Dynamics of Knowledge-Based Service Industry and Open Source*

Doh-Shin Jeon† Silvio Petriconi‡

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Abstract

In this paper, we build a model of a knowledge-based service industry focusing on customer collaboration and its dynamic feedback on the stock of knowledge of a service firm. We apply our service-based approach to explain why firms that capitalize on software-related services may want to release their software as open source. More precisely, we consider two variants of a general model. When the customer makes an ex ante investment that enhances her collaboration, we find that knowledge sharing (through open source, for instance) and/or market sharing can be a strategy that a dominant firm employs to boost the investment. When the project size is exogenous but the customer chooses collaboration level after selecting a service firm, we find that open source may be an aggressive entry strategy and the dominant firm may either voluntarily choose open source to boost collaboration or be forced to embrace open source in order not to lose competition.

Keywords: open source, service industry, dynamics, customer collaboration, customer-specific knowledge
JEL classifications: L17, L84, L86, D86

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†Universitat Pompeu Fabra and Toulouse School of Economics. doh-shin.jeon@upf.edu
‡Universitat Pompeu Fabra. silvio.petriconi@upf.edu

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1 Introduction

As anticipated in Eric Raymond's seminal book "The Cathedral and the Bazaar" [Ray99], the growing adoption of open source software has changed software business dramatically during the past years. In this paper, we provide an explanation about commercial firms' involvement in open source software development. For this purpose, we build a model that captures dynamics of a knowledge-based service industry and study how open source policy affects the dynamics of competition. Our "service-based approach" differs from the standard "commodity-based approach" in terms of its focus on customer collaboration and its dynamic effect on competition. More precisely, we idenitfy knowledge sharing and/or market sharing as mechanisms that the incumbent service firm uses to boost customer's collaboration and explain open source as a specific mechanism for knowledge sharing.

From an economic perspective, the dramatic growth of a large open source software ecosystem may appear rather paradox at first glance, since the open source principle implies that the outcome of costly development effort is voluntarily made available for free by its developers. Moreover, it is characteristic of open source software that beyond the explicit permission to freely redistribute the work in any form, it also includes the right to use the source code, make modifications, or merge it with another project[1]. Hence, the question arises immediately which incentives drive individuals to choose open source licensing instead of proprietary, revenue-generating licensing models based on their intellectual property rights. Initial contributions in the economic literature have mainly focused on discussing the incentives of voluntary individual participation in open source development, and have been able to give reasonable explanations such as career concerns (Lerner and Tirole, [LT02]); however, all explanation attempts based on personal incentives fall short of recognizing the huge commercial momentum that has been building up behind open source software over the past eight years.

For example, according to a study by Kroah-Hartmann et al. [KHCM08], over 70 percent of the more recent contributions to the Linux system kernel were made by programmers who were paid for their work. "Professional open source" companies such as JBoss (since 2006 a subsection of Red Hat) have

[1]The license terms for such derivative works differ, however, strongly depending on the open source license terms of the original product. For instance, all derivative works made from programs that are licensed under the most frequently used GNU General Public License (GPL) must be distributed under this very same license.

grown from small start-ups to 350 million dollar take-over candidates, with their only product being deployed under an open source license. Other large players in the software market, especially Sun Microsystems and IBM, have re-licensed millions of previously highly guarded source code lines under open source licenses, including the OpenOffice office suite, the Eclipse development platform, the Java programming language, or the complete Solaris operating system code.

Surprisingly, the range of explanations for commercial involvement in open source software development that has been given in the economic literature is still quite limited. Lerner and Tirole see positive externalities to complementary goods as the incentive behind releasing a previously commercial product as open source:

> "This strategy is to give away the razor (the released code) to sell more razor blades (the related consulting services that IBM and Hewlett Packard hope to provide)." [LT05], p. 106

Whilst enlightening in cases where the firm is the exclusive producer of very specific and nearly perfect complements for the open source software (hardware supported by open source hardware drivers, for example), we believe that this commodity-based perspective sheds insufficient light on the business models of an increasing number of firms that specialize in the delivery of services based on their open source product portfolio. Specifically, it fails to explain how service firms that develop and deploy open source solutions succeed in preventing competitors from free-riding on their development effort and from offering services of identical quality. We therefore propose in this paper a service-based approach to software, and we will use this approach to analyze the trade-off between open source and closed source software in a service-based setting.

This service-based approach will model important features of service exchanges that do not exist in commodity transactions where off-the-shelf products with pre-determined off-the-shelf value are to be sold. As emphasized in the literature on service industry (see Zeithaml, Parasuraman and Berry [ZPB85], Chesbrough [CS06], Lusch, Vargo and Wessels [LVW08]), a key aspect that makes a service exchange different from the purchase of a commodity good is its inherent two-sidedness: service value is not generated by the producer alone, but is co-created jointly with the client, and the degree of client participation may strongly affect the value of the outcome. Moreover, the value of a service tends to increase in a repeated transaction due to the accumulation of customer-specific knowledge by the service firm. All these aspects have important strategic implications that are entirely neglected when the sale of software services is investigated in a commodity-based approach.

To make a contrast between the two approaches, we precise what we mean by commodity-based approach: we mean by it a situation in which producers sell commodities to mass customers and hence commodities are not customized to each customer (although a producer can produce a portfolio of different commodities to fit different consumer "types"). This corresponds to the typical situation that many standard IO models represent. For instance, the software that Microsoft sells to mass customers can be more or less captured in a commodity-based approach. On the other hand, by service-based approach we have in mind a situation in which for instance IBM provides information technology services to GM. Such services include the customization, deployment, maintenance and support of complex and highly interconnected IT solutions.

We can summarize the key differences between the two approaches as follows:

Commodity-based approach	Service-based approach
The value of a commodity is **determined solely by** its producer.	The value of a service is **co-determined** by both the service-provider and the client.
Customers are **passive** since they simply choose the best deal among available commodities.	Customers are **active** since they choose collaboration level.
No accumulation of customer-specific knowledge	The collaboration level has **feedback on** the provider's stock of **customer-specific knowledge**

This paper is structured as follows: In section 2 we review the relevant literature. We present the general model and the model of endogenous project size in section 3. Section 4 analyzes the model of endogenous project size and section 4 analyzes the model of exogenous project size. Section 6 concludes.

2 Literature review

A substantial portion of the economic literature on open source software is dedicated to the analysis of participation incentives; however, the majority of these contributions focuses on participation incentives for the individual developer in a setting in which open source software development is an activity driven mainly by volunteers without any immediate commercial goals.[2]

However, in the case of "open source by commercial firm" which we analyze here, the question of incentives at the level of the individual becomes irrelevant: Professional developers are hired and paid by a company. The incentive puzzle rather lies at the firm level: why do firms choose to engage in the development of open source software? After all, due to the non-excludable nature of open source software, the commercial release of open source software is nothing less than the free provision of a public good by profit-maximizing companies. It is therefore immediate that one has to look for externalities in order to be able to answer this puzzle.

The most immediate form of explanation of commercial open source activity goes by a simple complementarity argument: it makes perfect sense to (costly) produce an open source good if the cost of its production is more than offset by its positive externality on complementary goods sold by the firm; this is exactly the scenario which Lerner and Tirole [LT05] alluded to when comparing the situation with that of a razor blade firm giving away the razor for free. We agree that there are situations in which the complementarity argument offers a good and sufficient explanation for commercial open source activities.[3] But for many real-life scenarios, the explanatory power of a complementarity argument is limited. For example, it simply remains unclear why firms invest in the continuous development of an open source product even if competing firms could potentially free-ride on their development effort. This point was noted, but not further explicated by Lerner and Tirole [LT05]. The complementary good argument therefore only works well

[2] Lerner and Tirole [LT02] have emphasized that developer participation in this kind of open source projects can, even in the absence of financial compensation, be explained sufficiently well by purely egoistic motives, such as career concerns and ego gratification. Other contributions addressing individual participation are Hars and Ou [HO01], Lakhani and Wolf [LW03] and Sauer [Sau07].

[3] For instance, Intel's strong participation in Linux kernel driver development [KHCM08] can be easily understood in terms of the benefits for the sales of its processor, graphics and wireless solutions that are now optimally supported under Linux.

for software that is tailored to support a very specific complementary good but does not offer any explanation for cases in which the open source firm does not sell any complementary good.

Related explanation attempts can be found in the literature on two-sided markets. Without specifically addressing open source software, Parker and Van Alstyne [PA05] discuss the free or subsidized release of information products in a two-sided market setting. Economides and Katsamakas [EK06] have analyzed more specifically the setting in which an open source platform competes against a closed-source alternative; they find that total industry profits are maximal if the platform is provided as open source whilst applications are sold under a proprietary license. This would help explain the participation of proprietary software vendors in open source platform development, but again it does not explain the incentives of firms to develop open source software even in the absence of a portfolio of proprietary software.[4]

Besides complementarity, network effects are another externality that can be used to explain a firm's incentive to participate in open source software development. This line of argumentation is presented by Mustonen [Mus05]: a closed-source software vendor may have incentive to sponsor open source development effort for a substitute (!) open source product if this can increase the network externality of his own product. Whilst such efforts are observed in practice, they constitute a negligible fraction of today's commercial open source activity.

In all the approaches to understand open source activity that we have mentioned so far, we miss a coherent view that explains

- why firms that do not sell any complementary goods engage in open source software development, and
- how commercial open source firms that only provide services based on

[4]Dual-licensing is a (practically very relevant) revenue model in open source industry that makes use of the complementary good idea: a software is developed by the commercial firm and then released under two licenses. The open source version is mostly licensed under a very restrictive license such as the GNU General Public License (GPL) and can therefore not be used to create proprietary applications that are based on (or link with) the open source product. Another version of the software is sold under a proprietary license, and allows for the deployment of proprietary applications. This licensing model has been investigated in a more recent work by Comino and Maneti [CM07], and it is practically most relevant for frameworks and toolkits that are used to create software products, such as Trolltech-Nokia's Qt toolkit.

their open source software portfolio succeed in protecting themselves from free-riding competitors.

In order to address these questions, we develop a new, service-based perspective on commercial open source software. We will show that by adding relationship-specific knowledge and customer collaboration, it is possible to understand the emergence of profitable IT service firms at a depth far beyond what is offered in a commodity-based view.

Before we proceed to present our service-based approach, we briefly mention contributions from the literature that we find relevant and related to our work, but that did not fit into the discussion above. A very early work by Kuan [Kua01] has emphasized the aspect of consumer integration into production through open source projects; von Hippel and von Krogh [vHvK03] have also made important points with respect to this user innovation aspect.

Casadesus-Masanell and Ghemawat [CMG06] employ a "demand-side learning" parameter in their dynamic model of competition between an open source and a closed source product; this idea comes close to the concept of knowledge accumulation from user collaboration that we have in mind. However, unlike in their model, we will assume collaboration as costly to the user in order to model key strategic dimensions of a knowledge-based service exchange: our model caputres B2B (Business to Business) transactions while their model captures B2C (Business to Consumers) transactions where consumers are not strategic.

Finally, the key message of our paper that the incumbent firm may want to maintain a certain level of competition is similar to the findings of Shepard (1987) and Farrell and Galini (1988) that a monopolist may want to create competition when it suffers from a commitment problem. What is new in our paper is the application to the dynamics of a knowledge-based service industry and open source.

3 The Model

3.1 Definitions of Service

Before presenting our model of a knowledge-based service industry, we review some definitions of service, which guide our modelling choices. First, Zeithaml, Parasuraman and Berry (1985) mention the following four characteristics of service with respect to commodity:

- Intangibility
- Heterogeneity (inability to standardize)
- Inseparability (of production and consumption)
- Perishability (inability to inventoried).

In contrast, in a standard IO model of commodity (in particular, the model of B2C), a producer first produces a tangible and storable commodity which is standardized and then sells it to (mass) consumers. Intangibility and perishabilty in general will make contracting on service value difficult. Therefore, we will assume that the value created by a service firm is not contractible. The notion of heteogeneity fits well the B2B service transactions we have in mind. The notion of inseparability is also related to the following definition emphasizing the role of a customer as a co-producer.

- **Definition 1** (Fitzsimmons, 2001 [FF01]): A time-perishable, intangible experience performed for a customer acting in the role of co-producer.

Definition 1 is crucial in our service model where we assume that the customer chooses a level of collaboration that affects the value of the service provided by a given firm. This is a key dimension of our service-based approach, which creates a departure from a commodity-based approach in which, due to the separation between production and consumption, a customer can hardly participate in the production. Furthermore, since we have in mind highly customized service, the amount of today's collaboration will enhance the service provider's stock of knowledge relevant to provide the service tailored to the need of the same customer in the future. This dynamic feedback of the customer's collaboration on the provider's stock of knowledge will form the second key dimension of our service-based approach.

The next definition is complementary to the first definition and is particulary relevant to the knowledge-intensive service industry.

- **Definition 2** (Gronroos, 1990 [Gro90]): An activity or series of activities... provided as solution to customer problems.

In the second definition, a customer is the holder of an interesting problem and a service provider uses his knowledge stock to provide a solution to the problem. This definition makes particular sense in today's knowledge-based society in which access to interesting problems to a large extent becomes a bottleneck and hence determines competitive standing of firms providing knowledge-intensive service. We will come back to this definition in section 5.

3.2 Commodity-based versus service-based approach

There are n number of competing firms to provide either a commodity or a service to a customer: we will use "he" for a firm and "she" for the customer. Let K_t^i represent firm i's stock of knowledge at period t, which is relevant to produce the commodity or the service for $i = 1, ..., n$: this knowledge can include both general elements and customer-specific elements as long as they matter to increase the value of the commodity or the service that firm i makes. Let $\mathbf{K}_t = (K_t^1, ..., K_t^n)$. Let x_t represent the customer's level of collaboration chosen at t: we will explain in details what we mean by x_t in the next subsection. We distinguish the commodity-based approach from the service-based approach in two respects: (i) how the customer's level of collaboration affects the value generated by the commodity or by the service and (ii) how the customer's level of collaboration affects a firm's future level of (accumulated) stock of knowledge. More precisely, suppose that firm i provides the commodity or the service to the customer at t and the customer chooses collaboration level x_t. Then,

- $V(K_t^i, \alpha x_t)$ with $\alpha = 0, 1$ represents the value generated by firm i. The function is differentiable and strictly increasing in both variables with $V(0, x_t) = 0$.
- $K_{t+1}^i = K_t^i + \beta k(x_t)$ with $\beta = 0, 1$ and $K_{t+1}^j = K_t^j$ for any firm $j \neq i$ show how each firm's stock of knowledge evolves. $k(\cdot)$ is differentiable and with $k(0) = 0$, $k'(0) > 0$ and $k''(0) < 0$.

By α, we capture the degree of customer participation in the generation of the value produced by the commodity or the service. If $\alpha = 0$, the customer cannot affect the value. In other words, there is a complete separation between the manufacturing process and the consumption process and the customer does not participate in the former. For instance, $\alpha = 0$ corresponds to a situation in which each firm i mass-produces a commodity of which the off-the-shelf value is completely determined by K_t^i and mass customers simply choose among already-made commodities.[5] In contrast, $\alpha = 1$ corresponds to the case in which the customer actively participates to determine the value of the service provided.

By β, we capture the degree of feedback from customer's collaboration to the future stock of knowledge of the firm which interacted with the customer. $\beta = 1$ is likely to hold in a service industry with high degree of customization. In this industry, as the level of customer collaboration increases, the service provider accumulates more customer-specific knowledge, which improves his ability to provide customized service for the same customer in the future. In other words, $\alpha = 1$ is likely to imply $\beta = 1$. In contrast, $\alpha = 0$ does not necessarily imply $\beta = 0$ since in many dynamic industries in which customers' taste evolve fast, customers' feedback is important even though there is a separation between the manufacturing process and the consumption process. However, even in this case, the relevant information is not specific to a particular customer but specific to a group of homogenous customers (for instance, customers of similar income, age, race etc). Furthermore, when $\alpha = 0$, customer feedback x_t will be made after manufacturing process (during or after consumption process): i.e. x_t refers to a sort of "ex post feedback". Finally, $\alpha = 0$ and $\beta = 0$ would hold in mature industries in which firms sell commodities.

In what follows, we mean by the commodity-based approach $\alpha = 0$ and $\beta = 0$ while we mean by the service-based approach $\alpha = 1$ and $\beta = 1$. Although there can be some intermediate cases such as $\alpha = 0$ and $\beta = 1$, we focus on the two extreme cases in order to sharpen the intuition. For instances, the software that Microsoft sells to mass customers can be more or less captured by $\alpha = 0$ and $\beta = 0$ while the information technology services that IBM provides to GM (including the customization, deployment, maintenance and support of complex and highly interconnected IT solutions) can be well captured by $\alpha = 1$ and $\beta = 1$.

[5] Note also that $\alpha = 0$ is totally consistent with a situation in which a firm produces several versions of commodities which differ in terms of their functionalities in order to enlarge choices available for heterogenous types of customers: in this situation as well, the manufacturing process is separated from the consumption process.

3.3 Size of project, customer collaboration and contracts

We will study two variants of a general model. In the general model, the customer chooses both the size of her project (before selecting a provider) and the level of collaboration (after selecting a provider). The two variants differ depending on whether we make the size of the service project endogenous or exogenous. In the case in which the project size is exogenously given, the value of a service is simply determined by $V(K_t^i, x_t)$. In the case in which the project size is endogenously determined, let s_t denote the size chosen by the customer. Then, the value of a service is determined by $V(K_t^i, x_t : s_t)$. In this case, we assume that the customer makes the investment related to the size of the project before soliciting an offer from service firms. Basically, what we have in mind is that the customer, for instance a big firm, decides, at the beginning of each period, her overall business plan and the strategic role of the IT service in this plan. This in turn determines the size of the IT service (that she will ask service providers to deliver). This decision on the size of the service to request has some irrevocable element since revising it requires revising the entire business plan. For example, General Motors decides to strongly promote IT awareness among its employees, this will enhance the value of any IT service contract, no matter whether the contract is awarded to IBM, Novell or Red Hat.

By *"customer collaboration level"*, we mean the intensity and quality of tasks and practices that are performed by the customer at her own cost, but that positively affect the value of the service. Examples of such tasks in an IT service transaction environment are: generating a robust customer-side requirement analysis in the run-up for project specification; providing the service firm with documentation on internal processes and business organization; ensuring the disposability of customer staff for coordination with the service firm (for activities such as specification refinement, testing and the preparation of migration); supporting maintenance issues that can only be resolved jointly (e.g., bug regression); and promoting high levels of user skills and IT awareness among end-users and management.

As the above discussions illustrate, the dimension of customer collaboration is virtually impossible to contract upon. We therefore assume that x_t *is not contractible* as in the incomplete contracting literature (Grossman-Hart [GH86] and Hart-More [HM88]), and as a consequence, the service value is not contractible either. Furthermore, we assume that the client cannot commit in advance to future choices of s_t and x_t and so the client and a firm cannot sign a long-term contract.

When the size of project is endogenous, for a given K_t^i, the optimal level of collaboration x_t will monotonically increase with the size of the project s_t. Since endogeneizing both s_t and x_t in our dynamic model adds complications without generating new insight (note that the issue related to the choice of x_t is examined when we study the case of exogenous project size), we will make the following simplifying assumption:

Assumption: In the model of endogenous project size, the level of collaboration is soly determined by the project size and increases with it.

Because of this assumption, we will identify the choice of project size with the choice of collaboration level when the project size is endogenous. Therefore, we will use throughout the paper (i.e. for both variants of the model) $V(K_t^i, x_t)$ for the service value and $C(x)$ for the cost related to the project size choice or the collaboration.

Regarding $C(x)$, it is convenient in the model if there exists a "low-level regime" of customer collaboration in which the cost incurred by the customer is negligible because all collaborative tasks can still easily be integrated with everyday business. A collaboration effort exceeding a certain minimum threshold x_m, however, will become costly. We therefore model collaboration cost as a twice differentiable convex function $C(x)$, with $C(x) = 0$ if $0 < x \leq x_m$, $C'(x_m) = 0$, $C'(x) > 0$ for all $x > x_m$ and $C'' > 0$.

Regarding the value function $V(K_t^i, x_t)$, we assume positive first-order cross derivatives i.e. $\partial^2 V/\partial K \partial x > 0$: higher specific knowledge K allows for higher returns to customer collaboration, and vice versa. Unless noted otherwise, we also assume diminishing returns to both x and K, i.e. $\partial^2 V/\partial K^2 < 0$, and $\partial^2 V/\partial x^2 < 0$. With respect to the cost incurred by the service provider, we postulate that the cost to deliver the service is constant with respect to K and x. For the sake of simplified notation, we will set them equal to zero.

In order to focus on the client's choice of collaboration level, we deliberately abstract from the moral hazard problem on the part of service providers, which arises because $V(K_t^i, \alpha x_t)$ is not contractible. More precisely, some papers on reputation such as Kreps [Kre90], Shapiro [Sha83], Choi [Choi98], Tadelis [Tad02] and Bar-Issac [BI07] study an agent's incentive to work (or shirk) when the quality of the service (or product) that he produces is not contractible and the client should pay the price before the service is produced (or before he consumes the product). Our $V(K_t^i, \alpha x_t)$ can be interpreted as the one generated either when reputational concern allows the service provider to overcome his incentive problem or when he cannot overcome the problem. In other words, we focus on the client's choice of collaboration for given degree of incentive problem on the part of the service providers.

3.4 The model of endogenous project size

We here specify the model with endogenous project size. The model of exogenous size will be very similar to this model and will be specified in section 5.

3.4.1 Open versus closed source

Let firm 1 represent the incumbent firm who owns a single proprietary software. At the beginning of the first period ($t = 1$), the incumbent should decide whether or not he will release it as open source software. The key question we are interested in is to know under what circumstances he releases it as open source. In our model, the key difference between open source and closed source is captured as follows. Under closed source, the incumbent is the monopoly and faces no competition. Under open source, the incumbent faces competition and furthermore releasing the software as open source increases the stock of knowledge of its competitors. More precisely, if 1 chooses the open source mode, any competing firm's stock of knowledge at $t = 1$ is equal to $K_1^i = K_1^2$ with $0 < K_1^2 < K_1^1$ for $i = 2, ..., n$. Now any competitor can make and sell a competing commodity or service since the source code is freely available and there is no infringement of the intellectual property right. However, we assume $K_1^1 > K_1^2$: the incumbent has more stock of knowledge since he has all the manpower who developed the software and has more experience with it.

3.4.2 Timing

We below present the timing of the game we study. As we said, the first decision in the game is:

- In period 1, firm 1 makes a once-and-for-all decision about whether or not to release his software as open source, which determines the number of competitors and their initial stock of knowledge.

We call Γ^C (Γ^O) the game under closed source (the game under open source). Let $\Gamma \in \left\{\Gamma^C, \Gamma^O\right\}$ represent a game.

The timing of a given game $\Gamma \in \left\{\Gamma^C, \Gamma^O\right\}$ for a given period t is given as follows:

1. $\mathbf{K}_t = (K_t^1, ..., K_t^n)$ is determined from what happened before.

2. The customer chooses x_t and incurs the cost $C(x_t)$.

3. Each firm makes a price offer to win the contract of the customer.

4. The customer chooses one among them. Let i denote the identity of the selected firm.

5. Value $V(K_t^i, \alpha x_t)$ accrues to the customer.

6. At the end of period t, $K_{t+1}^i = K_t^i + \beta k(x_t)$ and $K_{t+1}^j = K_t^j$ for any firm $j \neq i$.

Note that in 3, although each firm makes a price offer, the customer knows that the value she obtains from choosing firm i is given by $V(K_t^i, x_t)$. In 4, as a tie-breaking rule, we assume that if the customer is indifferent, the customer chooses the firm providing a higher gross value (i.e. the firm with the largest stock of knowledge). Note that under the commodity-based approach, x_t plays no role at all and hence we assume $x_t = 0$ for all t. Under closed source, firm 1 is monopoly and hence from 3 makes a take-it-or-leave-it offer. In what follows, we study a two-period model. Since all the entrants are ex ante identical, we will use $i = I$ to denote the incumbent (firm 1) and $i = E$ to denote an entrant: so 1 and 2 are used only to represent $t = 1$ or 2. Since for most part of the analysis, having more than one entrant is equivalent to having one entrant, we will do the analysis as if there were only one entrant except when the equivalence fails to hold.

3.4.3 Benchmark I: Commodity-based approach

In this section, as a benchmark, we study the commodity-based approach (i.e. when $\alpha = 0$ and $\beta = 0$). In this case, as we said, $x_t = 0$ for all t. Since $\beta = 0$, there is no change in the stock of knowledge of any firm. Hence, the two-period game is just the repetition of the static game.

Consider first the game under closed source Γ^C. Then, the incumbent charges as the price of the commodity $p_t^I = V(K_1^I, 0) > 0$ for $t = 1, 2$. His total profit is $(1 + \delta)V(K_1^I, 0)$.

Consider now the game under open source Γ^O. Then, the entrant is ready to produce a commodity of value $V(K_1^E, 0)$ at zero price each period. Therefore, the incumbent charges as the price of the commodity $p_t^I = V(K_1^I, 0) -$

$V(K_1^E, 0)$ for $t = 1, 2$. His total profit is $(1+\delta)\left[V(K_1^I, 0) - V(K_1^E, 0)\right]$. Therefore, the incumbent never adopts the open source mode in the commodity-based approach.

Observation: The incumbent never adopts the open source mode in the commodity-based approach.

3.4.4 Benchmark II: Service-based approach and closed source

As a second benchmark, we consider the service-based approach and the game under closed source Γ^C. Using backward induction, we first analyze the second period given the collaboration level from the previous period x_1. Then, we have $K_2^I = K_1^I + k(x_1)$. Suppose that the customer has chosen x_2. Then, the incumbent charges as the price for his service $p_2^I = V(K_1^I + k(x_1), x_2)$ to the customer and extracts full customer surplus. Hence, the customer payoff is zero in period 2 regardless of the current level x_2 of customer participation. The customer will therefore never want to choose any level x_2 higher than the minimum level x_m and we assume that this value (the highest value that leaves her indifferent) is the value she actually chooses.

The situation in period 1 is almost identical since the choice of x_2 does not depend on x_1. For given x_1, the incumbent charges as the price for his service $p_1^I = V(K_1^I, x_1)$ to the customer and extracts full customer surplus. Therefore, regardless of the value of x_1, the customer gets zero payoff for each period and hence chooses $x_1 = x_m$. Hence we have the following immediate, but important benchmark result. Let x_t^C the equilibrium level of collaboration in period t under closed source. Let Π_t^i represent firm i's profit in period t and Π^i represent firm i's total discounted profit. Let S_t represent the customer's surplus (net of the cost of collaborating) in period t and S represent the customer's total discounted surplus.

Proposition 3.1 *Under closed source, the incumbent's profit is*

$$\Pi^{I,C} = V(K_1^I, x_m) + \delta V(K_1^I + k(x_m), x_m)$$

whilst the customer receives a net surplus of zero each period $\left(S^C = 0\right)$. *The customer chooses in both periods the minium collaboration level* $x_1^C = x_2^C = x_m$.

4 Endogenous size of project

In this section, we consider the service-based approach (i.e. when $\alpha = 1$ and $\beta = 1$) when the project size is endogenous and study the game under open source Γ^O. We have deliberately abstained from discussing product-related services as complements in the preceding paragraph because we feel that the view of services as a complementary off-the-shelf good falls short of their peculiar transaction structure: services can be seen as the joint creation of value with the customer, and their value tends to increase substantially with the amount of accumulated customer-specific knowledge from previous service exchanges between the client and the service firm.

In this section, we will show that the trade-offs regarding the production of open source vs. closed source software by firms that provide services based on the software are quite different ones: Providing services based on an open source infrastructure will induce the customer to deepen her collaboration intensity with the vendor but lower immediate profitability due to the arrival of competition. Delivering services using a proprietary closed-source software infrastructure, on the other hand, keeps immediate profits high but negatively affects the long-term growth of service value because of lower customer participation and inferior learning effects.

4.1 Second Period

We solve the game by backward induction, starting with the second period given the collaboration of the period one x_1. We distinguish two cases depending on which firm was awarded with the service project in period one.

4.1.1 Case 1: The incumbent has been awarded the first period project

Suppose that the incumbent has run the project in the previous period, which implies $K_2^I = K_1^I + k(x_1)$ and $K_2^E = K_1^E$. Given x_2, the incumbent will charge a price of

$$p_2^I = V(K_1^I + k(x_1), x_2) - V(K_1^E, x_2). \quad (1)$$

We use the subscript $2, I$ to represent the second-period payoffs when when the incumbent was awarded with the project in period one. Given x_2, the customer surplus and each firm's profit in period two is given by

$$\begin{aligned} S_{2,I} &= V(K_1^E, x_2) - C(x_2) & (2) \\ \Pi_{2,I}^I &= V(K_1^I + k(x_1), x_2) - V(K_1^E, x_2); \quad \Pi_{2,I}^E = 0 & (3) \end{aligned}$$

Let $x_{2,I}$ represent the equilibrium x_2. It is given by:

$$C'(x_{2,I}) = \left. \frac{\partial V(K_1^E, x)}{\partial x} \right|_{x=x_{2,I}} \tag{4}$$

$x_{2,I}$ is independent of the previous period collaboration level x_1. Note also that $x_{2,I} > x_m$ since $C'(x_m) = 0$ while $\partial V / \partial x > 0$.

4.1.2 Case 2: The entrant has been awarded the first period project

If the customer has chosen the entrant in the first period as the service provider, we have: $K_2^I = K_1^I$ and $K_2^E = K_1^E + k(x_1)$. The outcome of the second period competition now crucially depends on whether the following inequality holds or not:

$$V(K_1^E + k(x_1), x_2) > V(K_1^I, x_2) \Longleftrightarrow k(x_1) > K_1^I - K_1^E. \tag{5}$$

In other words, we should see whether the learning effect from the client relationship is large enough to enable the entrant to provider a better service than the incumbent. In what follows, the case with $k(x_1) \leq K_1^I - K_1^E$ (respectively, $k(x_1) > K_1^I - K_1^E$) is called the case of non-*substantial learning* (respectively, substantial learning). We use the subscript $2, N$ (respectively, $2, S$) to represent the second-period payoffs when when the entrant was awarded with the project in period one and the learning is non-substantial (respectively, substantial).

Case 2.1: Non-substantial learning When $k(x_1) \leq K_1^I - K_1^E$, the incumbent will be able to match any second period offer of the entrant while making a strictly positive profit. Given x_2, the incumbent charges a price equal to $p_2^I = V(K_1^I, x_2) - V(K_1^E + k(x_1), x_2)$ while the entrant charges $p_2^E = 0$.

Therefore, the customer surplus and each firm's profit in period two is given by:

$$S_{2,N} = V(K_1^E + k(x_1), x_2) - C(x_2) \tag{6}$$

$$\Pi_{2,N}^I = V(K_1^I, x_2) - V(K_1^E + k(x_1), x_2); \quad \Pi_{2,N}^E = 0 \tag{7}$$

The level of collaboration chosen by the customer, denoted by $x_{2,N}$, is determined by:

$$C'(x_{2,N}) = \left. \frac{\partial V(K_1^E + k(x_1), x)}{\partial x} \right|_{x=x_{2,N}} \tag{8}$$

Note that in this case, from $\partial^2 V/\partial K \partial x > 0$, $x_{2,N}$ strictly increases with x_1.

Case 2.2: Substantial learning When $k(x_1) > K_1^I - K_1^E$, the entrant is able to continue the relationship with the client while making a positive profit. Given x_2, the entrant charges a price equal to $p_2^E = V(K_1^E + k(x_1), x_2) - V(K_1^I, x_2)$ while the incumbent charges $p_2^I = 0$. Therefore, the customer surplus and each firm's profit in period two is given by:

$$S_{2,S} = V(K_1^I, x_2) - C(x_2)$$

$$\Pi_{2,S}^I = 0; \quad \Pi_{2,S}^E = V(K_1^E + k(x_1), x_2) - V(K_1^I, x_2)$$

The level of collaboration chosen by the customer, denoted by $x_{2,S}$, is determined by:

$$C'(x_{2,S}) = \left. \frac{\partial V(K_1^I, x)}{\partial x} \right|_{x=x_{2,S}} \tag{9}$$

We observe that, in contrast to equation (8), $x_{2,S}$ is now again independent of the previous choice of x_1. Also note, from $\partial^2 V/\partial K \partial x > 0$, we have $x_{2,S} \geq x_{2,N}(x_1) \geq x_{2,I}$ where $x_{2,N}(0) = x_{2,I}$ and $x_{2,N}(\overline{x}_1) = x_{2,S}$ for $k(\overline{x}_1) \equiv K_1^I - K_1^E$.

For future analysis, it would be useful to note

$$S_{2,S} + \Pi_{2,S}^E = V(K_1^E + k(x_1), x_{2,S}) - C(x_{2,S}).$$

4.1.3 Comparison

For the analysis of period one competition, it is useful to compare the customer's period two surplus depending on which firm was awarded with the service project in period one. Let $\Delta S_{2,N}$ ($\Delta S_{2,S}$) represent the difference between the surplus when the entrant was selected in period one and the surplus when the incumbent was selected in period one when learning is not substantial (when learning is substantial). Then, we have

$$\begin{aligned}
\Delta S_{2,N} &\equiv S_{2,N}(x_{2,N}) - S_{2,I}(x_{2,I}) \\
&= V(K_1^E + k(x_1), x_{2,N}) - C(x_{2,N}) - \left[V(K_1^E, x_{2,I}) - C(x_{2,I})\right] \\
&= \int_0^{x_1} \left[V'(K_1^E + k(x), x_{2,N}(x) - C'(x_{2,N}(x))\right] dx \geq 0;
\end{aligned}$$

$$\begin{aligned}
\Delta S_{2,S} &\equiv S_{2,S}(x_{2,S}) - S_{2,I}(x_{2,I}) \\
&= V(K_1^I, x_{2,S}) - C(x_{2,S}) - \left[V(K_1^E, x_{2,I}) - C(x_{2,I})\right] \\
&= \int_0^{\overline{x}_1} \left[V'(K_1^E + k(x), x_{2,N}(x) - C'(x_{2,N}(x))dx\right] \geq \Delta S_{2,N}.
\end{aligned}$$

Note that the customer's surplus is determined by the payoff she can make when she has free access to the know how of the second best firm. Since the second best firm's knowledge is larger when it is the entrant who was awarded with the period one project than when it is the incumbent, we always have $\Delta S_{2,N} \geq 0$ and $\Delta S_{2,S} \geq 0$. Furthermore, in the first case, the second best firm's knowledge is larger when the innovation is substantial than when it is not substantial annd therefore we have $\Delta S_{2,S} \geq \Delta S_{2,N}$.

4.2 First Period

In period one, if the incumbent wants to win the contract, he can always win it. However, it may be optimal not to win the contract. We first conduct the analysis assuming that the incumbent wins the contract and then study when it is optimal for the incumbent to win the contract.

4.2.1 When the incumbent wins the contract

We now analyze the first period. We first analyze the competition for given x_1. Define $x_{2,E}(x_1)$ as $x_{2,E}(x_1) = x_{2,N}(x_1)$ for $x_1 \leq \overline{x}_1$ and $x_{2,E}(x_1) = x_{2,S}$

for $x_1 > \overline{x}_1$.

First, the price offer that the entrant makes depends on whether learning is substantial. If learning is not substantial, the best offer he can make is $p_1^E = 0$. If learning is substantial, he can also pledge the period 2 profit that he can realize if he is chosen as the provider in period one, implying

$$p_1^E = -\delta \max\left\{0, \left[V(K_1^E + k(x_1), x_{2,E}(x_1)) - V(K_1^I, x_{2,E}(x_1))\right]\right\}$$

.

Now, let us turn to the price offer that the incumbent should make to be selected in period one. It is important to note that it is not enough for the incumbent just to match the offer of the entrant in terms of the net surplus of period one. The reason is that the identity of the firm selected in period one affects the customer's period two payoff as well. We have seen that the customer's second period payoff is lower when the incumbent is selected in period one than when the entrant is selected. Therefore, in addition to matching the entrant's offer in terms of the period one surplus, the incumbent also need to compensate for the loss in the customer's period two payoff, which implies

$$p_1^I = V(K_1^I, x_1) - V(K_1^E, x_1) - p_1^E - \delta \Delta S_2 \text{ where } \Delta S_2 = \Delta S_{2,j} \text{ for } j = N, S.$$

Hence, the total surplus of the customer as a function of x_1 is given by:

$$S(x_1) = V(K_1^E, x_1) - C(x_1) + \delta\left(S_{2,j} + \Pi_{2,j}^E\right) \text{ for } j = N, S;$$

which is equivalent to

$$S(x_1) = V(K_1^E, x_1) - C(x_1) + \delta\left[V(K_1^E + k(x_1), x_{2,E}(x_1)) - C(x_{2,E}(x_1))\right]. \tag{10}$$

Basically, the customer's total suplus is given by the payoff that she can achive when she has free access to the entrant's knowledge. A minor qualification is that $x_{2,E}(x_1)$ maximizes $V(K_1^E + k(x_1), x_2) - C(x_2)$ only when the innnovation is not substantial.

The cusomer finally chooses x_1 to maximize $S(x_1)$. Let x_1^O denote the solution. We have:

$$C'(x_1^O) = \left.\frac{\partial V(K_1^E, x)}{\partial x}\right|_{x_1^O} + \delta\left[\frac{\partial V(K_1^E + k(x), x_{2,E}(x))}{\partial K} \cdot \left.\frac{\mathrm{d}k}{\mathrm{d}x}\right|_{x_1^O}\right] \tag{11}$$

Note that from the envelope theorem, we can neglect the indirect effect through the change $x_{2,N}$ when learning is not substantial: furthermore, when learning is substantial, $x_{2,S}$ does not depend on x_1. (11) has clear economic interpretation. It shows that period one collaboration generates two sources of benefits to the customer. First, it generates the immediate benefit of increasing the value of the period one service and the customer captures a part of it. Second, it increases the value that the entrant can produce in period two from accumulating customer-specific knowledge if the entrant is chosen in period one: since this determines the outside option of the customer, the customer benefits from it. In other words, the customer can sell the right to have deep relationship with her. Note also that $x_1^O > x_m$ since $C'(x_m) = 0$ while $\partial V/\partial x > 0$.

Finally, the incumbent's total profit is the difference between the total surplus and the customer's surplus:

$$\begin{aligned}\Pi^{I,O} &= V(K_1^I, x_1^O) - V(K_1^E, x_1^O) + \delta\left[V(K_1^I + k(x_1^O), x_{2,I})\right. \\ &\quad \left.-V(K_1^E + k(x_1^O), x_{2,E}(x_1^O))\right] + \delta\left[C(x_{2,E}(x_1^O)) - C(x_{2,I})\right].\end{aligned} \tag{12}$$

The incumbent's payoff is the total value it generates minus the total value that the entrant can generate. Note that the incumbent does not bear the customer's period one cost of collaboration since it is already sunk. The last term, $C(x_{2,E}(x_1^O)) - C(x_{2,I}(x_1^O))(\geq 0)$, represents the difference between the customer's period two collaboration cost when the entrant is selected in period 1 and the cost when the incumbent is selected in period 1.

Let $x_2^O = x_{2,I}$ denote the period two collaboration level in equilibrium. Summarizing, we have:

Proposition 4.1 *Suppose that the incumbent decides to win the contract in period one. Under open source, the customer chooses the collaboration level $x_1^O > x_m$ and $x_2^O > x_m$ and her surplus is given by*

$$V(K_1^E, x_1^O) - C(x_1^O) + \delta\left[V(K_1^E + k(x_1^O) - C(x_{2,E}(x_1^O))\right].$$

The incumbent's profit is given by

$$\begin{aligned}\Pi^{I,O}(x_1^O) &= V(K_1^I, x_1^O) - V(K_1^E, x_1^O) \\ &\quad +\delta\left\{V(K_1^I + k(x_1^O), x_2^O) - V(K_1^E + k(x_1^O), x_{2,E}(x_1^O))\right\} \\ &\quad +\delta\left\{C(x_{2,E}(x_1^O)) - C(x_2^O)\right\}.\end{aligned}$$

The entrant's profit is zero.

A direct consequence of the proposition is:

Corollary 4.2 *Customer collaboration level with an IT service firm is higher at all times under open source than under closed source:* $x_1^O > x_1^C = x_m$ *and* $x_2^O (= x_{2,I}(x_1^O) > x_2^C = x_m$.

4.2.2 When the incumbent wants to win the period one contract?

Up to now we assumed that the incumbent wants to win the period one contract. However, when the initial gap in terms of knowledge stock is large, the incumbent may be better off letting the entrant win the period one contract in order to boost period two collaboration. Furthermore, this might affect the choice of period one collaboration. To simplify our analysis, we explicitly assume that there are more than one identical entrants; therefore, they can never make a positive overall profit. Since this makes sure that the customer gets all the benefit from having a free access to an entrant's technology, the customer's payoff for a given x_1 is given as in the previous subsection, and hence the customer's choice of x_1 remains unchanged. Therefore, we only need to compare the incumbent's payoff conditional on winning the period one contract and his payoff conditional on losing it.

For this purpose, consider a static game with given $\left(K^I, K^E\right)$. Then, the customer chooses x by:

$$C'(x) = \frac{\partial V(K^E, x)}{\partial x}.$$

The incumbent's profit is

$$\Pi^I(K^E) = V(K^I, x(K^E)) - V(K^E, x(K^E)).$$

Assume that $\Pi^I(K^E)$ is concave and is maximized at $K^E = K^{E*}$. Then, in our two period model, if $K_1^E \geq K^{E*}$, letting the entrant win the first period contract is not optimal for the incumbent, which gives a sufficient condition to make winning the period one contract optimal. Furthermore, it is obvious that if the learning is substantial, the incumbent will never lose the period one contract.

More generally, if the incumbent lets an entrant win the priod one contract, his profit is

$$\widetilde{\Pi}^{I,O} = \delta \left\{ V(K_1^I, x_{2,E}) - V(K_1^E + k(x_1^O), x_{2,E}) \right\}.$$

The incumbent will let an entrant win the period one contract if $\widetilde{\Pi}^{I,O} > \Pi^{I,O}$.

Proposition 4.3 *If $\widetilde{\Pi}^{I,O} > \Pi^{I,O}$, the incumbent prefers losing the period one contract to allow an entrant to accumulate some knowldge stock and to boost the period two collaboration.*

This result suggests that the incumbent may use market segmentation as a mechanism to induce customer collaboration. Although we deliberately focused on the case of one buyer, it is easy to extend the result to a setting with two buyers where the knowledge accumulated from one customer is partially applicable to another and vice versa. In this situation, even though the incumbent's production technology has constant return to scale and hence can win both customers if he wants, the incumbent may deliberately leave a customer to a competitor in order to boost the customer's collaboration.

4.3 Comparison: Closed source vs. open source

We will first do social welfare analysis and then turn to the comparison of profits since studying the benchmak that maximizes social welfare facilitates the comparison of profits. We focus on the case in which the incumbent wins the period one contract.

4.3.1 Social welfare

Social welfare is given by:

$$SW(x_1, x_2) = V(K_1^I, x_1) - C(x_1) + \delta \left\{ V(K_1^I + k(x_1), x_2) - C(x_2) \right\}.$$

For given x_1, the socially optimal level of collaboration in period two, denoted by x_2^*, is given by:

$$C'(x) = \left. \frac{\partial V(K_1^I + k(x_1), x)}{\partial x} \right|_{x_2^\pi}$$

Note that $x_2^*(x_1)$ strictly increases with x_1. Furthermore, for any $x_1 > 0$, $x_2^*(x_1) > x_2^O \equiv x_{2,I}$. Therefore, the period two collaboration level under open souce is always lower than the socially optimal one. This is because the incumbent always wins the period one competition and hence his stock of knowledge in period two is larger than that of the entrant. Since the customer's surplus is dertmined by the entrant's stock of the knowledge, the customer will choose suboptimal level of collaboration.

Let $SW(x_1) \equiv SW(x_1, x_2^*(x_1))$. Social welfare maximizing collaboration level in period one, denoted by x_1^*, is given by:

$$C'(x) = \left.\frac{\partial V(K_1^I, x)}{\partial x}\right|_{x_1^\pi} + \delta \left[\frac{\partial V(K_1^I + k(x), x_2^*(x))}{\partial K} \cdot \left.\frac{\mathrm{d}k}{\mathrm{d}x}\right|_{x_1^\pi} \right]$$

Obviously, $x_1^* > x_m$. We now compare x_1^* with x_1^O. We have:

$$x_1^* \gtreqqless x_1^O \Leftrightarrow$$

$$\left.\frac{\partial V(K_1^I, x)}{\partial x}\right|_{x_1^\pi} + \delta \left[\frac{\partial V(K_1^I + k(x), x_2^*(x))}{\partial K} \cdot \left.\frac{\mathrm{d}k}{\mathrm{d}x}\right|_{x_1^\pi} \right] \gtreqqless \left.\frac{\partial V(K_1^E, x)}{\partial x}\right|_{x_1^O} + \delta \left[\frac{\partial V(K_1^E + k(x), x_{2,E}(x))}{\partial K} \cdot \left.\frac{\mathrm{d}k}{\mathrm{d}x}\right|_{x_1^O} \right]$$

If we compare the first terms, we have

$$\left.\frac{\partial V(K_1^I, x)}{\partial x}\right|_{x_1^\pi} > \left.\frac{\partial V(K_1^E, x)}{\partial x}\right|_{x_1^O}.$$

However, the comparison of the second terms is likely to lead to an opposite sign since for given x_2,

$$\frac{\partial V(K_1^I + k(x), x_2)}{\partial K} < \frac{\partial V(K_1^E + k(x), x_2)}{\partial K}.$$

Therefore, x_1^* can be larger or smaller than x_1^O. It is interesting to notice that open source can lead to socially excessive collaboration in period one. It is because the marginal impact of an increase of knowledge stock on productivity is higher to the entrant than to the incumbent from diminishing returns to knowledge.

The analysis shows that under open source, there is an intrinsic conflict between selecting the right service firm in period one and choosing an efficient level of collaboration in period two. On the one hand, the efficiency requires that the customer should select the incumbent, in particular, in period one. On the other hand, this selection of the incumbent in period one increases the gap between the incumbent's stock of knowledge and the entrant's one and thereby weakens the customer's barganing power in period two, which increases the inefficiency in period two collaboration level.

Proposition 4.4 *(collaboration level) (i). Under open source, there is an intrinsic conflict between selecting the right service firm in period one and choosing an efficient level of collaboration in period two.*

(ii) In period one, the collaboration level under open source can be either higher or lower than the socially optimal one (i.e. $x_1^* \gtreqless x_1^O$) but the socially optimal level is higher than the level under closed source (i.e. $x_1^* > x^C$). In period two, the collboration level under open source is lower than the socially optimal one (i.e. $x_2^* > x_1^O > x_1^C$).

In order to compare social welfare under open source with the one under closed source, we first note:

Lemma 4.5 *Social welfare*

$$SW(x_1, x_m) = V(K_1^I, x_1) - C(x_1) + \delta \left\{ V(K_1^I + k(x_1), x_m) - C(x_m) \right\}$$

is strictly concave in x_1.

Proof. It comes from the fact that $\partial^2 V/\partial K^2$, $\partial^2 V/\partial x^2$ and $\partial^2 k/\partial x^2$ are all negative and $\partial^2 C/\partial x^2$ is positive.■

Therefore, we have:

Proposition 4.6 *If open source does not lead to socially excessive collaboration in period one (i.e., $x_1^* > x_1^O$), social welfare is higher under open source than under closed source. Even if open source leads to socially excessive collaboration, social welfare is higher under open source than under closed source as long as $SW(x_1^O, x_m) > SW(x_m, x_m)$.*

Proof. The result comes from the concavity of $SW(x_1, x_m)$ and $SW(x_1^O, x_2^O) > SW(x_1^O, x_m)$■

4.3.2 Profits

When we compare the incumbent's profit under open source with the profit under closed source, we have:

$$\begin{aligned} \Pi^{I,O}(x_1^O) - \Pi^{I,C}(x_m) &= \left[V(K_1^I, x_1^O) - V(K_1^I, x_m) \right] \\ &\quad + \delta \left\{ V(K_1^I + k(x_1^O), x_2^O) - C(x_2^O) - V(K_1^I + k(x_m), x_m) \right\} \\ &\quad - V(K_1^E, x_1^O) - \delta \left\{ V(K_1^E + k(x_1^O), x_{2,E}(x_1^O)) - C(x_{2,E}(x_1^O)) \right\}. \end{aligned}$$

The first two terms are positive: they represent the gains from increasing the collaboration levels. The last term is negative and represents the loss due to the competition from the entrant. Therefore, we have:

Proposition 4.7 *The incumbent's profit can be higher under open source than under entrant: the incumbent prefers open souce when the increase in the pie from higher collaboration levels is larger than the surplus given to the customer from creating competition.*

4.4 Extension: endogeneous level of competition in a service industry

In the previous sections, we made two simplications. First, we identified the closed source with the monopoly. Second, we identified the service with one software. However, in real world, providing a service to a big client may need a large number of software and firms can use a different combinations of software to provide competing services, which may question the pure monopoly in the service market based on a single software. In this section, we relax these assumptions in the following way.

The incumbent can have a number of proprietary software: as is the case with IBM. Even if the incumbent keeps all his software under closed source, he faces competition from an entrant. However, in this situation, the entrant's initial stock of knowledge is minimal and normalized at zero. The incumbent can choose the stock of knowledge of the entrant between 0 and K_1^I by decideing how many software he will release as open source. The more software is released under open source, the higher is K_1^E. For instance, IBM released a large number of its software under open souce.

More precisely, the game we consider is the following.

In period one,

1. K_1^I is given. The incumbent chooses $K_1^E \in \left[0, K_1^I\right]$

2. The customer chooses x_1 and incurs the cost $C(x_1)$.

3. Each firm makes a price offer to win the contract of the customer.

4. The customer chooses one among them. Let i denote the identity of the selected firm.

5. Value $V(K_1^i, x_1)$ accrues to the customer.

At the beginning of period 2, $K_2^i = K_1^i + k(x_1)$ and $K_2^j = K_1^j$ for firm $j \neq i$. 2-5 is repeated for period two.

We call this game Γ^E since this game is equivalent to Γ^O plus endogeneous choice of K_1^E made by the incumbent. Therefore, we can intensively use the previous results to analyze Γ^E.

We first need to understand how x_t^O changes with K_1^E.

Lemma 4.8 *(i) x_2^O increases with K_1^E. $x_{2,N}$ increases with K_1^E. $x_{2,S}$ does not depend on K_1^E*

(ii) The dependency of x_1^O on K_1^E is not unambiguously determined.

Proof. (i) is obvious. (ii) Applying the implicit function theorem to first-order condition (11) gives a derivative that is positive if

$$\frac{\partial V}{\partial K \partial x}(K_1^E, x_1) + \delta \frac{\partial^2 V}{\partial K^2}\left(K_1^E + k(x_1), x_{2,E}(x_1)\right) \left.\frac{dk}{dx}\right|_{x_1^O}$$

has a positive value[6]. The first term is positive but the second is negative.■

The intuition for the ambiguous sign in (ii) of the above lemma is the following. On the one hand, a direct consequence of an infinitesimal increase in K_1^E is that returns to x_1 in the first period will increase, which induces the customer to increase her choice of collaboration level x_1^O. On the other hand, there is an "indirect effect" with opposite direction: if V exhibits strongly diminishing returns to K, higher K_1^2 will reduce the next-period marginal benefits of x_1 from learning. The argument suggests that x_1^O increases with K_1^E for δ small while it decreases with K_1^E for δ large.

In what follows, we assume that x_1^O either increases with K_1^E (i.e. δ is small enough) or decreases with K_1^E (i.e. δ is large enough) and compare the K_1^E chosen by the social planner and the K_1^E chosen by the incumbent.

4.4.1 Social welfare

Suppose that the social planner chooses to maximize social welfare. Then social welfare is given by:

$$SW(x_1^O(K_1^E), x_2^O(K_1^E)) = V(K_1^I, x_1^O) - C(x_1^O) + \delta\left\{V(K_1^I + k(x_1^O), x_2^O) - C(x_2^O)\right\}.$$

[6] In the non-substantial learning regime, there is another positive term for the second period indirect effect; we omit its discussion since it is even more favourable for getting a positive derivative of x_1^O with respect to K_1^E.

Note that there is no direct effect from K_1^E on social welfare. The indirect effect from the change in x_1^O is

$$\left[\frac{\partial V(K_1^I, x)}{\partial x}\bigg|_{x_1^O} + \delta \, \frac{\partial V(K_1^I + k(x_1), x_2^O)}{\partial K} \cdot \frac{dk}{dx}\bigg|_{x_1^O} - C'(x_1^O) \right] :$$

the indirect effect from the change in x_2^O is

$$+\delta \left[\frac{\partial V(K_1^I + k(x_1), x)}{\partial x} \cdot \bigg|_{x_2^O} - C'(x_2^O) \right].$$

Note that the indirect effect from the change in x_2^O is always positive. Regarding the indirect effect from the change in x_1^O, suppose that δ is small enough. Then, $x_1^* > x_1^O$. Then, increasing K_1^E increases x_1^O and hence is welfare-improving. When δ is large enough, we have $x_1^* < x_1^O$. Then, increasing K_1^E decreases x_1^O and hence is welfare improving. Therefore, in either case, $K_1^E = K_1^I$ maximizes social welfare. In general, if $x_2^O = x_2^*$, $K_1^E = K_1^I$ is always socially optimal. However, $K_1^E = K_1^I$ does not always maximize social welfare because of the distortion in x_2^O. All other things being equal, $x_2^O < x_2^*$ decreases x_1^O compared to the case $x_2^O = x_2^*$. Suppose that when $K_1^E = K_1^I$, $x_1^O > x_1^*$. If x_1^O increases with K_1^E, then decreasing K_1^E from K_1^I would be socially optimal.

4.4.2 Profit

We now study the incumbent's choice of K_1^E

$$\begin{aligned}
\Pi^{I,O}(K_1^E, x_1^O(K_1^E), x_2^O(K_1^E), x_{2,E}(K_1^E, x_1^O(K_1^E))) &= V(K_1^I, x_1^O) - V(K_1^E, x_1^O) \\
&\quad + \delta \left\{ V(K_1^I + k(x_1^O), x_2^O) - V(K_1^E + k(x_1^O), x_{2,E}(x_1^O)) \right\} \\
&\quad + \delta \left\{ C(x_{2,E}(x_1^O)) - C(x_2^O) \right\} \\
&= SW(x_1^O(K_1^E), x_2^O(K_1^E)) + C(x_1^O(K_1^E)) - V(K_1^E, x_1^O(K_1^E)) \\
&\quad - \delta \left\{ V(K_1^E + k(x_1^O), x_{2,E}(x_1^O)) - C(x_{2,E}(x_1^O)) \right\}
\end{aligned}$$

Note that the incumbent does not care about $C(x_1^O)$ since it is already sunk when he makes an offer. First, the direct effect of K_1^E is negative.

$$- \frac{\partial V(K, x_1^O)}{\partial K}\bigg|_{K_1^E} - \delta \, \frac{\partial V(K + k(x_1^O), x_{2,E}(x_1^O))}{\partial K} \cdot \bigg|_{K_1^E}$$

Second, to isolate the indirect effect through the change in x_1^O, we compute $\partial\Pi^{I,O}/\partial x_1^O$ and simplify it using equation (11) to obtain

$$\frac{\partial\Pi^{I,O}}{\partial x_1^O} = \left.\frac{\partial V(K_1^I, x)}{\partial x}\right|_{x_1^O} + \delta\left[\frac{\partial V(K_1^I + k(x_1), x_2^O)}{\partial K}\cdot\left.\frac{dk}{dx}\right|_{x_1^O}\right] - C'(x_1^O) \quad (13)$$

Note that this term is identical with the term we found in social welfare.

Third, the indirect effect through the change in x_2^O is

$$+\delta\left[\frac{\partial V(K_1^I + k(x_1), x)}{\partial x}\cdot\Big|_{x_2^O} - C'(x_2^O)\right].$$

This term is also identical with the term in social welfare.

Last, the indirect effect through the change in $x_{2,E}$ can be neglected from the envelope theorem.

Therefore, the incumbent faces the following trade-off when choosing K_1^E: the incumbent maximizes the change in social welfare minus the change in the outside option of the buyer (i.e. the buyer's payoff from choosing the entrant). Since the latter increases with K_1^E, the incumbent always chooses a suboptimal level of K_1^E, which is no surprise since when $K_1^E = K_1^I$, the incumbent makes zero profit. However, our result generalizes the insight from the previous section in which the choice of the incumbent is binary (i.e. open source or closed source).

Proposition 4.9 *1. When K_1^E is chosen by the incumbent, the level chosen by the incumbent is always lower than the level chosen by the social planner.*

2. For δ small enough or large enough, increasing K_1^E increases social welfare by improving collaboration choices but also increases the outside option of the customer by strengtheing the entrant. The incumbent maximizes the difference between social welfare and the outside option.

5 Exogenous size of project

In this section, we study the case in which the size of the project is exogenously given and normalized at one for each period. We focus on the level of collaboration chosen **after** the customer selects a service firm. We also take the definition of service as providing a solution to the customer's problem: in particular, we assume that the knowledge created during the problem solving is given by $k(K, x)$ and is materialized into a software: since the quality of the solution depends on the service firm's knowledge K, the knowledge materialized in software should depend on K as well. We assume that the software belongs to the problem solver (the service firm)[7]. In particular, the firm's knowledge stock increases by $k(K, x)$. How the software affects the knowledge stock of a rival firm depends on whether the service firm made a commitment to open source or not. In the case of closed source, any rival firm's stock of knowledge is not affected. In the case in which the service firm is committed to open source, a rival firm's stock of knowledge increases by the same amount $k(K, x)$.[8] We consider two firms: the incumbent and the entrant with initial stock of knowledge $K_1^I > K_1^E$.

The timing is the following: In period one,

1. Each firm simultaneously chooses whether to adopt open-source policy or not.
2. Each firm makes a bid
3. The customer selects a firm.
4. The customer determines the level of collaboration.
5. The knowledge stock of each firm is adjusted.

In period two, 2-5 is repeated.

5.1 Benchmark: one period

We first consider a one-period game. Since there is no second period, each firm's choice regarding open or closed source does not matter. Since the price that each firm proposes is fixed and does not depend on the level of collaboration (which is not contractible), conditional on selecting firm i with $K_i = K$, the customer chooses the level of collaboration determined by:

$$C' = \frac{\partial V(K, x)}{\partial x}.$$

[7]The case it belongs to the customer is less interesting to study.

[8]For simplicity, we assume complete spillover regardless of whether the firm benefiting from spillover chooses open source or closed source.

In what follows, we use $x_t(K)$ to represent the optimal static collaboration level given K for $t = 1, 2$. Since the customer gets the whole benefit from $V(,)$, her level of collaboration is optimal and in this sense there is no incentive problem. Since the cross-derivative of V is positive, the level of collaboration is higher when the incumbent is selected than when the entrant is selected. Obviously, the incumbent wins the contract.

The payoff of the customer is

$$V(K^E, x(K^E)) - C(x(K^E))$$

Observations: In a one period model, (i) each firm's policy regarding open source does not matter.

(ii) the level of collaboration is optimal for given selection of the servic firm: it is higher when the incumbent is chosen than when the entrant is chosen

(iii) the incumbent always wins the service contract.

5.2 Two periods

As before, we solve the two period game by backward induction. Although there are four different cases to be considered (due to the possible choices with respect to licensing of both the incumbent and the entrant), the characterization of the second period is the same for each case: profits and prices in second period depend only on the knowledge stock levels of the two competing firms at the beginning of the second period, and the second period outcomes are those of the static benchmark. Especially, customer collaboration in period 2 will always be socially optimal, and the firm which emerges from period one with the highest knowledge stock will always win the second period contract. The socially optimal level of customer collaboration in period one is attained when the sum of the direct and indirect (next period) effect of collaboration just equals its marginal cost:

$$C' = \frac{\partial V(K_1^1, x)}{\partial x} + \delta \frac{\partial V(K_1^I + k(K_1^I, x_1), x_2(K_2^I))}{\partial K} \frac{\partial k(K_1^I, x)}{\partial x}.$$

5.2.1 Incumbent chooses Closed Source

a) Incumbent Closed Source, Entrant Closed Source Suppose the incumbent chooses a closed source license policy, and the entrant also decides in favor of closed source licensing. Due to the proprietary nature of the projects, there is no knowledge spillovers between the two firms.

Suppose that the incumbent is selected in period one. Then, the payoff of the customer as a function of period one collaboration level x_1 is given by:

$$V(K_1^I, x_1) - C(x_1) - p_1^I + \delta \left[V(K_1^E, x_2(K_1^E)) - C(x_2(K_1^E)) \right].$$

Note that the period two payoff of the customer does not depend on x_1. Therefore, we have

$$C' = \frac{\partial V(K_1^I, x)}{\partial x}.$$

We observe an immediate consequence of the incumbent's lack of commitment power: Since the customer does not take into account the dynamic gain, the collaboration level is too low from the social point of view.

Suppose now that the entrant is selected in period one. Then, the payoff of the customer as a function of period one collaboration level x_1 is given by:

$$V(K_1^E, x_1) - C(x_1) - p_1^E + \delta \left[V(K_2^{\min}, x_2(K_2^{\min})) - C(x_2(K_2^{\min})) \right],$$

where $K_2^{\min} = \min(K_1^E + k(K_1^E, x_1), K_1^I)$. Note that, as long as learning is non-substantial, the period two payoff of the customer now depends on x_1. In this range of knowledge parameters, the period one collaboration level is determined by taking into account both the direct (static) and the indirect (dynamic) effects of collaboration:

$$C' = \frac{\partial V(K_1^E, x)}{\partial x} + \delta \frac{\partial V(K_1^E + k(K_1^E, x_1), x_2(K_2^E))}{\partial K} \frac{\partial k(K_1^E, x)}{\partial x}. \tag{14}$$

We will use the notation $x_{1,E}(K_1^E)$ to represent the dynamic period one collaboration level when the entrant with stock of knowledge K_1^E is selected. If learning is non-substantial, there is dynamic gain from higher entrant knowledge stock in the next period, and therefore the collaboration level is higher when the entrant is selected rather than the incumbent. This picture is no longer correct in the case of substantial learning (i.e. $K_1^E + k(K_1^E, x_1(K_1^E)) > K_1^I$) because the entrant's increasing commitment problems lets customer collaboration continuously drop towards the static level. We abstain from giving all details since the substantial learning case is straightforward and delivers few new insights; especially, the incumbent will always be able to outbid the entrant in first period and hence get the project for both periods.

Since period one collaboration level can be higher when the entrant is selected than when the incumbent is chosen, this might allows the entrant to win the period one contract. However, we can show that the incumbent wins both periods' contracts. Again, we explicitly develop the argument only for the case of non-substantial learning. In this case, the incumbent's profit if he loses the period one contract is

$$\begin{aligned}&\delta\left[V(K_1^I, x_2(K_1^I)) - C(x_2(K_1^I))\right]\\ &-\delta\left[V(K_1^E + k(K_1^E, x_{1,E}(K_1^E)), x_2(K_2^E)) - C(x_2(K_2^E))\right]\end{aligned}$$

If he wins the period one contract, on the other hand, his profit amounts to

$$p_1^I + \delta\left[V(K_1^I, x_2(K_1^I)) - C(x_2(K_1^I))\right] - \delta\left[V(K_1^E, x_2(K_1^E)) - C(x_2(K_1^E))\right].$$

Therefore, he is indifferent between losing the period one contract and winning it if he can win it at the following price

$$\begin{aligned}p_1^I &= -\delta\left[V(K_1^E + k(K_1^E, x_{1,E}(K_1^E)), x_2(K_2^E)) - C(x_2(K_2^E))\right]\\ &\quad +\delta\left[V(K_1^E, x_2(K_1^E)) - C(x_2(K_1^E))\right].\end{aligned}$$

When p_1^I is given as above, the customer's total payoff from selecting the incumbent is

$$V(K_1^I, x_1(K_1^I)) - C(x_1(K_1^I)) + \delta\left[V(K_1^E + k(K_1^E, x_{1,E}(K_1^E)), x_2(K_2^E)) - C(x_2(K_2^E))\right]$$

The best offer that the entrant can make at period one is zero since he cannot win the period two contract. Then, the customer's surplus is

$$V(K_1^E, x_{1,E}(K_1^E)) - C(x_{1,E}(K)) + \delta\left[V(K_1^E + k(K_1^E, x_{1,E}(K_1^E)), x_2(K_2^E)) - C(x_2(K_2^E))\right]$$

Since $V(K_1^I, x_1(K_1^I)) - C(x_1(K_1^I)) > V(K_1^E, x_{1,E}(K_1^E)) - C(x_{1,E}(K))$ holds, the incumbent always wins the period one contract.

However, note $p_1^I < 0$ and therefore the incumbent may fail to win the period one contract if he cannot charge a negative price. Furthermore, we will show that this result is not robust to a change of entrant strategy: conditional on the incumbent's adoption of a closed-source policy, the entrant may win the period one contract by adopting open source policy.

b) Incumbent Closed Source, Entrant Open Source By adopting an open source policy in response to the incumbent's proprietary offer, the entrant can reduce the commitment problems on his side and increase the attractiveness of his offer because of the spillover effect on the incumbent's second period offer. On the other hand, the incumbent will always have higher knowledge level in period 2 (due to the complete spillover from the entrant) and win the period two project.

We calculate separately what the customer can expect to receive from the entrant under open source conditions (the payoff from the incumbent is the same as before, with collaboration levels remaining at the static level). If the entrant is awarded period 1, the customer receives

$$V(K_1^E, x_{1,\tilde{E}}) - C(x_{1,\tilde{E}}) - p_E + \delta \left[V\left(K_1^E + k(K_1^E, x_{1,\tilde{E}}), x_2\right) - C(x_2)\right]$$

where p_E is the price charged by the entrant. The customer collaboration level $x_{1,\tilde{E}}$ is therefore determined by the equation

$$C'(x_{1,\tilde{E}}) = \frac{\partial V(K_1^E, x_{1,\tilde{E}})}{\partial x} + \delta \frac{\partial V(K_1^E + k(K_1^E, x_{1,\tilde{E}}), x_2)}{\partial K} \left.\frac{\partial k}{\partial x}\right|_{(K_1^E + k, x_{1,\tilde{E}})}$$

In order to make the customer indifferent between the entrant and the incumbent, the incumbent must charge a price p_I as low as

$$\begin{aligned} p_I \;=\; & V\left(K_1^I, x_1(K_1^I)\right) - C\left(x_1(K_1^I)\right) \\ & + \delta\left[V(K_1^E, x_1(K_1^E)) - C(x_1(K_1^E))\right] \\ & - V(V_1^E, x_{1,\tilde{E}}) + C(x_{1,\tilde{E}}) \\ & - \delta\left[V(K_1^E + k(K_1^E, x_{1,\tilde{E}}), x_2) - C(x_2)\right] \end{aligned}$$

Note that this price can become negative as K_1^E approaches K_1^I. If, on the other hand, K_1^E is so low that $K_1^E + k(K_1^E, x_{1,\tilde{E}}) > K_1^I$ holds, prices are guaranteed to remain strictly positive. (To see this, simply compare the element in the third line of the above expression with its optimal counterpart at static collaboration intensity to find that the first line is always larger than the third and the difference hence is positive). Incumbent's profits conditional on the incumbent submitting a competitive bid for both periods become

$$\begin{aligned}\Pi_I &= V(K_1^I, x_1(K_1^I)) - C(x_1(K_1^I)) \\ &\quad +\delta \left[V(K_1^I + k(K_1^I, x_1(K_1^I)), \hat{x}_2) - C(\hat{x}_2)\right] \\ &\quad -V(K_1^E, x_{1,\tilde{E}}) + C(x_{1,\tilde{E}}) \\ &\quad -\delta \left[V(K_1^E + k(K_1^E, x_{1,\tilde{E}}), x_2) - C(x_2)\right]\end{aligned}$$

Now it becomes obvious that for a very small knowledge gap between the two rival firms, i.e. $K_1^E \to K_1^I$, the incumbent's higher knowledge at static collaboration (first two lines of the equation) will not be able to compensate the higher learning of the entrant due to better customer collaboration under open source (lines 3 and 4); in this case, incumbent profits turn negative, and the incumbent is better off to leave the first period of the project to the entrant.

We note that among all four scenarios, the is the only case in which the incumbent can be forced out of the market in the first period. This surprising result underlines the competitive relevance of the commitment aspect of open source software.

5.2.2 Incumbent chooses Open Source

The preceding paragraph should already have formed the intuition for what we can expect if the incumbent chooses open source. Suppose that the incumbent chooses open source. Then, conditional on that the customer picks up the incumbent, her period one level of collaboration (and hence period two level as well) does not depend on whether the entrant chooses open source or closed source.[9] More precisely, the payoff of the customer as a function of period one collaboration level x_1 is given by:

$$V(K_1^I, x_1) - C(x_1) - p_1^I + \delta \left[V(K_1^E + k(K_1^I, x_1), x_2(K_2^E)) - C((x_2(K_2^E))\right].$$

Now the period two payoff of the customer depends on x_1 since open source creates knowledge spillover. Therefore, we have

$$C' = \frac{\partial V(K_1^I, x)}{\partial x} + \delta \frac{\partial V(K_1^E + k(K_1^I, x_1), x_2(K_2^E))}{\partial K} \frac{\partial k(K_1^I, x)}{\partial x}.$$

[9]This is also due to our stark assumption that spillover is complete regardless of whether the receiving firm chooses open source or closed source.

Therefore, commitment to open source boosts customer collaboration such that the collaboration can be higher or lower than the socially optimal level. This allows the incumbent to win the period one contract (and the period two contract) regardless of the strategy of the entrant. However, if the entrant chooses open source, it increases competition and hence increases the customer's payoff.

5.3 Open source versus closed source

Summarizing, we have

Proposition 5.1 *In the model of exogenous size of project,*

(i) if both firms choose closed source, the period one collaboration level is higher when the entrant is chosen when the incumbent is chosen

(ii) if a firm chooses open source, conditional on that the firm is selected, the period one collaboration level is higher than under closed source

(iii) if the incumbent chooses closed source and the entrant chooses open source, the incumbent may not be able to win the period one contract. Therefore, open source can be a strategy for entry.

(iv) therefore the incumbent may adopt open source for two different reasons

a. even when the entrant chooses closed source, he may do it to boost periond one collaboration

b. if the entrant chooses open source, he may be forced to choose open source in order not to lose the period one contract.

6 Concluding remarks

We built a simple dynamic model of a knowledge-based service industry that focuses on customer collaboration as a core element. We studied two related models. In the model with ex ante choice of project size, we found that knowledge sharing through open source and market sharing can be a strategy that the dominant firm can employ to boost customer collaboration. In the model with exogenous size of project and endogenous collaboration level, we found that open source constitutes an aggressive entry strategy and the dominant firm may embrace open source for two reasons: either to boost the collaboration level or in order not to lose the competition.

Although our discussion has been concentrated on open source service industry, the line of argumentation presented in our model is far more general and not limited to software industry in any way. Specifically, we think that our theory can, by its focus on knowledge accumulation in a repeated service relationship, also be used to analyze the competitive dynamics between top management consulting firms such as McKinsey and Boston Consulting Group.

We deliberately focused on the case of a single buyer. In the future, it would be interesting to extend our analysis to the case of multiple buyers when knowledge is transferable across different buyers. This would raise coordination issues among the buyers. More generally, our paper is a first step toward to the IO of a knowledge-based service industry and more studies are needed to characterize the characteristics of this industry with respect to the traditional manufacturing industry.

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