Consider first the optimal exercise strategy by S: After successful inventing-around, S exercises the option if

$$\frac{a}{2}(Y_M + \sigma I) - P \geq 0 \quad (23)$$

If inventing-around failed, the option is exercised if

$$\frac{a}{2}(Y_M^X + \sigma I) - P \geq 0 \quad (24)$$

If both inequalities are (neither inequality is) satisfied, the equilibrium is the same as under S-ownership (M-ownership).

Next, we derive the equilibrium conditions in case of asymmetric option exercise. (8) and (9) yield the best response functions

$$I^C = \frac{\sigma}{2}(1 + aq^C) \quad (25)$$

and

$$q^C = \frac{V_C}{4c} + \frac{1}{c} \left(P - \frac{a}{2}(Y_M + \sigma I^C) \right) \quad (26)$$

where I^C and q^C denote equilibrium choices under asymmetric option exercise. These two equations yield equilibrium investments

$$I^C = \frac{\sigma(4c + aV_C - 2a^2Y_M + 4aP)}{2(4c + a^2\sigma^2)} \quad (27)$$

and

$$q^C = \frac{V_C - a\sigma^2 - 2aY_M + 4P}{4c + a^2\sigma^2} \quad (28)$$

Solving conditions (23) and (24) for P at equality yields the minimum and maximum strike for asymmetric exercise. Evaluating S's best response function at these levels yields, at the lower boundary, $q^C = q_{S,\sigma}$ and, at the upper boundary, $q^C = q_{M,\sigma}$. Hence, equilibrium inventing-around by S is continuous in P and increases in P in case of asymmetric exercise. For M's investment, note that the equilibrium level in case of asymmetric exercise is increasing in P (see (27)) and lies strictly between the levels under S-ownership and M-ownership (see (25) and note that $0 < a < 1$ and $0 < q^C < 1$).

In order to ensure consistency of M's investments with the subsequent exercise by S, solve conditions (23) and (24) for I and combine these conditions with M's optimal investments: Combining $I_{S,\sigma}$ and condition (23) yields $P \leq P_1$; combining $I_{M,\sigma}$ and the reverse of condition (24) yields $P \geq P_4$; and for I^C to satisfy condition (24) and violate condition (23) requires $P_2 \leq P \leq P_3$.

For $P \in (P_1, P_2)$, neither I^C nor $I_{S,\sigma}$ are consistent with S's optimal option exercise: If S were expected to exercise asymmetrically, then the equilibrium

investment by M would be high enough to induce S to always exercise the option; if S were expected to exercise always, the equilibrium investment would be so low that asymmetric exercise would be optimal. Hence, M's optimal feasible investment is such that S is indifferent about exercising in case of successful inventing-around. This implies that the investment is such that (23) holds with equality, $I(P) = \frac{2P}{a\sigma} - \frac{Y_M^X}{\sigma}$, for $P \in (P_1, P_2)$. Consequently, $q = q_{S,\sigma}$ over the same interval. The equivalent holds for $P \in (P_3, P_4)$: M's optimal investment is such that (24) holds with equality, $I(P) = \frac{2P}{a\sigma} - \frac{Y_M}{\sigma}$, and $q = q_{M,\sigma}$. This shows that both investments are continuous functions in P and increasing in the respective intervals.

Lastly, consider the case of initial S-ownership and a put option for S: As the strike price is now a transfer from M to S, asymmetric exercise is now optimal if inventing-around was successful. For a low (high) strike price, S never (always) exercises the option and investments are as under S-ownership (M-ownership). The critical levels triggering changes in the optimal exercise remain the same, as does the post-exercise ownership structure. As a consequence, the structure of payoffs given P is identical to the previous case of initial M-ownership and a call for S. Hence, we get the same equilibrium as before. ■

A.6 Proof of Proposition 4

Part 1. This follows directly from $\Delta < V_C/2$ and the proof of lemma 1. The expected payoffs of the bargaining process are then

$$\pi_M = (1 + a_i) \frac{V_M(\hat{\sigma})}{2} \quad (29)$$

$$\pi_S = (1 - a_i) \frac{V_M(\hat{\sigma})}{2} + \frac{V_C}{2} \quad (30)$$

Parts 2. and 3. Expected payoffs depending on the final use of the good, ownership and the technology (specific/general) are:

$$E[\pi_M] = \begin{cases} \frac{1}{2}(Y_M + I) - \frac{1}{2}I^2 & \text{for } S, 0 \\ \frac{1+a}{2}(Y_M + I) - \frac{1}{2}I^2 & \text{for } M, 0 \\ \frac{1}{2}(Y_M^X + \sigma I) - \frac{q}{2}\Delta - \frac{1}{2}I^2 & \text{for } S, \sigma \\ \frac{1+a}{2}(Y_M^X + \sigma I) - \frac{q}{2}(1+a)\Delta - \frac{1}{2}I^2 & \text{for } M, \sigma \end{cases} \quad (31)$$

$$E[\pi_S] = \begin{cases} \frac{1}{2}(Y_M + I) + \frac{V_C}{2} - \frac{c}{2}q^2 & \text{for } S, 0 \\ \frac{1-a}{2}(Y_M + I) + \frac{V_C}{2} - \frac{c}{2}q^2 & \text{for } M, 0 \\ \frac{1}{2}(Y_M^X + \sigma I) + \frac{q}{2}(V_C - \Delta) - \frac{c}{2}q^2 & \text{for } S, \sigma \\ \frac{1-a}{2}(Y_M^X + \sigma I) + \frac{q}{2}(V_C - (1-a)\Delta) - \frac{c}{2}q^2 & \text{for } M, \sigma \end{cases} \quad (32)$$

These yield the investment levels of M equal to those of lemma 2 and, for $c > V_C/2$ and choice of the specific technology, inventing-around of $q_{S,\sigma} = \frac{1}{2c}(V_C - \Delta)$ or $q_{M,\sigma} = \frac{1}{2c}(V_C - (1-a)\Delta)$ with $q_{S,\sigma} < q_{M,\sigma}$.

With these investments, we get the joint surplus:

$$TS = \begin{cases} Y_M + \frac{V_C}{2} + \frac{1}{8} & \text{for } S, 0 \\ Y_M + \frac{V_C}{2} + \frac{3+2a-a^2}{8} & \text{for } M, 0 \\ Y_M^X + \frac{3\sigma^2}{8} + \frac{V_C^2+3\Delta^2-4V_C\Delta}{8c} & \text{for } S, \sigma \\ Y_M^X + \frac{(3+2a-a^2)\sigma^2}{8} + \frac{V_C^2+(3-2a-a^2)\Delta^2-4V_C\Delta}{8c} & \text{for } M, \sigma \end{cases} \quad (33)$$

For part 2., note that $TS_{S,0}$ is always smaller than $TS_{M,0}$ for $a \in (0, 1)$. Part 3. follows from solving $TS_{S,\sigma} = TS_{M,\sigma}$ and $TS_{S,\sigma} = TS_{M,0}$ with respect to c . ■

A.7 Proof of Corollary 2

The pairwise differences in joint surplus are

$$TS_{S,\sigma} - TS_{M,\sigma} = \frac{a}{8c} (\Delta^2(2+a) - (2-a)c\sigma^2) \quad (34)$$

$$TS_{M,0} - TS_{M,\sigma} = \frac{1}{8c} \left(8c \left(\frac{V_C}{2} - \Delta \right) - c(\sigma^2 - 1)(3 - 2a + a^2) - (V_C - (1-a)\Delta)(V_C - (3+a)\Delta) \right) \quad (35)$$

$$TS_{M,0} - TS_{S,\sigma} = \frac{1}{8c} \left(8c \left(\frac{V_C}{2} - \Delta \right) - c(3(\sigma^2 - 1) + 2a - a^2) - (V_C - 2\Delta)^2 + \Delta^2 \right) \quad (36)$$

The pairwise comparative static effects can then be confirmed directly, where the signs are either immediately visible or follow from $c > V_C/2$ (see proposition 4). Finally, combination of all three pairwise comparisons yields the overall changes at indifference between all three ownership/technology structures. ■

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