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Open Sourcing as a Profit-Maximizing Strategy for Downstream Firms

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Abstract. This paper characterizes and explores a corporate strategy in which downstream firms collaborate to develop open substitute designs for proprietary hardware they would otherwise purchase from upstream suppliers. This strategy centrally involves the downstream firms distributing design costs over multiple downstream firms—a strategy that is routine to producers selling to multiple downstream firms but which has been in the past typically not practical for coalitions of downstream firms. Today, downstream firms find it increasingly feasible to codesign products they may all purchase because of two technological trends. First, computer-aided design/computer-aided manufacturing and other design technologies are lowering downstream firms' costs to develop designs for purchased hardware inputs. Second, better communication technologies are lowering the costs of doing such projects collaboratively, even among large groups of downstream customer firms. Downstream firms collaborating to develop a design for a hardware input they can all purchase could in principle choose to protect their design as a club good. However, opening up collaboratively created designs to free riders can increase the profits of the contributing firms for several reasons we explore and model. Important among these is that free revealing draws free riders away from purchases of proprietary software or hardware to customer-developed free substitutes. This "scale-stealing" mechanism reduces the markets of upstream suppliers of competing proprietary inputs. In the case of hardware only, free riders also contribute to reducing the average manufacturing costs of the open hardware by increasing purchase volumes and so creating increased economies of scale. Resulting reduced unit purchase costs benefit downstream firms contributing to the free design as well as free riders.

Keywords: competitive advantage • competitive strategy • open innovation • technology strategy • corporate strategy • user innovation paradigm • user–producer interactions • social welfare • complementarities • division of innovative labor • externalities • economics of user innovation

1. Introduction and Overview

In markets and situations where there are many potential downstream firms rather than a monopsony, it has historically been assumed that the party that can justify investing the most in developing a proprietary design is upstream suppliers rather than the downstream firms. The reason is that suppliers can spread their development costs over many downstream firms, whereas individual downstream firms have historically not been in a similar position. In line with that logic, a major focus of the strategy literature has been on investments in design development *by* suppliers intended for sale *to* downstream firms. In this literature, it is implicitly assumed that the role of the downstream firms is simply to choose which input supplier to patronize. In this paper we explain that, because the impacts of two technological trends, downstream firms can increasingly also spread the costs of input development over many downstream firms. The two technological trends are (1) the increasing digitization of both design and manufacturing processes (computer-aided design/computer-aided manufacturing [CAD/CAM]) and (2) decreasing costs of project communication enabled by the internet, coupled by improved project coordination possibilities enabled by improved online management tools. The mechanism for spreading the costs these trends enable is a collaborative innovation design project carried out by downstream firms—with design costs spread among contributors.

In this paper we work out the implications of the disappearance of suppliers' relative advantage over downstream firms in designing inputs that many downstream firms purchase. We show that the most profitable locus of input design is increasingly shifting from monopoly supplier firms to collaborations of downstream firms. We also show under which conditions the most profitable strategy available to such downstream collaborations is to freely reveal the designs they create to all rather than create a club good. We show that not only does this claim hold for collaborations among nonrival downstream firms—downstream firms that purchase the same input but are not rivals in the marketplace—but it also holds in the case of downstream firms that *are* marketplace rivals.

Downstream development of free inputs, the strategy we describe and analyze, is orthogonal to the *horizontal* strategy suppliers engage in that has been described by and explored by Teece (1986), Casadesus-Masanell and Llanes (2011), Alexy et al. (2018), and others. In that horizontal strategy, suppliers make some products in a bundle of complements free to concentrate rent capture in other elements of the bundle. By contrast, in the strategy we describe, downstream firms collaboratively create substitute free designs for proprietary upstream inputs they purchase; it is a *vertical* strategy.

The decision of downstream design collaborators to make their designs open to free riders, instead of protecting them as proprietary club goods, is driven both by a desire to avoid the costs that would be required to prevent free riding and by positive benefits associated with granting access to free riders. One of the positive benefits is that some free riders also become valuable contributors when granted full access to design information. Furthermore, as a previously unrecognized benefit, in this paper we show by modeling that, in the case of collaboratively developed designs embodied in hardware, demand for the free design by free riders increases economies of scale in production of that open hardware design—while at the same time "stealing scale" from producers of closed, proprietary designs. Both effects lower purchase costs for both contributors and noncontributors who switch from purchasing inputs incorporating proprietary designs to those incorporating open hardware designs.

In our model, we show that an open strategy equilibrium arises endogenously; that is, even competing downstream firms can find it profitable to share knowledge and to distribute it openly outside their coalition. Our model and outcomes do not rely on ad hoc arguments: we show that the open strategy emerges as an equilibrium strategy that can dominate the alternative strategies of relying on the supply of an upstream supplier or producing the input within a proprietary coalition of downstream firms (club good).

The likely general importance of an "open inputs" strategy based on collaborative development of input designs by downstream firms can readily be seen. After all, every firm resides in a supply chain and buys inputs from upstream suppliers to incorporate into the products, processes, and services that they use or sell. Widespread adoption of the open inputs strategy we describe can therefore produce a general shift toward design openness. This in turn, as we discuss, has important implications for national economies in general as well as for supplier strategies in particular. Suppliers impacted by the development of open substitutes for their proprietary design may need to recenter their competitive strategies on designs and other assets that may differ from their core competences but that *cannot* be economically replicated by downstream firms. These may involve, for example, linking potentially vulnerable individual designs to proprietary complements that cannot be economically replaced by open designs from input purchasers—a strategy regularly and profitably resorted to by platform owners (Zhu and Iansiti 2012).

An example of the pattern we describe is the Open Compute Project. This very successful open source hardware design project was launched in 2011 by Facebook to create open substitutes for proprietary hardware designs it had previously purchased from suppliers. Rather than using the technology only internally, or creating a club good open only to a few firms, Facebook created an open design collaboration to further develop the designs, and it freely revealed the designs to all. Facebook terms this strategy *open source hardware*. Hardware incorporating the free designs developed by Open Compute Project participants is available from a number of producers as "white box" nonproprietary products (Dignan 2015). The open compute website claims these customer-developed designs are 38% more energy efficient and 24% less expensive to run than proprietary hardware substitutes available for purchase (Open Compute Project 2018a).

The remaining sections of this paper are organized as follows. We first explain the exogenous technical trends that we believe are causing a general shift in the locus of design from proprietary design development by input suppliers to open design development by customer collaborations in Section 2. Next, we review the literature relevant to our topic and argumentation in Section 3. Then, we set up and present our model in Section 4. Finally, we conclude with a general overview of findings; a discussion of recent examples of downstream open source collaborations; some exceptions to the general trend toward openness; and strategy, economic, and policy implications of the spread of free input designs over time in Section 5.

2. Technical Trends Affecting the Locus of Design

2.1. Impacts of CAD/CAM on the Relative Advantage of Producer vs. Customer Designers

We define a design to be a set of instructions that specify how to produce a product or service (Simon 1981; Romer 1990; Suh 1990; Baldwin and Clark 2000, 2006). These instructions can be thought of as a recipe for accomplishing the functional requirements of the design (Suh 1990, Dosi and Nelson 2010, Winter 2010). The cost of developing a design includes the cost of identifying the functional requirements (i.e., what the design is supposed to do). It also includes testing and modifying the design until its performance is found to be satisfactory in the intended use environment. In the case of products or services that themselves consist of information such as software, a design for an innovation can be identical to the usable product itself. In the case of a physical product such as a computer or medical device, the design recipe must be converted into a physical form before it can be used.

In pre-CAD/CAM days, the design of hardware was a specialized process most efficiently done by colocated experts. In those days, there were major economies achievable by concentrating a design effort within a single organization. To explain, consider that, prior to the advent of CAD, designs were created and documented by designers leaning over drafting boards and physically drawing part shapes and dimensions on large sheets of paper called engineering drawings. Integration of the design of individual parts into a complete hardware product was achieved by a continuous flow of discussions among colocated engineers and by the sharing and comparison of engineering drawings. Periodically, a design under development would be transferred to a model maker via a set of these drawings, with instructions to build a physical prototype. When the model maker completed the task, the prototype would be physically tested on specialized engineering test equipment run by specialized test engineers. Test information would be analyzed and transferred back to the designer as input to a next design improvement cycle. Each such design-build-test cycle could take days or weeks, depending on the complexity of the design.

The transition to CAD digital design tools completely changed this laborious process. Today, the tools needed to test an evolving design are cheap, digital, and built into CAD software. The result is a great reduction in the cost and expense formerly required to build and test physical models. Designers—whether working in a customer firm or in a producer firm—are now able to test the performance of their evolving designs via simulation in minutes. For example, a car designer using CAD can, as an integral part of the design process, invoke a simulation technique such as finite element analysis to assess how a single component or an entire car design will react to the forces of a crash. Each such assessment is done by the designer him- or herself entirely within CAD software, without the need for specialized assistance or specialized physical equipment. The designer then can immediately revise and refine his or her design in response to what is learned.

Next, consider that CAD software also contains information about the capabilities of many types of standard production machines that will be used to produce the design once completed. For example, the precision with which a specific process machine can three-dimensionally print a part can be embedded in CAD design software. The CAD software can then automatically inform a designer whether a design being created will require modifications to be producible on that printer. When a design is completed in CAD, it can be directly transferred as a digital file to computerized manufacturing machines (CAM). These machines are driven by the CAM information to produce component parts of the design in small or large quantities, ready for final assembly. The consequence of embodying the characteristics of manufacturing processes in CAM is that, except in specialized cases, both customer design engineers and supplier design engineers increasingly have access to the same manufacturing information.

In sum, as a result of the introduction of CAD/CAM, the requirement for specialized design and manufacturing knowledge and equipment beyond what is imbedded in design software is decreasing over time. Along with that change, any cost advantage of basing design groups within producer firms where production specialists are concentrated—rather than within customer firms where engineers familiar with the specific requirements of application of the design within the use context are concentrated—is disappearing, and producers are becoming increasingly interchangeable. Indeed, both "producers" such as IBM and collaborating customers are increasingly outsourcing the production of their designs to the same set of specialist low-cost producers such as Foxconn, which make their factories available to all on the same terms (Pine 1993, Tseng and Piller 2003).

2.2. Impacts of the Internet and Online Project Coordination Support Tools

CAD-based design can be carried out by even widely dispersed contributors to a design project because of advances in internet-based communication. Information transfer via the internet is so cheap today that the information exchange advantage of physical colocation of project contributors within a specific firm is vanishing. In addition, the development of online project management systems such as GitHub (https://github.com) means that innovation projects can be efficiently coordinated by contributors working within very lightly managed collaborative teams: the project management software itself largely substitutes for coordination functions traditionally provided by human managers. Indeed, GitHub and similar technologies have made it easier for individuals and firms to collaborate in every element and stage of design development, including idea generation, idea sharing and evaluation, idea selection, prototyping, and iterative testing and collaborative improvement as well.

Open source software project participants have generally been the pioneers in increasing the capabilities of online project management systems. However, the principles of the systems they have developed are equally applicable to any project subject matter. Thus, GitHub was designed by Linus Torvalds and his colleagues to coordinate development work in open source software projects. However, today it is used for a wide range of online hardware design projects as well. GitHub software specifies a coordinated workflow that allows independent design work by contributors, followed by processes to test and correct and improve that work with the assistance of others before the contribution is added to the overall design. GitHub is available for free to open source and public projects and at a fairly modest price to commercial projects. A modular architecture, often used in modern design practice, enhances the efficiency with which contributions can be made and coordinated (Baldwin and Clark 2000).

The net result of combining CAD/CAM with low-cost internet-based communication and modern project coordination tools is that the design cost advantage that monopoly producers used to have over multiple customers in creating a design has diminished and perhaps even reversed. Advantages formerly held by producers such as the need for costly investments in specialized, collocated development processes and equipment have largely become irrelevant in the age of CAD/CAM. Furthermore, the wider range of potential contributors likely to be available to an open customer coalition is likely to give access to more usefully diverse design and problem-solving knowledge than can even the largest of closed, in-house producer design teams (Jeppesen and Lakhani 2010).

3. Literature Review

3.1. The Locus of Design as a Function of Market Concentration

Under conditions of monopsony it is reasonable that the downstream firms, rather than potential producers, have the highest incentive to invest in developing a product design specific to that single customer (Harhoff 1999). The downstream firm can spread its costs over the entire market—consisting only of itself—with a high degree of certainty. By contrast, an input supplier faces risk in responding to that market opportunity, because the monopsony may make another choice or may engage in opportunism once the supplier has made buyer-specific investments. Accordingly, potential suppliers systematically view the opportunity as having less value than would a monopsonist.

As the market for a proprietary design becomes less concentrated, it has been traditionally assumed, for reasons discussed in Section 2, that the potential reward to individual downstream firms from developing their own design progressively drops. At that point, it generally pays suppliers more to develop a proprietary product design to serve downstream input needs. The reason traditionally adduced is that suppliers can spread their design costs over many downstream firms and also reap economies of scale by producing for and serving many buyers. Harhoff (1999), in a pioneering analysis of research and development (R&D) intensity in vertical supply chains, both proposed and documented this effect. Specifically, he found that fragmented buyer industries that receive relatively large cost shares of their inputs from concentrated supply sectors have a significantly lower R&D intensity than sectors relying on more competitive supply structures. He also found that this effect is weakened and eventually reversed as the concentration of the downstream industry increases.

3.2. Innovation and Free Revealing Strategies by Suppliers

Following seminal work by Teece (1986, 2006), an important focus in the strategy literature is that producers are best positioned to capture customer surplus arising from a proprietary product design to the extent that they successfully execute a strategy involving (1) establishing tight control over a focal innovation and/or over one or more complements essential to design purchasers (a “bottleneck”) and (2) making all other complements needed by the customer either free or as low profit as feasible while ensuring a supply (Jacobides et al. 2006, Baldwin 2018). The strategic goal is to enable firms to capture a greater portion of the potentially available customer surplus with reduced investment. Thus, Alexy et al. (2018) analyze strategies related to management of a “bundle” of resources related to a market. They say, “Conventional wisdom holds that firms must control scarce and valuable resources to obtain competitive advantage. That being said, over the past decade many firms—amongst them Computer Associates, IBM, and Nokia—embarked on open strategies and made parts of their valuable resources available for free. . . . Firms significantly improve their performance when (1) opening resources reduces their cost base while (2) strongly increasing demand for their still-proprietary resource(s)” (Alexy et al. 2018, p. 1704).

They also explain how openness can reshape markets by weakening competitors, particularly in highly rivalrous environments.

Similarly, Casadesus-Masanell and Llanes (2011) develop a rich model about the strategy suppliers can use when deciding whether to make some of their products free. They find conditions under which the supplier firm is best off keeping all its products proprietary, making them free, or adopting a "mixed-source" strategy in which some products are kept proprietary and others are made free. As with Alexy et al. (2018), the logic of the mixed-source strategy these authors propose is that the availability of a product for free can concentrate rents into the sale of proprietary complements. In addition, the quality of freely revealed complements can be increased as a result of feedback and improvements from others. Henkel et al. (2013) discuss circumstances in which customers may pressure suppliers to partially open up only some *aspects* of their proprietary designs in order to make their products more attractive for customers to purchase and use.

Papers such as Alexy et al. (2018) and Casadesus-Masanell and Llanes (2011) explain, for example, the strategy of IBM when it decided to support the free operating system called Linux. Its goal was to reduce the profitability of its rival, Microsoft, by improving a free substitute to Microsoft's proprietary operating system called Windows. It also hoped to gain profits from increased sales of the complementary computer hardware products it sold—and that Microsoft did not sell. More generally speaking, the same logic is applied in papers that study the reasons why firms manage spillovers strategically (e.g., Giarratana and Mariani 2013). Again, openness is pursued only to the extent that it enables the firms to enjoy increased rents on other assets that are kept proprietary.

3.3. Downstream Firms' Choices to Freely Reveal Their Designs

A downstream firm's decision to develop a design for an innovation does not automatically lead to a decision to also freely reveal it. However, many collaborative projects do freely reveal both in-process development work and final designs. This can be understood in light of the fact that the cost of screening or other protective measures to exclude free riders would raise communication costs and thus shrink the pool of potential contributors—hence the overall scale of the project. The network properties of the open collaborative model (the fact that the value to everyone increases as the total number of contributors increases) mean that this reduction in the contributor pool would reduce the value of the project to the contributors that remain as well as to free riders (Raymond 1999, Baldwin and Clark 2006, Baldwin 2008, Baldwin and von Hippel 2011, von Hippel 2017).

An additional reason to not invest in discouraging free riding is that a design, even if freely revealed, can benefit contributors more than free riders for a number of reasons (von Hippel and von Krogh 2003). First, consider that contributors can create an overall design and specific features that are tailored to their own specific needs. Free riders cannot do this by construction, as they do not contribute to the design. If, as a result, they are less advantageously situated with respect to the design that is freely shared, they may incur a lasting competitive disadvantage (Hirschleifer 1971, Allen 1983). Second, contributors to a design systematically gain advantages over free riders simply as a result of participation in the design process. Active developers have a deeper understanding of an evolving design and the possibilities it offers than do free riders. This can enable better, faster use of the design by developers than by free riders. A careful empirical study by Nagle (2018) has shown that firms contributing to open source software do benefit more from that software than do free riders.

Harhoff et al. (2003) explored the conditions under which a single downstream firm that developed a process innovation for its own use could profit by then freely revealing it. The path to free revealing assumed in the paper is that the innovating downstream firm would reveal the design to a process machine producer that was then free to sell copies to all—including to rivals of the innovator. The authors modeled the situation as a prisoners' dilemma involving a pair of input user (downstream) firms. It was assumed that an innovation was developed by one of the two downstream firms, and the question was, under what conditions would it be more profitable for that downstream firm to keep the design it had developed for itself or to reveal it without protection to a producer? The producer was then assumed to commercialize the design and make it available to both the innovator and the second downstream firm—a free rider.

Free revealing to a producer was found more likely to pay if (1) the intensity of competition among the two downstream firms was less, (2) the degree to which the innovation had a bias favoring the innovating downstream firm was higher, (3) the value to the innovating downstream firm of the improvements that free revealing induces the supplier (and others) to make and commercialize was higher. The authors concluded that the benefits to an innovating downstream firm from revealing to the machine-building firm—and therefore, in effect, free revealing to the entire market—very generally made free revealing the most profitable course of action. Note that unlike Casadesus-Masanell and Llanes (2011) or

Alexy et al. (2018), who explore the economics of free revealing by suppliers, Harhoff et al. (2003) focus on the economics of free revealing of developments made by individual downstream firms.

Baldwin and von Hippel (2011) explain that potential contributors will choose to participate in an *open* collaborative innovation project if the increased communication cost each incurs by joining the project is more than offset by the value of designs obtained from others. They formalize this idea by assuming that a large-scale innovation opportunity is perceived by a group of N communicating designers. As rational actors, each member of the group (indexed by i) will estimate the value of the large design and parse it into two subsets: (1) that part, valued at v_{si}, which the focal individual can complete himself at a reasonable cost (by definition, $v_{si} > d_{si}$); and (2) that part, valued at v_{oi}, which would be "nice to have" but which he cannot complete at a reasonable cost given his skills and other information on hand (by definition, $v_{oi} \leq d_{oi}$).

They further assume that member i has the option to communicate his portion of the design to other members and receive their feedback and complementary designs at a cost c_i. It then makes sense for i to share his designs if he expects to receive more value from others than his communication cost. The lower the cost of communicating with the group, the lower the threshold other members' contributions must meet to justify an attempt to collaborate. Higher communication costs affect inequality (2) in two ways: they increase the direct cost of contributing, and they reduce the probability that others will reciprocate. It follows that if communication costs are high, an open collaborative project cannot get off the ground. But if communication costs are low for everyone, it is rational for each member of the group to contribute designs to the general pool and expect that others will contribute complementary designs or improve on his own design.

Studies also explore innovation and competition among "open source" and "closed source" software suppliers. According to this literature, "open source projects" supply their code for free; they do not behave strategically in competition with commercial substitutes. Users can choose to contribute to the supply of open source software code, to free ride on the effort of others, or to buy the producer software. Their choices are determined by heterogeneity in users' willingness to pay, development capabilities, adoption costs, and impatience for a solution meeting their needs. Conclusions of this emerging literature are as follows: open source projects can establish themselves as competitors to closed software producers, producers lose profit as a result of this competition, and consumers benefit from the existence of an open source alternative unless it forces proprietary firms to exit the market (Kuan 2001, Baldwin and Clark 2006, Casadesus-Masanell and Ghemawat 2006, Sen 2007, Lin 2008).

4. The Model

4.1. Model Overview

We develop a model that explains the mechanisms that can give rise to an equilibrium in which downstream firms develop an open strategy to collaboratively create a design embedded in a hardware input. In the model, the downstream firms we focus on compete to sell a final product. These competing firms all purchase the same proprietary hardware product as an input from a monopoly supplier. The design for that input is incorporated in a physical good that must be manufactured. This brings economies of scale in manufacturing into our analysis in the case of open source hardware. To make this important distinction clear, we call the type of input we analyze "open source hardware" as opposed to the case of a pure information input, which we call "open source software."

We focus on a monopolistically competitive market in which the degree of competition is captured by the number of competitors in the final market and the elasticity of demand across the final products of the firms. In these models the profits of firms decline if the number of rivals increase or the elasticity of demand is higher. However, our model shows that a large number of downstream rivals also implies that a manufacturer of a good that embodies the design enjoys a greater scale efficiency if more downstream firms demand the same product, which increases the scale of the quantity of input employed in the industry. Thus, a larger number of competing firms has two countervailing effects: on the one hand, it enhances competition, but on the other hand, it raises the profitability of strategies that rely on a common input. Our model discusses the conditions under which a larger number of downstream firms raises the benefits of an open strategy relatively more than the competitive effect that would push firms to adopt closed strategies.

In our model, the downstream firms can choose among three strategies. First, they can buy the input from a monopolist upstream supplier. Second, one or more downstream firms can vertically integrate and produce the innovation for itself/themselves as a proprietary individual or club good rather than buying it from the supplier. Third, downstream firms can collaborate to produce a substitute design and adopt an open strategy with respect to that design, making the design available to all downstream firms. The model explains which factors make any one of these three strategies more profitable than the other two. We show that relative profitability depends fundamentally on our two technological trends—that is, the design efficiency of collaborating downstream firms versus producers, and the efficiency of communication among firms—as well as the scale of demand by downstream firms using the design and the extent to which free riders benefit from the open design.

Our model additionally brings a new perspective on the role of free riders. They are crucial in making the open equilibrium possible because, by leaving the monopolist supplier, they reduce its scale efficiency, encouraging more downstream firms to leave the monopolist and use the open design. However, a crucial assumption, which we discussed in the previous section, is that free riders benefit less from using a good than do firms that contribute to it. This assumption makes it possible that as more buyers leave the monopolist, reducing the efficiency with which it is produced, only some firms that use the open design free ride, whereas others find it more profitable to contribute to it. The model shows that, in equilibrium, the share of firms that free ride versus those that contribute depends on the extent to which free riders benefit from using the open design. If the penalty compared with contributors is low, more firms free ride than contribute, making the open equilibrium less likely. Thus, for an open equilibrium to arise, free riders play the important role of inducing more contributors. However, there must be some advantage in contributing; otherwise, there are too many free riders vis-à-vis contributors to make the open strategy profitable.

This also highlights why an open strategy is more likely to arise with open source hardware than open source software. In open source hardware, when free riders leave the monopolist, they reduce the scale efficiency of the proprietary physical product that embodies the design—an effect that is not present when the good is an information product, consisting only of the design (e.g., software). This makes the role of the free riders more important in "scale stealing" from the monopolist and favoring the open coalition. As a result, in open source hardware, each free rider pushes more firms—and therefore more contributors—to move to the open design, making the open strategy equilibrium more profitable and therefore more likely.

Finally, our model speaks to the literature in industrial organizations that focuses on firm's strategies to raise rivals' costs. Salop and Scheffman (1983, 1987) provide a general model in which firms maximize profits by raising rivals' costs. Their model encompasses several strategies. However, their goal is to discuss strategies that increase rivals' costs without violating antitrust laws (such as predatory pricing). In our case, firms focus on a scale-stealing effect that is not discussed by this literature. Moreover, the strategy that we envision makes firms relatively more efficient than the rival (e.g., the supplier), which is clearly a permissible strategic behavior. Our model is also a value creation strategy, very much in the sense of Brandenburger and Stuart (1996). In this case as well, not only do we highlight a value creation strategy based on openness not studied by Brandenburger and Stuart, but we also introduce a new scale-stealing effect, which is the key mechanism that makes openness profitable.

4.2. The Model

Demand for the Final Product. There are n downstream firms that compete by producing quantity q_i, $i = 1, 2, \ldots, n$, of a good that embodies a design. Firms can buy the design from a monopolist upstream supplier, or they can use a design produced by a coalition of downstream firms that collaborate. Each firm produces a different variant of the good. A standard Dixit–Stiglitz consumer utility function yields the following demand for the ith variety:

$$q_i = \frac{p_i^{-\sigma} x}{P},$$

where $\sigma > 1$ is the elasticity of demand, and $P \equiv \sum_{j=1}^{n} p_j^{1-\sigma}$ is the price index. The variable x measures the quality of the design. A higher x attracts more customers than an outside numeraire good. The quality of design x is the same for all the firms using the design from the same supplier (which can be an upstream supplier or a downstream coalition) but can differ between the two suppliers.

Gross Profits of the Downstream Firms. For simplicity, the quantity of input needed to produce q_i is q_i. The downstream firms pick the optimal price p_i that maximizes gross profits; that is,

$$\underset{p_i}{\text{Max}}(p_i - r_g)q_i,$$

where r_g is the price of the input and the index $g = U, D$ according to whether the firm buys from the upstream supplier (U) or uses the design of the downstream coalition (D). Using the expression for q_i, the optimal price is $p_i = \sigma r_g/\sigma - 1$, the unitary profit is $p_i - r_g = r_g/\sigma - 1$, and gross profits are

$$\pi_D^g = \frac{\rho_g x_g}{\sigma}, \tag{1}$$

where $\rho_g = r_g^{1-\sigma}/\rho$, $\rho \equiv (m r_D^{1-\sigma} + (n-m) r_U^{1-\sigma})$, m is the number of downstream firms that use the design produced by the coalition, and $n - m$ is the number of downstream firms that use the design produced by the upstream supplier.

Total Demand. By replacing optimal prices in p_i and in the price index P, the demand for variety i is equal to

$q_{ig} = (\sigma - 1)\rho_g x_{ig}/\sigma r_g$. Total demand is equal to the sum of demands across all varieties, or

$$Q_g = \frac{(\sigma - 1)\rho_g}{\sigma r_g} \sum_{i \in g} x_{ig}, \tag{2}$$

where the summation runs over all the varieties purchased from the upstream supplier ($g = U$) or downstream firms ($g = D$).

Manufacturing Costs. Manufacturing costs are equal to $C(y_g) = c(y_g)Q_g + y_g$, where y_g is the quantity of a fixed input employed in manufacturing such that the unit variable cost $c(y_g)$ declines with y_g. We use a special functional form for the unit variable cost; that is, $c(y_g) = c_0 y_g^{-\alpha}$, where $c_0, \alpha > 0$. Manufacturing costs are then equal to

$$C(y_g) = c_0 y_g^{-\alpha} Q_g + y_g.$$

The parameter α measures of the strength of the economies of scale in manufacturing, and c_0 is the marginal cost when there are no scale economies ($\alpha = 0$).

Cost minimization implies first-order condition (foc) $-c_0 \alpha y_g^{-\alpha-1} Q_g + 1 = 0$, which yields

$$y_g = (c_0 \alpha Q_g)^{\frac{1}{1+\alpha}} \tag{3}$$

and unit variable costs $c(y_g) = c_0{}^{1/1+\alpha}(\alpha Q_g)^{-\alpha/1+\alpha}$.

Upstream Supplier. The upstream supplier chooses r_U and x_U to maximize net profits Π_U; that is,

$$\underset{r_U x_U}{\text{Max}}\, \Pi_U = [r_U - c(y_U)]Q_U - y_U - \frac{x_U^2}{2}.$$

Using total demand (2), this problem yields the following focs:

$$1 - \frac{r_U - c(y_U)}{r_U}\tilde{\sigma} = 0, \tag{4a}$$

$$\frac{r_U - c(y_U)}{r_U} \frac{(\sigma - 1)\rho_U(n - m)}{\sigma} - x_U = 0, \tag{4b}$$

which yield

$$\frac{r_U - c(y_U)}{r_U} = \frac{1}{\tilde{\sigma}}, \tag{5a}$$

$$x_U = \frac{(\sigma - 1)\rho_U(n - m)}{\sigma\tilde{\sigma}}, \tag{5b}$$

where $\tilde{\sigma} \equiv \sigma - (\sigma - 1)\rho_U(n - m)$. In standard monopolistic competition models, the markup is simply $1/\sigma$, which stems from the assumption that because of the large number of competitors, the choice of the price by the individual firms does not affect the price index. In our case, the supplier is a monopolist, and, especially when it covers a large share of the market, we cannot ignore the effect of r_U on the denominator of ρ_U, which yields the markup $1/\tilde{\sigma}$. It is easy to see that $\tilde{\sigma} \geq 1$, that $\tilde{\sigma} \leq \sigma$, and that $\tilde{\sigma}$ increases if σ increases. Moreover, the second-order condition is satisfied because $\tilde{\sigma}$ increases with r_U, making the derivative of the left-hand side of (4a) with respect to r_U negative.

Finally, as $m \to 0$, $\tilde{\sigma} \to 1$, and from (5a), $r_U \to \infty$. This is because increases in r_U increase x_U, and the downstream firms can transfer the increase in price to the final customers by charging an infinite price p_i. To bound the prices, we only need to ensure that the demand of the final customers drops to 0 before the price goes to infinity because of competing demands for other products. Rather than incorporating such competing demands in the utility of the final consumers, which complicates our analysis, we make the simplifying assumption that there is an indivisible quantity q_0 of q_i such that q_i drops to 0 if it falls below q_0. All this ensures that even if $m = 0$, r_U is finite, and $\tilde{\sigma} > 1$. However, in what follows, we assume for simplicity that when $m = 0$, r_U is sufficiently large such that $\tilde{\sigma}$ is close to 1.

Upstream Supplier's Viability Condition. Using (2) and foc (4b), $x_U^2 = [r_U - c(y_U)]Q_U$. From (5a), $[r_U - c(y_U)] = c(y_U)/\tilde{\sigma} - 1$. Using (3) and the expression of $c(y_U)$, $\Pi_U = \left[1/2\alpha(\tilde{\sigma} - 1) - 1\right]y_U$. Therefore, the upstream supplier operates if and only if $2\alpha(\tilde{\sigma} - 1) \leq 1$ or $\tilde{\sigma} \leq 1 + 2\alpha/2\alpha$, which implies that the markup cannot be smaller than a lower bound.

External Contractor Producing Copies of Design. When the design is produced by a coalition of downstream firms, the artifact that embodies the design can be produced by one of the downstream firms or by an external contractor. The important point is that the artifact is supplied to the downstream firms at the average cost of production because there is no upstream supplier that seeks a rent from this activity. For simplicity, we assume that manufacturing is performed by an external contractor.

The price of the input produced by the contractor is $r_D = c(y_D) + y_D/Q_D$. Using our expression for $c(y_D)$, and the cost minimization choice for y_D, we obtain

$$r_D = (1 + \alpha)c_0^{\frac{1}{1+\alpha}}(\alpha Q_D)^{-\frac{\alpha}{1+\alpha}}. \tag{6}$$

Net Profits of the Downstream Firms When They Buy the Design from the Upstream Supplier. Use (1) and (5b) to obtain

$$\Pi_D^U = \left(\frac{\rho_U}{\sigma}\right)^2 \frac{(\sigma - 1)(n - m)}{\tilde{\sigma}}, \tag{7}$$

where here and in what follows we use superscripts to denote the source of the design and subscripts to denote the user of the design.

Note that the net profits of the downstream buyers increase with the supplier's markup, which is the inverse of $\tilde{\sigma}$. This is important for our discussion below when we compare these profits with the profits of the downstream firms when they use the open design. The alignment between downstream firms' profits and the supplier's markup stems from the fact that a higher markup induces the supplier to invest more in x_U, which benefits the downstream firms. At the same time, the downstream firms can transfer the increase in the price of the input r_U on the final consumers via the final price p_i.

Net Profits of the Downstream Firms When They Use the Design Produced by an Open Coalition of Downstream Firms. Downstream firms can produce the design in-house bearing costs $k/2\,x_D^2$ of producing quality x_D. The parameter $k > 0$, which measures the relative efficiency of the downstream firms with respect to the supplier, is our proxy for the exogenous technological trend that improves the ability of the downstream firms to design their inputs, discussed in Section 2.1.

If m downstream firms develop and share their design outcomes ($m \leq n$), they produce overall design quality

$$X_D = \left(\sum_{i=1}^{m} x_{Di}^{\eta-1/\eta}\right)^{\eta/\eta-1},$$

where $\eta \in (1, 2)$ is a parameter measuring the spillovers across investment qualities x_D. The parameter η is the second dimension of the exogenous technological trend that we discussed in Section 2.2. It improves the ability of downstream firms to communicate among each other, which is captured by a higher η.

Each one of the m downstream firms that contribute to the open coalition picks its own x_D to maximize profits. Use (1) for gross profits and subtract design costs $k/2\,x_D^2$. The maximization problem is

$$\underset{x_D}{\text{Max}}\,\Pi_D^O = \frac{\rho_D^O X_D}{\sigma} - \frac{k x_D^2}{2},$$

whose foc is

$$\rho_D^O\big/\sigma\left(\sum_{i=1}^{m} x_{Di}^{\eta-1/\eta}\right)^{1/\eta-1} x_{Dj}^{\frac{-1}{\eta}} - k x_{Dj} = 0.$$

(The superscript O stands for open coalition.) Because this foc is the same for all firms, all x_{Dj} are the same, which yields $x_D^O = \rho_D^O m^{\frac{1}{\eta-1}}/\sigma k$, and therefore, $X_D^O = \rho_D^O m^{\frac{\eta}{\eta-1}}/\sigma k$. This yields the following profits for a firm that participate in the open coalition:

$$\Pi_D^O = \left(\frac{\rho_D^O}{\sigma}\right)^2 \frac{\left(m^{\frac{\eta}{\eta-1}} - \frac{1}{2} m^{\frac{1}{\eta-1}}\right)}{k}. \tag{8}$$

Because the open coalition makes the design openly available, there are free riders. The free riders enjoy design quality X_D but do not incur the cost $k/2\,x_D^2$. However, as discussed in Section 3.3, they do not benefit from the design as much as if they contribute to it. We assume that free riders enjoy θX_D rather than X_D, with $0 \leq \theta \leq 1$. The free riders then earn gross profits (1) with $x_g = \theta X_D$; that is,

$$\Pi_D^F = \theta\left(\frac{\rho_D^O}{\sigma}\right)^2 \frac{m^{\frac{\eta}{\eta-1}}}{k}, \tag{9}$$

where the superscript F denotes free riders.

The number of firms that collaborate to produce the open design rather than free riding is determined by the condition $\Pi_D^F \geq \Pi_D^O$. Using (8) and (9), this yields $m \geq m^O \equiv [2(1-\theta)]^{\eta-1/2-\eta}$. Thus, an open coalition will be composed of m^O firms, and any other firms that use the open design will find it more profitable to free ride than to contribute to it. The number of firms m^O that contribute to the open coalition decreases with θ and increases with η as long as $\theta \leq 1/2$. The intuition is that as free riding becomes more profitable (higher θ), more firms prefer to free ride instead of providing a costly contribution. Similarly, as the communication technology improves, more firms are motivated to use the open design. If the penalty from free riding is high (low θ), the marginal firm finds it more profitable to use the open design and contribute to it; conversely, if the penalty is small (high θ), it finds it more profitable to free ride.

The number of firms that contribute yields the following profits in equilibrium:

$$\Pi_D^O = \Pi_D^F = \left(\frac{\rho_D^O}{\sigma}\right)^2 \frac{\Theta}{k}, \tag{10}$$

where $\Theta \equiv \theta[2(1-\theta)]^{\eta-1/2-\eta}$. These profits increase with θ if $\theta \leq 2-\eta/2$, and they increase with η if $\theta \leq 1/2$. This stems from the trade-off between the communication technology η and the penalty from free riding θ. A better communication technology raises the profits from using the open design. However, if the penalty from free riding is small, there are too strong incentives to free ride, which reduce profits.

Compare Profits from Using the Open vs. Supplier Design. The downstream firms use the open versus supplier design only if $\Pi_D^U \leq \Pi_D^O$. Using (7) and (10), this implies $(\rho_U/\sigma)^2(\sigma-1)(n-m)/\tilde{\sigma} \leq (\rho_D^O/\sigma)^2\Theta/k$. Because all downstream firms are identical, in equilibrium, they all use either the open or the proprietary design. This implies $\rho_D^O = \rho_U = 1/n$, and in the proprietary equilibrium, $m = 0$. As discussed earlier, by picking the highest possible markup, the supplier raises its own profits and the net profits of the downstream firms when the buy from the supplier. Thus, we can approximate $\tilde{\sigma} \approx 1$ and obtain

$$k \le \frac{\Theta}{n(\sigma - 1)} \equiv k^O, \tag{11}$$

where k^O is the threshold level of k such that if the technology to produce the design by the downstream firms falls below the threshold, an open design strategy on the part of the downstream firms is more profitable than buying the design from the upstream supplier. Note that k^O decreases with the extent of the competition across downstream firms (high n or σ). The intuition is that stronger competition increases the disadvantage of creating free riders for the contributing firms, which reduces the benefits of the open strategy. Also, k^O increases with θ if $\theta \le 2 - \eta/2$ and increases with η if $\theta \le 1/2$, which is a direct consequence of the effects of Π_D^O with respect to these variables that we discussed earlier.

Net Profits of the Downstream Firms When They Use the Design Produced by a Closed Coalition of Downstream Firms. A third possible case is the one in which the design is produced by a closed coalition of downstream firms. This is a fairly broad case that encompasses both vertical integration, when the number to downstream firms that produce and use the design is equal to 1, and private alliances. Unlike the open coalition, in this case, the firms do not allow others to use the design that they produce. For simplicity, we consider the case in which there is only one "club." For example, only one firm or its coalition can produce the good, whereas the other firms that do not participate in the coalition have to buy from the supplier. This is not a restrictive assumption. We could allow for the formation of more private coalitions. However, in this way we can focus on the comparison between the private alliance and the supply from the upstream provider of the design.

The problem of the closed coalition is similar to the open coalition, with two differences. First, the costs are $k/2\, m^\beta x_D^2$, where β is a parameter and m^β is the cost that the firms in the coalition have to bear to keep the design proprietary. These costs are likely to be higher if there are more firms in the coalition, and they are likely to increase if the investment x_D is larger. A higher number of firms raise the complication of contracts and the coordination among them, especially if the operations (x_D) are sizable. Another important cost, which is likely to increase with the number of partners, is the cost to ensure that the information about the technology does not leak out—that is, there is a cost associated to the very goal of keeping the knowledge proprietary, especially when there are many partners (which is also why this cost is less pronounced in the case of the supplier). As a matter of fact, we typically observe that alliances do not involve more than few firms, and on many occasions, they involve two firms. Second, the term ρ_D^C, where the superscript C now denotes the closed coalition, is no longer equal to $1/n$ such as in the case of ρ_D^O and ρ_U, but $\rho_D^C \equiv [m + (n-m)r^{1-\sigma}]^{-1}$, where $r \equiv r_D/r_U$. Specifically, in this case, $0 < m < n$, and we cannot simplify it to $m = 0$ or $m = n$ because, in equilibrium, some firms use the closed design, whereas others use the supplier's design.

It is not difficult to show that in this case the optimization problem of the firms in the closed coalition yields $x_D^C = \rho_D^C m^{1/\eta-1-\beta}/\sigma k$ and $X_D^C = \rho_D^C m^{\eta/\eta-1-\beta}/\sigma k$, and profits are equal to

$$\Pi_D^C = \left(\frac{\rho_D^C}{\sigma}\right)^2 \frac{M}{k}, \tag{12}$$

where $M \equiv m^{\eta/\eta-1-\beta} - 1/2m^{1/\eta-1-\beta}$.

The open coalition cannot choose the optimal number of contributing firms because, as shown earlier, this number is determined by the exogenous conditions that affect the benefits of free riding. Conversely, the closed coalition can make this choice, especially if, as we posit, the coalition is created by one firm that takes the initiative of vertically integrating or creating an alliance. The closed coalition then picks the optimal m^C that maximizes (12). In this optimization problem, m appears in ρ_D^C and in M. However, $\partial \rho_D^C 2/\partial m = 2(r^{\sigma-1} - 1)\rho_D^C 3$, and for n sufficiently large, this expression is close to 0. In brief, this assumes that the competitive effect of adding one more partner to the coalition is small. This implies that the optimal m maximizes M, and it is not difficult to show that this optimal level is $m^C = \left[2(\eta - \beta(\eta-1))/2 - \beta(\eta-1)\right]^{\eta-1/2-\eta}$. In what follows, we assume that β is sufficiently high such that m^C is small. If n is relatively large, this simplifies to $\rho_D^C \approx r^{1-\sigma}/n$.

Equilibrium Level of r. In the case of the closed coalition, we need to determine the equilibrium level of r. Take the ratio of (6) and the expression for r_U derived from (5a). This yields

$$r = \frac{(1+\alpha)(\tilde{\sigma} - 1)}{\tilde{\sigma}} \left(\frac{Q_U}{Q_D^C}\right)^{\frac{\alpha}{1+\alpha}}. \tag{13}$$

We can use (2), (5b), the expression for X_D^C, and the fact that $\rho_U = 1/n$ and $\rho_D^C \approx r^{1-\sigma}/n$ to obtain

$$\frac{Q_U}{Q_D^C} = \frac{n^2(\sigma - 1)k}{m^C \phi \tilde{\sigma}} r^{2\sigma - 1}, \tag{14}$$

where $\phi \equiv \eta/\eta - 1 - \beta + 1$. This yields the equilibrium level of r, or

$$r = \left[\frac{(1+\alpha)(\tilde{\sigma}-1)}{\tilde{\sigma}}\right]^{\frac{1+\alpha}{d}} \left[\frac{n^2(\sigma-1)k}{m^C\phi\tilde{\sigma}}\right]^{\frac{\alpha}{d}}, \quad (15)$$

where $d \equiv 1 - 2\alpha(\sigma - 1) \geq 0$, or $\sigma \leq 1 + 2\alpha/2\alpha$.[1]

Compare Profits from Using the Closed vs. Supplier Design. The downstream firms use the closed versus supplier design only if $\Pi_D^U \leq \Pi_D^C$. Using (7) and (12), this implies $(\rho_U/\sigma)^2(\sigma-1)(n-m)/\tilde{\sigma} \leq (\rho_D^C/\sigma)^2 M/k$. Again, on the left-hand side, $\rho_U = 1/n$, $m = 0$, and we approximate $\tilde{\sigma} \approx 1$, which, as noted earlier, stems from the fact that if the downstream firms buy from the supplier, both the suppliers and the downstream firms benefit from a high markup that generates a higher x_U. On the right-hand side, $\rho_D^C = r^{1-\sigma}/n$, and we replace r with its equilibrium level (15). In this expression, $\tilde{\sigma}$ is the optimal markup defined implicitly by (4a). Solving the inequality above for k (and taking into account that k also appears in the expression for r), we obtain

$$k \leq \frac{\Psi}{n(\sigma-1)} \equiv k^C, \quad (16)$$

where

$$\Psi \equiv M^d\left[\frac{\tilde{\sigma}}{(1+\alpha)(\tilde{\sigma}-1)}\right]^{2(\sigma-1)(1+\alpha)} \left[\frac{m^C\phi\tilde{\sigma}}{n}\right]^{2(\sigma-1)\alpha}, \quad (17)$$

and k^C is the threshold level of k such that if the technology to produce the design by the downstream firms falls below the threshold, a closed coalition is more profitable for the firms that set it up than buying from the supplier.

Compare Profits from Using the Closed vs. Open Design. Finally, compare profits using the closed versus open design; that is, $\Pi_D^O \leq \Pi_D^C$. Using (10) and (12), this implies $(\rho_D^O/\sigma)^2\Theta/k \leq (\rho_D^C/\sigma)^2 M/k$. Again, on the left-hand side, $\rho_D^O = 1/n$, and on the right-hand side, $\rho_D^C = r^{1-\sigma}/n$. Replace r with its equilibrium level (15). Solving for k, which also appears in the expression for r, yields

$$k \leq \frac{\left(\frac{\Psi}{\Theta^d}\right)^{\frac{1}{1-d}}}{n(\sigma-1)} \equiv \tilde{k}, \quad (18)$$

where $\tilde{k}$ is the threshold level of k such that if the technology to produce the design by the downstream firms falls below the threshold, a closed strategy is more profitable than an open strategy.

Interestingly, this suggests that as the technology to produce the design by the downstream firms keeps falling, eventually, the closed strategy becomes more profitable than the open strategy. The intuition is that the competitive advantage of the closed coalition becomes so strong that an open strategy, which resets the competitiveness of the firms that cannot access the superior technology, becomes less appealing.

Open, Closed, and Supplier Equilibria. Using the thresholds (11), (16), and (18) we can write

$$\frac{k^C}{k^O} = \frac{\Psi}{\Theta}, \quad (19a)$$

$$\frac{\tilde{k}}{k^C} = \left(\frac{\Psi}{\Theta}\right)^{\frac{d}{1-d}}. \quad (19b)$$

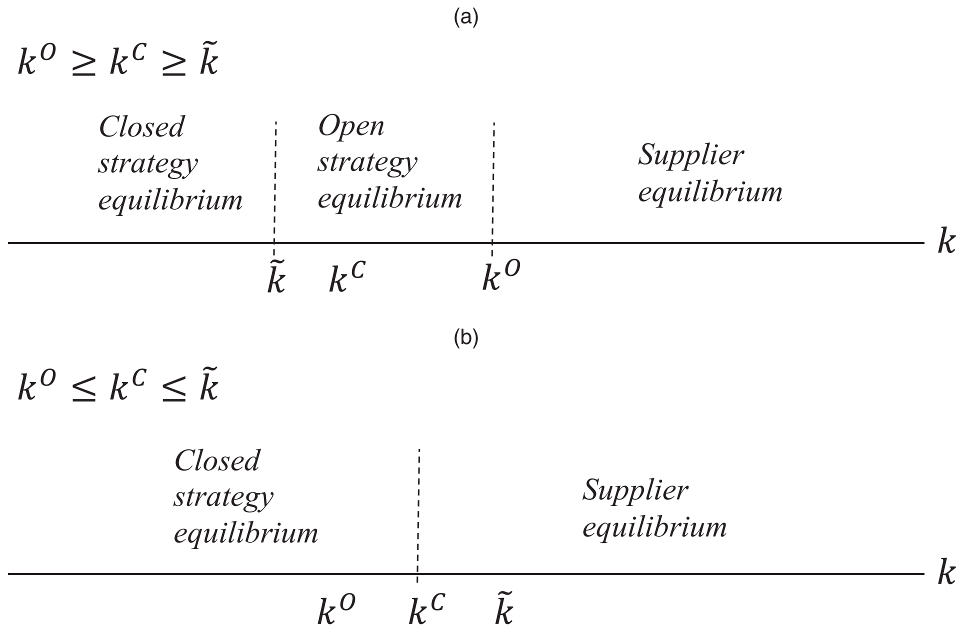
Because $d/1 - d > 0$, if $k^C/k^O < 1$, then $\tilde{k}/k^C < 1$, and vice versa. We can then characterize our equilibria in Figure 1 and in the following lemma. As it can be readily seen from (19a) and (19b), the critical condition is whether $\Psi < \Theta$.

Lemma (Equilibria). *If $\Psi < \Theta$, as the relative efficiency of downstream firms increases (k lowers), we move from a* supplier equilibrium (*all firms buy from the supplier), to an* open strategy equilibrium (*a coalition of downstream firms produces the design and distributes it freely), and finally to a* closed strategy equilibrium (*a coalition of firms produces the design and keeps it proprietary). If $\Psi \geq \Theta$, as k lowers no open equilibrium arises, and we move directly from a supplier to a closed strategy equilibrium.*

It is easy to see that if $\Psi < \Theta$, then $k^O \geq k^C \geq \tilde{k}$. In this case, as also represented in Figure 1, when k falls below k^O, it can still be higher than $\tilde{k}$, which implies that an open strategy equilibrium is feasible. Specifically, as Figure 1 also shows, we have a smooth transition as k keeps falling: from the supplier equilibrium when $k \geq k^O$, to the open equilibrium when $\tilde{k} \leq k \leq k^O$, and to the closed equilibrium when $k \leq \tilde{k}$. By contrast, if $\Psi \geq \Theta$, then $k^O \leq k^C \leq \tilde{k}$, which implies that whenever k falls below k^O, it is already smaller than $\tilde{k}$. The key threshold is then k^C such that $k \geq k^C$ generates a supplier equilibrium, whereas $k \leq k^C$ produces a closed equilibrium.

Communication Technology and Open Equilibria. The next step is to understand what makes $\Psi < \Theta$, which makes the open equilibrium possible. In this and the next subsection we state two propositions, one about the effects of the communication technology η and the other about manufacturing scale economies (n and α). We have to be careful in that to characterize the effects of Ψ with respect to our parameters, we need to take into account that in (15) these parameters also affect the equilibrium level of r, which affects $\tilde{\sigma}$ in (17).

Figure 1. Equilibrium Configurations



Notes. In Figure 1(a), when k falls below k^O, an open strategy becomes more profitable than buying from the supplier. However, only when k falls below $\tilde{k}$ does the closed strategy becomes more profitable than the open strategy. In Figure 1(b), when k falls below k^C, it is also smaller than $\tilde{k}$, which implies that a closed strategy is more profitable than an open strategy. For the open equilibrium to arise, it is crucial to check whether $\Psi < \Theta$. See definitions (17) and (10) in the text and the conditions (19a) and (19b).

As far as communication technology is concerned, if the costs of the partnership, captured by the parameter β, are high, such that m^C is close to 1 (vertical integration), it is not difficult to see from (15) that r and therefore $\tilde{\sigma}$ and Ψ are not affected by advances in communication technology captured by η. We already established that Θ increases with θ if $\theta \leq 2 - \eta/2$ and increases with η if $\theta \leq 1/2$. We can then write the following proposition.

Proposition 1. *An open strategy equilibrium is more likely to arise if* (i) *the communication technology among contributing firms is efficient (high* η*)*, (ii) *free riding is costly (low* θ*), and* (iii) *the costs of forming a private partnership are sizable (high* β*)*.

Basically, an improvement in communication technology facilitates collaboration among downstream firms. When k declines, these collaborations become more profitable than buying from the supplier, and if there are sizable costs of forming a private partnership (high β) and free riding is not costless, an open strategy dominates the formation of a closed coalition.

In essence, this proposition speaks to the standard context in our economies in which an individual firm has to choose between vertical integration and an open strategy. This is, for example, the case of the Open Compute Project discussed in the introduction. Facebook developed the technological capabilities to improve the technology of data centers and decided to diffuse it openly. The opportunity to develop a digital platform for setting up the open community and the opportunities to exchange knowledge and information on the web clearly helped to create a community that involves many contributors, and possibly some free riders. More generally speaking, as noted earlier, we rarely see closed alliances composed of a large number of partner firms. This suggests that the partnership costs are likely to be high when many partners are involved. As a result, in practice, the optimal m^C is likely to be small, with the implication that the impact of improvements in communication technology η is likely to be stronger for open as opposed to closed strategies of downstream firms.

Scale and Open Equilibria: Open Source Hardware vs. Open Source Software. The other effect is the scale. In (17) the scale of downstream suppliers n affects Ψ both directly and through $\tilde{\sigma}$. From the definition of $\tilde{\sigma}$, the scale of downstream firms n affects $\tilde{\sigma}$ directly and through r, as defined by (15). Using the definition of $\tilde{\sigma}$, it is not difficult to see that the variations of $\tilde{\sigma}$ with respect to r and n are negligible as n becomes large relatively to m^C. As a result, as n gets larger, the variation of Ψ with respect to n depends mostly on the direct effect of n in (17). Intuitively, as n gets larger, changes in n have a relatively negligible effect on the markup of the supplier vis-à-vis the scale effects on the open coalition. Because the direct effect of Ψ with respect to n is negative, as the scale of downstream firms increases, an open equilibrium is more likely.

This effect depends crucially economies of scale in manufacturing, which in our model are governed by α. It is easy to see from (17) that if $\alpha = 0$, the direct effect of Ψ with respect to n disappears. As a result, increases in n no longer make the open equilibrium more likely. The rise of an open equilibrium depends on other factors.

This has a natural interpretation. Economies of scale in manufacturing, as we have modelled them in this paper, are associated with the production of design embodied in final goods that generate such economies of scale. In turn, this highlights the distinction we made earlier between open source hardware and open source software. In open source software, there are no economies of scale in manufacturing but only in the production of the design, which in our model amounts to $\alpha = 0$. The open equilibrium becomes less likely because, when $\alpha = 0$, the marginal cost of producing the good that embodies the design does not decline when y increases, which implies, from (3), that the marginal cost of manufacturing the good does not fall with the scale of total demand Q. This leads to the important conclusion of our model that open source is more likely to become a widespread and diffused strategy when designs are embodied in goods that enjoy economies of scale in manufacturing, and the scale of downstream user firms is large. We capture this discussion in the following proposition.

Proposition 2. *An open strategy equilibrium is more likely to arise if the scale of downstream users is large (high n) and there are economies of scale in manufacturing ($\alpha > 0$). This also implies that an open strategy is more likely to arise in open source hardware than in open source software.*

5. Discussion

Recall from our introduction that downstream development of open inputs, the *vertical* strategy we have described and analyzed, is orthogonal to the *horizontal* strategy suppliers engage in that has been described by and explored by Teece (1986), Casadesus-Masanell and Llanes (2011), Alexy et al. (2018), and others. In that horizontal strategy, suppliers make some products in a bundle of complements free to concentrate rent capture in other elements of the bundle. By contrast, in the strategy we have described, downstream firms seek to create substitute free designs for upstream inputs they purchase in order to increase profits in the products they sell downstream—it is a *vertical* strategy involving selective openness.

With respect to this vertical strategy, we have explored the impacts of major technological trends on the economics of open, collaborative input designs versus closed, proprietary input designs. We have found that these technological trends have opened a pathway for downstream firms as well as upstream suppliers to distribute the cost of creating an input design across many customers. The result is to reduce or even reverse the advantages input producers have historically enjoyed relative to collaborations of downstream firms with respect to profiting from creating their own product designs.

We believe the research we report on here offers three major contributions to the literature. First, we show that an open strategy equilibrium arises endogenously; that is, downstream firms find it profitable to collaboratively develop substitute designs for proprietary inputs they all purchase *and* find it profitable to offer their designs openly to free riders outside their coalition, even when there is competition across them.

Second, we do not explain the open strategy using ad hoc arguments but instead show it to be an alternative that can dominate these other strategies within the very same framework of analysis. We also show that this outcome is robust to the reaction of the supplier. That is, the supplier may react by increasing the quality of the design at the expense of its profits if this enables the supplier to keep its clients and prevent from more pronounced reductions in its profits. However, as the relative efficiency of downstream firms in producing the design, which we indicate with k, keeps declining, there is no viable reaction open to the supplier to counter the strategy of the downstream firms while earning nonnegative profits.

Third, by including economies of scale in manufacturing in our analyses, we show that open strategies are likely to become more common in open source hardware than in open source software. In other words, although most of the common wisdom suggests that open design strategies are more common when we focus on intangibles, we conclude that open design strategies may be more common and profitable when designs are embodied in hardware.

The general shift toward open design we predict would clearly have major ramifications for both firm strategies and the overall economy. We therefore should note that changes of scope and import similar to the ones that we describe are far from unprecedented in economic history. As many have argued, successful organizational forms, the locus of activities within industry structures, and the associated theoretical propositions do fundamentally change as historical circumstances and environments evolve over time (Woodward 1965; Chandler 1977; Nelson and Winter 1982; Aoki 1984, 2001; Williamson 1985, 1991; Langlois 1986; Baldwin and Clark 2000; Langlois 2002; Jacobides et al. 2006) and in turn have significant impacts at the firm, economic, theoretical, and societal levels.

We next discuss the generalizability of and very important limitations to our findings and the general trend toward openness (Section 5.2). Finally, we conclude by offering some strategic implications for firms and policy implications for governments (Section 5.3).

5.2. Generalizability and Limitations

The economic comparison we have made between inputs developed by downstream design teams and shared openly versus the purchase of inputs of proprietary design from monopoly suppliers is a quite general one. Recall that *all* firms are positioned within in supply chains: they *all* purchase inputs to incorporate into products and services they use or sell. As each level in a supply chain increasingly seeks economic advantage by creating open designs as a substitute for purchasing proprietary input designs from monopoly suppliers, firms in that level can also expect that *their* customers will be making the same calculations and choices. Rival firms at each supply chain level all have access to same inputs on the market, and so a purchase does not convey any competitive advantage to one input purchaser relative to another. However, all purchasers of a proprietary input must pay monopoly rents to the design owner—something that they would, of course, all prefer to avoid if possible. As a result, as noted earlier, we think that openness will spread quite broadly throughout the economy.

With respect to which markets are most likely to first experience the formation of downstream coalitions, it is reasonable to assume that individual downstream firms would choose to first create substitutes for the proprietary inputs they are purchasing, which have the largest rent payments associated with them. Then, it would be reasonable to move on to the next most attractive targets, until all profitable options have been addressed. From the perspective of likelihood of generating a sufficiently large coalition, it is reasonable to predict that markets for relatively standard and homogeneous products or services will be especially attractive opportunities. In such cases, it is possible that many proprietary designs can be substituted for by a single open design. The increase in the quantity demanded and supplied in equilibrium implies that the greater efficiency of the coalition of customers spreads over a larger volume of output, making the efficiency gains wider.

At the same time, there *are* at least three important exceptions to the general trend toward increased openness we have described. First, and most obviously, firms and individuals that are end users—the final link in a supply chain—will not be subjected to the creation of open input alternatives to their own outputs; as final supply chain links, they consume those outputs themselves and do not serve as producers of outputs for others.

A second very important and less obvious exception occurs when substituting for the *function* of the design of a proprietary input supplied by a producer depends on complementary assets held by the supplier in addition to the innovation itself. Here, we must integrate in the reasoning and modeling of Alexy et al. (2018) and others previously cited involving supplier control of "bottlenecks" that are complements to the focal innovation. The cost of developing a substitute for the *function* of a proprietary input must include the cost of access to such complements. For example, it is likely that a substitute for the artificial intelligence algorithms created by Google to recognize images or speech can be created at a favorable cost by a coalition of customers. In addition, downstream users can purchase neural network hardware from the same sources as can Google. However, enormous troves of images or speech are today necessary complements required to train such algorithms to a high level of accuracy. Customers very generally cannot get access to the massive—and, more importantly, proprietary—databases required. Only Google, Baidu, Facebook, and a few other firms are in a position to compile them as a costless side effect of conducting their businesses. The end result is that a collaboration of downstream users is unlikely to be able in this instance to have an economically viable case to create an open input to substitute for the *function* of proprietary offerings of firms such as Google. Again, the general lesson is that the costs calculated to determine the viability of coalition designs must in each instance include the costs of access to all complements required to achieve functional equivalence to the proprietary designs offered by monopolist suppliers (Zhu and Iansiti 2012).

Third, and finally, our description of the general trends increasingly lowering the costs of downstream firm innovation relative to producer innovation applies unevenly across the economy. Thus, in the case of production of very-high-volume products such as automobiles, specialized tooling in specialized factories is still the order of the day. This is also the case for very complex semiconductor products such as the central processing units produced by Intel for computers and the graphical processing units produced by Nvidia. In all such areas, production and design are still highly interdependent, and supplier-specific production equipment is often present. Whenever this is so, downstream firms and producers are not equally advantaged with respect to creating producible designs. Furthermore, when these conditions hold, downstream design coalitions cannot assume they can get equivalent production capabilities at the same price from "white box suppliers" as they can from incumbent proprietary producers.

For these three reasons we do not, as was mentioned earlier, believe that the design of proprietary inputs will disappear, but we do expect it to become less pervasive and ubiquitous than was the case during most of the 20th century and to be combined with free and open input designs in many settings. This also suggests that although we have cast our analysis in terms of technological trends that are making open strategies more likely over time, the reader can equally interpret our analysis as suggesting that open strategy is more likely in some industries or contexts (e.g., countries), as opposed to others where some of the parameters of our model are such that they make open strategies by downstream firms more likely.

5.3. Strategy, Project Design, and Policy Implications

Strategy implications for firms derivable from our findings and discussion are quite clear. The most direct strategy implications for downstream firms seeking to reduce rent streams that they currently pay for proprietary inputs is to assess the opportunity to increase profits by creating an open input (or closed club good) substitute for each such input. The most direct implications for those same firms when they act as producers is that they should actively protect the markets for their proprietary designs against the emergence of open substitutes. They can do this by assessing and attempting to increase the total cost to their downstream customers of creating a substitute that will function as effectively as their proprietary design. Such assessments will include downstream firms' costs of developing the focal design *and* acquiring access to related complements necessary or valuable for its functioning.

Very generally, all firms attempt to find ways to protect and assert monopoly rights with respect to their outputs they sell and to defeat or skirt monopoly rights with respect to the inputs they purchase. It will be a very interesting matter for both research and practice to learn how these dual objectives can best be attained. In this regard, it is important to notice that a firm's "core competences" are not the same as defensible competences under the modern conditions we have described. It is possible that firms may have to find new sources of competitive advantage over time.

With respect to the design and governance of open input design projects, a detailed understanding of best practices should be developed, explored, and tested by both interested user firms and by academics. There can be considerable complexity involved in achieving best practices. For example, if one looks at the website of the Open Compute Project, one can see a set of project participation rules laid out, implementing the general principles we have laid out in this paper at a much more detailed and specific level. Thus, we noted earlier that an important benefit contributors to an open design project can have over free riders is that only contributors have a pathway to express and incorporate their own particular design interests as a project evolves. By contrast, free riders can only adopt or not adopt the open design that has been created by others. The Open Compute Project instantiates this principle and seeks to optimize incentives to contribute by offering increasing levels of design control to project contributors as a function of the amount of money and design effort they agree to contribute (Open Compute Project 2018b).

With respect to government policy implications, we may say that monopolies in general and intellectual property rights in particular create deadweight losses and reduce social welfare (Machlup and Penrose 1950, Penrose 1951, MacLeod 2007). If and as k, the cost of producing an open design on the part of the coalition, falls below a certain level, we show that an open strategy equilibrium arises endogenously; that is, downstream firms find it profitable to share knowledge and to distribute it openly outside their coalition. Under these conditions there will be no need to "force" openness, as the monopolist cannot supersede the open coalition even if it reacted strategically by lowering the price of the design to keep its customers. However, if potentials for reducing k are somehow being impeded, antitrust authorities may find ways to create the conditions for reducing k and trigger the underlying openness mechanisms we have described.

6. Conclusion

In this paper we have shown that important technological trends have very broadly invalidated the traditional assumption that producer firms are advantaged over coalitions of downstream firms with respect to spreading the costs of design over many downstream firms. The invalidation of this assumption, in turn, opens the way to understanding the present rise and favorable economics of efforts to develop substitutes for proprietary producer products by coalitions of downstream firms, such as in the Open Compute Project discussed earlier. We hope that by opening up and exploring this increasingly viable strategic option for downstream firms in this paper we will encourage research by others to develop and explore the possibilities further. We think it likely that input development, especially in the case of hardware, will over time migrate away from closed proprietary designs offered by producers to substitute designs developed by and openly shared among downstream firms.

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Endnote

[1] The condition $d \geq 0$ is necessary for the equilibrium. In the space formed by Q_U/Q_D^C on the y axis and r in the x axis, the two curves (13) and (14) must be such that $n^2(\sigma - 1)k/m^{C^\phi}\tilde{\sigma} > (\tilde{\sigma}/(1+\alpha)(\tilde{\sigma} - 1))^{\frac{1+\alpha}{\alpha}}$, which is satisfied if, for example, n is sufficiently large, and (13) cuts (14) from below, which requires $d \geq 0$. Note that because $\tilde{\sigma} \leq \sigma$, the condition $\sigma \leq 1 + 2\alpha/2\alpha$ implies the condition $\tilde{\sigma} \leq 1 + 2\alpha/2\alpha$ imposed earlier. Also, in (15), r_U affects r and the left-hand side through $\tilde{\sigma}$. However, r_U affects r negatively and the left-hand side positively, which implies that (15) is an equilibrium.

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