Open Source Software, Competition and Potential Entry

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Abstract

We analyze a model with two software firms, quality improving coding expenditures and potential competition. The firms can publish parts of their software as open source. Publishing software implies positive spillovers and thus reduces the firms' coding costs. On the other hand there exist two negative effects. First, lower coding costs induce higher coding expenditures which decreases the firms' profits if their programs are substitutes. Second, open source encourages entry and increases the expenditures required to deter entry. The firms' optimal open source decisions balance these opposite effects.

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1 Introduction

Open source software (OSS), such as the Linux operating system or the Apache web server have recently found increasing interest in the software industry as well as in the economic research community. OSS is software, of which the source code (i.e. the code instructions showing how the software works) is published and thus "made open". In contrast, most software today is only available in binary code, which hides the way the program works.[1]

Typically, this source code can be accessed free of charge and compiled into a binary program, which can be executed on computers. However, OSS is not free in the sense of "you can do with it what you want". Rather, it is protected by copyright just like all other forms of software. Its usage requires acceptance of and adherence to the terms of the licence under which it has been published. Often, these licenses pose certain conditions upon some usage forms, such as altering the program or integrating it with other applications. Nevertheless, OSS code is free for everyone to inspect and to derive from this inspection how the programmer has solved a certain problem.[2]

At first sight, the existence of OSS seems to be a puzzle. Why should anyone take the effort to write a program, which is then made available free of charge to the world and from which everybody can "steal" ideas about how a tricky problem can be solved? Obviously leisure or altruistic motives are able to explain these activities of programmers and therefore early work on OSS focussed on these explanations.

Most current work, however, emphasizes reciprocity or individual labor market considerations. For instance, Lerner/Tirole (2002) argue that a programmer can signal her coding abilities by participating in open source projects. This should raise her expected future wage or give her access to programming jobs, as Raymond (2000, Chapter 5) already pointed out, although he considers the latter as rare and marginal motivation for most "hackers".

Although important for explaining the open source phenomenon, the focus on the individual programmer neglects an important open source driver: firms. Part of the open source community consists of individuals employed explicitly for developing open source software. Ghosh et al. (2002) surveyed OSS developers and

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[1] Just like Coca-Cola does not publish its recipe on its bottles.

[2] This short description only describes coarsely what OSS is. There are many variants of OSS as well as more extensive concepts like free software. A short introduction to the different issues can be found in Wichmann/Spiller (2002).

found that 16% of them were paid directly for developing open source software. For another 13% the development of OSS is part of their work. Thus, their contributions to open source projects are the result of firms' deliberate decisions to finance the development of OSS. In addition there exist several examples of companies that have made available formerly proprietary software as open source software.[3]

Despite these considerable activities the companies' motivations behind their OS engagement is not as well understood as the motivation of individual developers. Although discussed in passing by, e.g., Lerner/Tirole (2002a) or Schmidt/Schnitzer (2002), much less attention has been devoted to firms' open source activities than to open source activities of individuals. If OS activities by firms are discussed at all, they are often explained as activities to sell complimentary goods: Firms give away their software for free in order to sell more of a complementary good, i.e., hardware or other software programs.

However, even these arguments miss a crucial part of the story. Since open source software is available to everyone, the OSS developed by one firm can be integrated into the products of another firm and vice versa. Thus, the OSS activities seem to resemble much more the firms' engagements in basic research or in standardization activities (see Lerner/Tirole (2002b) or Wichmann (2002)).

Just like in basic research there exist counteracting positive and negative effects: Making the source code of a program publicly available enables educated users to find flaws and errors in the code and thus increases the quality of the software. "Given enough eyeballs, all bugs are shallow" (Raymond, 1998) is a mantra of the open source community. Additionally, other programers may also contribute to the solutions of certain problems and may thus decrease the firm's own coding costs. However, there also exist negative effects from "going open source": OSS published by a firm is available to all other firms. Therefore, also the firm's rivals may directly benefit from the firm's OSS, which in most cases a firm would rather not happen.

These counteracting forces form the starting points of our paper. We study the effects, of different technology and market environments on firms' decisions to publish their software under an open source license.

We discuss a simple world, in which firms sell software products to consumers.

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[3]One example is Netscape, which made the source code for its browser available as OSS. The browser Mozilla has developed out of this project. Another famous example is Sun, which has published the source code to its office suite StarOffice leading to the open source suite OpenOffice.

As the price for pure open source software for consumers is typically zero, this can best be thought of as a world of hybrid software. The best-known example of such software is probably the MacOS X operating system by Apple. MacOS X is based on an open source version of the operating system Unix called Darwin and in fact includes an increasing number of OSS components, but it also includes components that are not open source. Thus, software used by the consumers is of the type of a "package" or "bundle", which consists of several components. Some of them may be OSS.[4]

Firms can decide to publish some of their software components under an open source license. In our model we assume a rather liberal license that basically allows each user to use, modify, integrate and distribute the software components without restrictions. Several OS license types are very close to this ideal scenario, e.g. BSD-type licenses (governing Apache or the FreeBSD Unix) or the Artistic License (governing the programming language Perl). Modelling other, more restrictive, license forms such as the General Public License (GPL) is left to future work.[5]

Publishing software components under an open source license implies positive spillover effects and thus reduces the firms' coding costs. However, there are also two negative effects. First, lower coding costs induce higher coding activities, which decrease the firms' profits if their software programs are substitutes. Second, published software components encourage entry and increase the investment required to deter entry. We analyze the interaction of these different effects and show that some software will be published as OSS even if the firms' programs are substitutes and even if open source encourages market entry. Furthermore, we show that open source decisions can be interpreted as either strategic substitutes or complements depending on whether the firms' programs are substitutes or complements.

In the next section we set out our model. Section 3 considers the optimal open source decisions. Solving the model we first present an overview of the economic effects which determine the solution of the model. With respect to the formal solutions we do not provide a detailed discussion; rather, we try to illustrate the main results graphically. In section 4 we provide a short summary.

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[4]For example, a word processor typically consists of a core program and many additional components, which provide functionality for spell checking, drawing diagrams or mathematical equations. In the same way an operating system consists of many different components.

[5]For a comparison of the relative importance of the different OS license types see Lerner/Tirole (2002b).

2 The Model

We consider a four stage game with initially two firms $i = 1, 2$ and potential market entry. We start by explaining the timing of our model and then turn to the specific assumptions on costs and demand.

Timing Two firms $i = 1, 2$ offer different software programs composed by a variety of components. In the first stage each firm decides, which of these components it publishes as open source software. In the second stage the firms choose their coding expenditures in order to develop the qualities q_1 and q_2 of their software programs. Market entry takes place in the third stage. In our model entrants can benefit from the open source components revealed by firms 1 and 2. We restrict entry such that for every market there is one potential entrant $e_i = 1, 2$. Finally, the two firms 1 and 2 and any actual entrant set their prices. Summarizing, we have:

t_0 : Firms 1, 2 decide on their open source components.

t_1 : Firms 1, 2 decide on their qualities q_1 and q_2.

t_2 : Entrants decide whether to enter or not and on their qualities q_{e_i}.

t_3 : All firms set their prices, demand and profits are realized.

Costs Both firms can not only decide how much they spend on coding, i.e., in developing their software programs, they can also decide which of their software components they publish as open source programs. To simplify the analysis of these decisions we use the following reduced form approach: Let q_i denote the quality of firm i's software program and assume that q_i also measures the software components needed for this program. With $\alpha_i \in [0, 1]$ denoting the fraction of open source components that each firm publishes, the firms' costs for developing a quality q_i are given by $(i, j = 1, 2, \ i \neq j)$

$$c_i(q_i, q_j, \alpha_i, \alpha_j) = \frac{1}{2 + \alpha_i q_i + \alpha_j q_j} q_i^2. \tag{1}$$

According to this cost function, three factors influence costs: The costs are increasing in the own quality chosen by each firm due to higher coding expenditures. They are decreasing in the fraction of their open source components due to bug fixing and improvement of these components by users. And finally, the costs of firm i also decrease with $\alpha_j q_j$ as it can use and learn from the OSS components of its competitor.

Turning to the costs of potential entrants we have to take into account that market entry takes place in stage 3. Hence, entrants can use the open source

components that firms 1 and 2 have made public to create a software clone for each market at lower costs than the incumbent firms. The costs of an entrant in market i are thus given by

$$c_{e_i}(q_{e_i}, q_i, q_j, \alpha_i, \alpha_j) = \frac{1}{2 + \alpha_i q_i + \alpha_j q_j}(q_{e_i} - \alpha_i q_i)^2 \text{ for } q_{e_i} \geq \alpha_i q_i \qquad (2)$$

where q_{e_i} denotes the quality of the entrant's software program.

Demand We start by characterizing demand in the case where only the two programs of firms $i = 1, 2$ are available. With p_i as the programs' prices demand $D_i^M(p_i, p_j, q_i, q_j, \beta)$ for program i is in our model given by

$$D_i^M(\cdot) = \max\left\{\frac{1}{1+\beta}\left[\sqrt{q_i} - p_i + \beta(\sqrt{q_j} - p_j)\right], 0\right\} \text{ with } \beta \in \left[-\frac{1}{2}, \frac{1}{2}\right]. \qquad (3)$$

While $\beta < 0$ implies that the programs are substitutes, the programs are complements if $\beta > 0$. The factor $1/(1+\beta)$ normalizes aggregate demand such that the sum of D_1 and D_2 only depends on qualities and on prices but not on the magnitude of β.

Since firms may publish software components as open source and since entrants may offer programs with qualities q_{e_1} and q_{e_2}, we have to modify (3) in order to derive the demand functions firms face in case of open source or entry. With respect to the first point note that the qualities of the open source components are given by $\alpha_1 q_1$ and $\alpha_2 q_2$ and that their prices are equal to zero. Concerning market entry, assume that entry has taken place and that entrants offer programs with qualities q_{e_i} and prices p_{e_i}.

We assume that the consumers' decisions to either buy q_i, buy q_{e_i} or simply use the open source components can be traced back to a comparison of the consumers' rents as implied by (3). The alternative that yields the highest consumer rent will be chosen. Using the assumption that $D_i^M(\cdot)$ is linear in prices, we get the following demand functions $D_i(\cdot)$ and $D_{e_i}(\cdot)$ for the firms $i = 1, 2$ and for the entrants e_i (formally, $D_i(\cdot)$ and $D_{e_i}(\cdot)$ depend on $p_i, p_{e_i}, q_i, q_{e_i}, \beta$ and α_i with $i = 1, 2$)

$$D_i(\cdot) = \begin{cases} \frac{1}{1+\beta}\left[\sqrt{q_i} - p_i + \beta\Theta_j\right] & \text{if } p_i \leq \overline{p}_i \\ 0 & \text{else} \end{cases} \qquad (4)$$

$$\text{with} \quad : \quad \overline{p}_i := \max\left\{\min\left\{\sqrt{q_i} - \sqrt{q_{e_i}} + p_{e_i}, \sqrt{q_i} - \sqrt{\alpha_i q_i}\right\}, 0\right\}$$

$$\text{and} \quad : \quad \Theta_j := \max\left\{\sqrt{q_j} - p_j, \sqrt{\alpha_j q_j}, \sqrt{q_{e_j}} - p_{e_j}\right\}$$

$$D_i^e(\cdot) = \begin{cases} \frac{1}{1+\beta}\left[\sqrt{q_{e_i}} - p_{e_i} + \beta\Theta_j\right] & \text{if } p_{e_i} < \overline{p}_{e_i} \\ 0 & \text{else} \end{cases} \qquad (5)$$

$$\text{with} \quad : \quad \overline{p}_{e_i} := \max\left\{\min\left\{\sqrt{q_{e_i}} - \sqrt{q_i} + p_i, \sqrt{q_{e_i}} - \sqrt{\alpha_i q_i}\right\}, 0\right\}$$

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Having specified the firms' costs and their demand functions we now turn to the solution of the game, which is solved by backward induction.

3   Optimal Open Source Decisions

Before we analyze the various stages of the game in more detail let us briefly summarize the main effects which determine the solution of the model. The basic incentives for firms 1 and 2 to publish software components as open source are due to the induced reductions of their own coding costs. However, as consumers might be satisfied using the open source components, going open source implies that the consumers' reservation prices for the (commercial) software programs decrease. Moreover, it also leads to positive spillover effects with respect to the other firms' costs. Open source thus strengthens the firms' incentives to develop higher qualities and—more important—encourages market entry.

We first discuss how these effects interact and how they affect the firms' open source decisions. We then turn to the formal analysis of the model where we skip most of the details. Rather, we illustrate the main results graphically.

3.1   Entry Deterrence and Strategic Interdependencies

Potential entry combined with Bertrand competition on the last stage of the game implies that entry deterrence is both feasible and optimal for firms 1 and 2. Entry deterrence is feasible if the firms' open source fractions α_i are relatively low. Since the reservation prices $\overline{p}_{e_i}$ of the entrants' demands decrease with the qualities q_1 and q_2, respectively (see (5)), firms 1 and 2 can deter entry by choosing relatively high qualities. Furthermore, due to the positive spillover effects the entry deterring qualities are higher, the higher the number of software components the firms publish as open source. Entry deterrence is optimal since (profitable) entry in market i leads to $p_i = 0$. Using our assumptions on costs and demand it turns out that the firms' open source decisions are such that the firms are in fact forced to choose entry deterring qualities. Hence, the optimal open source decisions of firms 1 and 2 balance the positive effects due to cost reductions and the negative effects due to the tightened restriction with respect to entry deterrence.

In order to characterize the strategic interdependence between the firms' open source decisions note that—neglecting positive spillovers due to open source— the firms' qualities are strategic substitutes (complements) if their programs are

substitutes (complements), i.e., if $\beta < 0$ $(\beta > 0)$. Combining these observations with the result that the entry deterring qualities increase with the number of software components published as open source, we find that the open source decisions are either strategic substitutes or complements. If the firms' programs are substitutes their open source decisions tend to be strategic substitutes. The firms' marginal profits from increasing their own qualities are lower the higher the quality of the other firm. Since each firm's (entry deterring) quality increases with it's level of open source, we find that the firms' incentives to provide open source are lower the more open source components the other firm publishes. With software programs that are complements the converse holds. The firms' marginal profit from increasing their own qualities are higher the higher the other firm's quality. Thus, the firms' incentives to provide open source increase with the other firm's open source level. In other words, with complementary programs open source serves as a commitment device for choosing high qualities.

3.2   The Price Subgame

Combining revenues and costs yields the following profit functions $\pi_i(\cdot)$ and $\pi_{e_i}(\cdot)$ for the firms 1 and 2 and for the entrants e_1 and e_2:[6]

$$\pi_i(\cdot) = p_i(\cdot)D_i(\cdot) - c_i(\cdot) \text{ and } \pi_{e_i}(\cdot) = p_{e_i}D_{e_i}(\cdot) - c_{e_i}(\cdot). \tag{6}$$

Consider first the optimal prices of firm i and of entrant e_i. Using (4) and (5) and maximizing $\pi_i(\cdot)$ and $\pi_{e_i}(\cdot)$ with respect to p_i and p_{e_i}, respectively, yields the following price reaction functions

$$p_i^r(\cdot) = \min\left\{\frac{1}{2}\left[\sqrt{q_i} + \beta\Theta_j\right], \overline{p}_i\right\} \text{ and } p_{e_i}^r(\cdot) = \min\left\{\frac{1}{2}\left[\sqrt{q_{e_i}} + \beta\Theta_j\right], \overline{p}_{e_i}\right\} \tag{7}$$

Using $-0.5 < \beta < 0.5$ and (7) shows that there exists a unique price equilibrium in pure strategies. The equilibrium prices $p_i^*(\cdot)$ and $p_i^{e*}(\cdot)$ on both markets are characterized in the following

Result 1 *The equilibrium prices $p_i^*(\cdot)$ and $p_i^{e*}(\cdot)$ satisfy (for $i, j = 1, 2$, $i \neq j$)*[7]

$$p_i^*(\cdot) \quad = \quad \max\left\{\min\left\{\frac{1}{2}\left[\sqrt{q_i} + \beta\Theta_j^*\right], \sqrt{q_i} - \sqrt{q_{e_i}}, \sqrt{q_i} - \sqrt{\alpha_i q_i}\right\}, 0\right\}, \tag{8}$$

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[6]To shorten the notation we often omit the arguments of the functions. Clearly, the firms' as well as the entrants' profits depend on all prices, on all qualities, on the firms' open source decisions α_i with $i = 1, 2$ as well as on β.

[7]Note that the equilibrium prices $p_i^*(\cdot)$ and $p_i^{e*}(\cdot)$ only depend on the qualities q_i and q_i^e with $i = 1, 2$.

$$p_{e_i}^*(\cdot) \;=\; \max\left\{\min\left\{\frac{1}{2}\left[\sqrt{q_{e_i}} + \beta\Theta_j^*\right], \sqrt{q_{e_i}} - \sqrt{q_i}\right\}, 0\right\} \tag{9}$$

$$\text{with} \quad : \quad \Theta_j^* := \max\left\{\sqrt{q_j} - p_j^*, \sqrt{q_{e_j}} - p_{e_j}^*\right\}$$

Proof. With $-0.5 < \beta < 0.5$ and (7) we have $-1 < \partial p_i^r(\cdot)/\partial p_j < 1$ and $-1 < \partial p_{e_i}^r(\cdot)/\partial p_j < 1$. These properties guarantee the existence of a unique pure strategy equilibrium. Using (7) and considering both markets 1 and 2 leads to $p_i^*(\cdot)$ and $p_{e_i}^*(\cdot)$. ∎

Result 1 reveals $p_{e_i}^*(\cdot) > p_i^*(\cdot) = 0$ iff $q_{e_i} > q_i$. That is, entry can be profitable iff the entrant's quality is higher than the quality q_i. Vice versa, if entry occurs with $q_{e_i} > q_i$ firm i will incur losses, which immediately implies that entry deterrence is optimal for firm i.

Furthermore, even without entry, i.e., even in a situation with $q_{e_1} = q_{e_2} = 0$, the equilibrium prices of firms 1 and 2 can be restricted by the consumers' alternative to use the open source components. Using $q_{e_1} = q_{e_2} = 0$ to characterize the situation without entry (8) yields[8]

$$p_i^*(\cdot) = \min\left\{\frac{1}{2}\left[\sqrt{q_i} + \beta(\sqrt{q_j} - p_j^*)\right], \sqrt{q_i} - \sqrt{\alpha_i q_i}\right\}. \tag{10}$$

Note that the restriction $p_i \leq \sqrt{q_i} - \sqrt{\alpha_i q_i}$ tends to be more severe, the larger β, i.e., the higher the complementary between the firms' programs.

3.3   Market Entry and Entry Deterrence

Although it turns out that the firms 1 and 2 will deter entry, we have to specify the entrants' optimal quality decisions. Using these qualities yields the entrants' reduced profit functions, which indicate whether entry is profitable or not. Thus, we first characterize the equilibria in the entry game. We also introduce an equilibrium selection criterion and we show that entry deterrence is profitable for each firm 1 and 2 as long as the number of software components published as open source is not too high.

The equilibrium prices (9) obviously imply that the entrants can earn positive profits $\pi_{e_i}(\cdot)$ only if $q_{e_i} > q_i$ holds. Furthermore, with $\pi_{e_i}(\cdot) > 0$ the entrants' prices $p_{e_i}^*(\cdot)$ are either determined by the interior solution, i.e., by $\frac{1}{2}\left[\sqrt{q_{e_i}} + \beta\Theta_j^*\right]$, or by the corner solution $p_{e_i}^*(\cdot) = \sqrt{q_{e_i}} - \sqrt{q_i}$. Considering the solution of the complete game we find that the quality decisions of firms 1 and 2

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[8]With $q_{e_1} = q_{e_2} = 0$ we have $p_1^{e*} = p_2^{e*} = 0$..

as well as their open source decisions are such that we have $\pi_{e_i}(q_{e_i}, \cdot) < 0$ for all $q_{e_i} > \left[2\sqrt{q_i} + 2\beta\Theta_j^*\right]^2$.[9] We therefore restrict the following analysis to the case in which $p_{e_i}^*(\cdot) = \sqrt{q_{e_i}} - \sqrt{q_i}$ holds.

Using $q_{e_i} > q_i$ and $p_{e_i}^*(\cdot) = \sqrt{q_i^e} - \sqrt{q_i}$, the reduced profit function $\pi_{e_i}^*(\cdot)$ of entrant e_i can be written as

$$\pi_{e_i}^*(\cdot) \;\; = \;\; \frac{1}{1+\beta}\left[\sqrt{q_i^e} - \sqrt{q_i}\right]\left[\sqrt{q_i} + \beta\Psi_i\right] - \frac{(q_{e_i} - \alpha_i q_i)^2}{2 + \alpha_i q_i + \alpha_j q_j} \tag{11}$$

$$\text{with} \;\; : \;\; \Psi_i := \begin{cases} \max\left\{\sqrt{q_j} - \frac{1}{2}\left[\sqrt{q_j} + \beta\sqrt{q_i}\right], \sqrt{\alpha_j q_j}\right\} & \text{if} \;\; q_{e_j} = 0 \\ \sqrt{q_j} & \text{if} \;\; q_{e_j} \geq q_j\,. \end{cases}$$

Differentiating (11) with respect to q_{e_i} leads to the following first order condition (assuming $q_{e_i} \geq q_i$)

$$\frac{\partial \pi_{e_i}^*(\cdot)}{\partial q_{e_i}} \;\; = \;\; \frac{1}{1+\beta}\frac{1}{2\sqrt{q_{e_i}}}\left[\sqrt{q_i} + \beta\Psi_i\right] - \frac{2(q_{e_i} - \alpha_i q_i)}{2 + \alpha_i q_i + \alpha_j q_j} \leq 0 \tag{12}$$

$$\text{and} \;\; : \;\; \frac{\partial \pi_{e_i}^*(\cdot)}{\partial q_{e_i}} q_{e_i} = 0. \tag{13}$$

Since we also have $\partial^2 \pi_{e_i}^*(\cdot)\big/\partial q_{e_i}^2 < 0$, (12) and (13) implicitly define the entrants' optimal quality $\tilde{q}_{e_i}^r(q_i, \cdot) \geq q_i$. Taking into account that the entrant's profit must be positive, we can specify the entrant's profit maximizing quality $q_{e_i}^r(\cdot)$ as (note that $q_{e_i}^r(\cdot)$ depends on $q_i, q_j, q_{e_j}, \alpha_i, \alpha_j$ and β)

$$q_{e_i}^r(\cdot) := \begin{cases} \tilde{q}_{e_i}^r(q_i, \cdot) & \text{if} \;\; \pi_{e_i}^*(\tilde{q}_{e_i}^r(q_i, \cdot), \cdot) > 0 \\ 0 & \text{else.} \end{cases} \tag{14}$$

Considering entry in both markets (11) and (14) reveal that the entrants' reduced profits and hence their optimal quality decisions $q_{e_i}^r(\cdot)$ depend on whether entry in the other market has taken place or not. With $\beta < 0$, i.e., with software programs that are substitutes, $\pi_{e_i}^*(\cdot)$ decreases if entry occurs in market j. With complementary software programs entry in market i is more profitable if entry takes also place in market j. Therefore, the entry game may have multiple equilibria.

Result 2 *The equilibria of the entry game are characterized by the following*

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[9]This result is due to the fact that—in order to deter entry—firms 1 and 2 will choose relatively high quailities q_1 and q_2. Since the entrants' costs are strictly convex in q_{e_i}, relatively high qualities q_1 and q_2 imply that the entrants' optimal qualities satisfy $q_{e_i} < \left[2\sqrt{q_i} + 2\beta\Theta_j^*\right]^2$.

qualities $q_{e_i}^*(q_i, q_j, \alpha_i, \alpha_j, \beta) := q_{e_i}^r(q_{e_j}^*(\cdot), \cdot)$

$$q_{e_i}^*(\cdot) \begin{cases} = 0 & \text{if} \quad q_{e_i}^r(\cdot)\big|_{q_{e_j}^*=0} = 0 \text{ or } q_{e_j}^r(\cdot)\big|_{q_{e_j}^*>q_j} = 0 \\ > q_i & \text{if} \quad q_{e_i}^r(\cdot)\big|_{q_{e_j}^*=0} > 0 \text{ or } q_{e_i}^r(\cdot)\big|_{q_{e_j}^*>q_i} > 0. \end{cases} \qquad (15)$$

Proof. (11) and (12) lead to either $q_{e_i}^r(\cdot)\big|_{q_{e_j}=0} = q_{e_i}^r(\cdot)\big|_{q_{e_j}>q_j}$ or to $q_{e_i}^r(\cdot)\big|_{q_{e_j}=0} \neq q_{e_i}^r(\cdot)\big|_{q_{e_j}>q_j}$. Furthermore, (11) and (14) imply $\partial q_{e_i}^r(\cdot)\big|_{q_{e_j}>q_j} \big/ \partial q_{e_j} = 0$, i.e., given that entry takes place in both markets the entrants' optimal qualities do not depend on each other. Therefore, the solutions of equation (15) fully characterize all possible equilibria. ∎

Using result 2 we could turn to the next stage of the game, i.e., the specification of the quality decisions of firms 1 and 2. However, considering all possible equilibria would lead to a rather complex analysis. We therefore assume

$$q_{e_i}^r(\cdot)\big|_{q_{e_j}>q_j} > q_i \wedge q_{e_i}^r(\cdot)\big|_{q_{e_j}=0} = 0 \Rightarrow q_{e_i}^*(\cdot) = q_{e_j}^*(\cdot) = 0. \qquad \text{A}$$

In other words, we assume that the entrants can not coordinate their decisions such that they both enter even if entry in each of the markets yields negative profits.

Taking into account that entry deterrence is optimal for firms 1 and 2, (A) does not restrict the analysis if $\beta \leq 0$ holds. Entry in both markets is deterred as long as entry in each single market is not profitable. (A) implies that the same result holds for $\beta > 0$. Furthermore, analyzing the (entry deterring) quality decisions of firms 1 and 2, we can concentrate on the entrant's profits given that entry in the other market does not occur. If $q_{e_i}^r(q_i, q_j, \cdot)\big|_{q_{e_j}=0} = 0$ holds for both entrants the firms' qualities q_1 and q_2 are such that entry in neither market occurs.

Therefore, let us characterize the properties of $\pi_{e_i}^*(q_{e_i}^r(\cdot), \cdot)\big|_{q_{e_j}=0}$ and let us also consider the profit $\pi_i^r(q_i, q_j, \alpha_i, \alpha_j, \beta)$ of firm i given $q_{e_i}^r(q_i, q_j, \cdot)\big|_{q_{e_j}=0}$ and $q_{e_j} = 0$ ($p_i^*(\cdot)$ is defined in (8)):

$$\pi_i^r(q_i, q_j, \alpha_i, \alpha_j, \beta) := p_i^*(\cdot) D_i(\cdot) - c_i(\cdot) \text{ with } q_{e_i} = q_{e_i}^r(\cdot)\big|_{q_{e_j}=0} \text{ and } q_{e_j} = 0 \quad (16)$$

Analyzing $\pi_{e_i}^*(q_{e_i}^r(\cdot), \cdot)\big|_{q_{e_j}=0}$ and $\pi_i^r(\cdot)$ we obtain

Result 3 *If entry occurs only in market i the entrant's profit $\pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)\big|_{q_{e_j}=0}$ increases in the number of software components published as open source*

$$\frac{\partial \pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)}{\partial \alpha_i}\bigg|_{q_{e_j}=0} > \frac{\partial \pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)}{\partial \alpha_j}\bigg|_{q_{e_j}=0} > 0 \text{ for } q^r_{e_i}(\cdot)\big|_{q_{e_j}=0} = 0 > q_i. \quad (17)$$

With moderate open source decisions, i.e., with $\alpha_i, \alpha_j < 0.375$, there exists a quality $q^d_i(q_j,\alpha_i,\alpha_j,\beta)$ such that

$$\pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)\big|_{q_{e_j}=0} > 0 \ \forall \ q_i < q^d_i \ \wedge \ \pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)\big|_{q_{e_j}=0} = 0 \ \forall \ q_i \geq q^d_i, \quad (18)$$

$$\frac{\partial q^d_i(q_j,\alpha_i,\alpha_j\cdot)}{\partial \alpha_i} > 0 \ and \quad (19)$$

$$\pi^r_i(q^d_i(\cdot),q_j,\cdot) > 0. \quad (20)$$

Proof. The sign of $\partial \pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)\big/\partial\alpha_i$ and $\pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)\big/\partial\alpha_j$ with $q_{e_j}=0$ can be determined by using the envelope theorem. Restricting the analysis to $\alpha_i,\alpha_j < 0.375$, employing (11) and (12) we obtain $\pi^*_{e_i}(q^r_{e_i}(\cdot),\cdot)\big|_{q_{e_j}=0} > 0$ for $q_i = 0$ and $\lim_{q_i\to\infty}\pi^*_{e_i}(q_{e_i},\cdot) < 0$ for all $q_{e_i} > q_i$. Differentiating $\pi^*_{e_i}(q^r_{e_i}(q_i\cdot),\cdot)\big|_{q_{e_j}=0}$ with respect to q_i reveals that $\pi^*_{e_i}(q^r_{e_i}(q_i\cdot),\cdot)\big|_{q_{e_j}=0}$ is strictly concave in q_i which also implies $q^d_i(\cdot)\big/\partial\alpha_i > 0$. Evaluating $\pi^r_i(q^d_i(\cdot),q_j,\alpha_i,\alpha_j,\beta)$ for all $\alpha_i,\alpha_j < 0.375$ and $\beta \in [-0.5,0.5]$ confirms $\pi^r_i(q^d_i(\cdot),q_j,\alpha_i,\alpha_j,\beta) > 0$. ∎

Obviously, positive spillover effects due to open source imply that the entrants' profits are higher, the more software components firms 1 and 2 have published as open source. On the other hand, the entrants' prices, i.e., $p^*_{e_i}(\cdot) = \sqrt{q_{e_i}} - \sqrt{q_i}$, decrease in q_i but their costs are strictly convex in their qualities q_{e_i}. Hence, moderate open source decisions imply that entry in market i can be deterred if the firms' qualities q_i are high enough. Furthermore, the entry deterring qualities $q^d_i(q_j,\alpha_i,\alpha_j,\beta)$ increase in α_i and entry deterrence is profitable as long as the number of software components published as open source is not too high.

3.4 Quality Decisions of Firms 1 and 2

Turning to the quality decisions of firms $i = 1, 2$ we already know that the firms' quality decisions must be such that entry in their own markets does not take place. Result 3 implies that we can also restrict the analysis to $\alpha_1, \alpha_2 < 0.375$, i.e., to the range of open source decisions, in which entry deterrence is feasible and profitable.

Employing (A) we determine the equilibrium qualities of firms 1 and 2 by the following procedure: Using the reduced profit function of firm i given that entry can only occur in market, i.e., $\pi_i^r(q_i, \cdot)$ (see (16)), assume that maximizing $\pi_i^r(q_i, \cdot)$ with respect to q_i leads to a unique solution $q_i^r(q_j, \cdot)$. Assume further that $q_1^r(q_2, \cdot)$ and $q_2^r(q_1, \cdot)$ have a unique fixed point $(q_1^*(\alpha_1, \alpha_2, \beta), q_2^*(\alpha_2, \alpha_1, \beta))$. If neither firm has an incentive to deviate from $q_i^*(\cdot)$ in order to induce entry in the other market, $(q_1^*(\alpha_1, \alpha_2, \beta), q_2^*(\alpha_2, \alpha_1, \beta))$ also constitutes a pure strategy equilibrium of the complete game in which entry in both markets is possible.

Now, analyzing (16) shows that there exists a unique profit maximizing quality $q_i^r(q_j, \cdot)$ which satisfies

$$\frac{\partial \pi_i^r(\cdot)}{\partial q_i} \leq 0, \ \frac{\partial \pi_i^r(\cdot)}{\partial q_i}(q_i - q_i^d(q_j, \alpha_i, \alpha_j, \beta)) = 0 \text{ and } q_i \geq q_i^d(q_j, \alpha_i, \alpha_j, \beta). \quad (21)$$

With (21) the optimal quality $q_i^r(q_j, \cdot)$ is either determined by the interior solution, i.e., by the quality that maximizes the firm's profit if entry deterrence is not binding, or by the entry deterring quality $q_i^r(q_j, \cdot) = q_i^d(q_j, \alpha_i, \alpha_j, \beta)$. Furthermore, simple comparative statics reveals

$$\frac{\partial q_i^r(\cdot)}{\partial \alpha_i} > \frac{\partial q_i^r(\cdot)}{\partial \alpha_j} > 0 \text{ for } q_i^r(q_j, \cdot) \geq q_i^d(q_j, \alpha_i, \alpha_j, \beta). \quad (22)$$

That is, an increase in the number of software components the firms publish as open source reduces the firms' costs and thus increases their optimal qualities. Figure 1 shows $q_i^r(q_j, \cdot)$ for $\beta = -0.25$. The left picture is based on $\alpha_1 = \alpha_2 = 0$ which leads $q_i^r(q_j, \cdot) > q_i^d(q_j, \cdot)$. The right picture shows $q_i^r(q_j, \cdot) = q_i^d(q_j, \cdot)$ for $\alpha_1 = \alpha_2 = 0.2$. It also depicts the firm's optimal quality $\widetilde{q}_i^r(q_j, \cdot)$ if entry is disregarded.
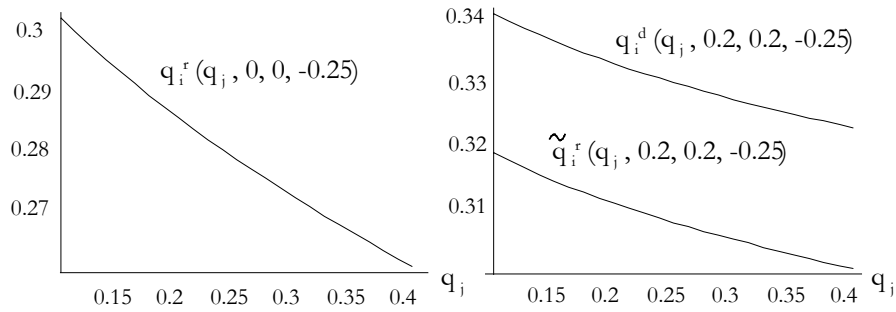

Figure 1: Firm i's optimal quality $q_i^r(q_j, \cdot)$ with $\beta = -0.25$, $\alpha_1 = \alpha_2 = 0$ and $\alpha_1 = \alpha_2 = 0.2$.

Figure 2 depicts $q_i^r(q_j, \cdot)$ for $\beta = 0.25$. Again, $\alpha_1 = \alpha_2 = 0$ leads to $q_i^r(q_j, \cdot) > q_i^d(q_j, \cdot)$ (see the left picture of Figure 2). With $\alpha_1 = \alpha_2 = 0.2$ we get $q_i^r(q_j, \cdot) = q_i^d(q_j, \cdot)$ (see the right picture of figure 2).
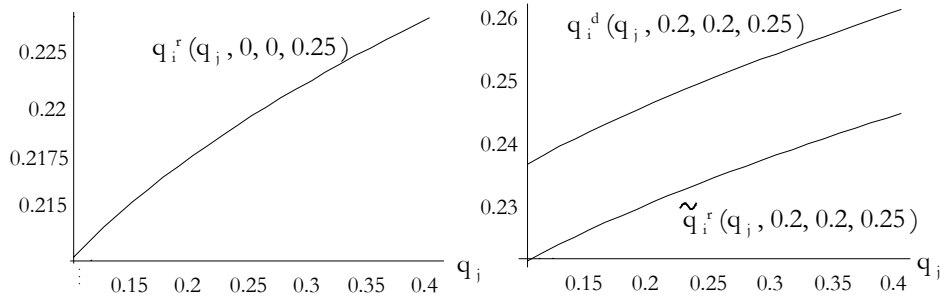
Figure 2: Firm i's optimal quality $q_i^r(q_j, \cdot)$ with $\beta = 0.25$, $\alpha_1 = \alpha_2 = 0$ and $\alpha_1 = \alpha_2 = 0.2$.

Turning to the equilibrium qualities of firms 1 and 2, inspection of $q_1^r(q_2, \cdot)$ and $q_2^r(q_1, \cdot)$ yields that there exists a unique fixed point $(q_1^*(\alpha_1, \alpha_2, \beta), (q_2^*(\alpha_2, \alpha_1, \beta))$. To verify that $(q_1^*(\alpha_1, \alpha_2, \beta), (q_2^*(\alpha_2, \alpha_1, \beta))$ is a pure strategy equilibrium of the complete game, in which entry in both markets is possible, we additionally have to show that any deviation from $q_i^*(\alpha_i, \alpha_j, \beta)$, which would induce entry into market j, is not profitable. Entry in market j would occur with $q_{e_j} > q_j$ and would furthermore lead to $p_{e_j}^*(\cdot) = \sqrt{q_{e_j}} - \sqrt{q_j}$. With $\beta < 0$, i.e., with software programs that are substitutes, a higher quality in market j decreases the profit of firm i. On the other hand, with $\beta > 0$ entry in market j would not only increase the profit of firm i but would also make entry in market i more profitable. Hence, inducing entry in market j would force firm i to increase q_i in order to deter entry in its own market. Evaluating these effects shows that any deviation from $q_i^*(\alpha_1, \alpha_2, \beta)$ decreases firm i's profit.

Summarizing and using (22) we obtain

Result 4 *If the firms' open source decisions are such that entry deterrence is profitable, there exists a unique pure strategy equilibrium with qualities $q_i^*(\alpha_i, \alpha_j, \beta)$ which obey $\partial q_i^*(\cdot) / \partial \alpha_i > 0$.*

To analyze $q_i^*(\alpha_i, \alpha_j, \beta)$ further and to specify whether the firms' qualities are determined by entry deterrence let us start with $\alpha_1 = \alpha_2 = 0$. Calculating $q_i^*(0_i, 0, \beta)$ for all $\beta \in [-0.5, 0.5]$ we find that the equilibrium qualities do not induce entry, i.e., we have

$$q_i^*(\cdot)|_{\alpha_1 = \alpha_2 = 0} > q_i^d(q_j^*(\cdot), \cdot)\Big|_{\alpha_1 = \alpha_2 = 0} \quad \forall\, \beta \in [-0.5, 0.5] \,. \tag{23}$$

Since open source decreases the entrants' costs, it turns out that there exists a critical level of α_i^d at which entry deterrence becomes a binding restriction.

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Defining $\alpha_i^d(\alpha_j, \beta) := \max \left\{ \alpha_i \mid q_i^*(\cdot) \geq q_i^d(q_j^*(\cdot), \cdot) \right\}$ we obtain

$$-1 < \frac{\partial \alpha_i^d(\alpha_j, \beta)}{\partial \alpha_j} < 1$$

which implies that $\alpha_i^d(\alpha, \beta) = \alpha$ has a unique solution $\alpha^d(\beta)$. Figure 3 shows the graphs of $\alpha^d(\beta)$ and the corresponding qualities $q_i^*(\cdot) = q_i^d(q_j^*(\cdot), \cdot)$ and $q_{e_i}^r(q_i^*(\cdot), q_j^*(\cdot), \cdot)\big|_{q_{e_j}=0}$.
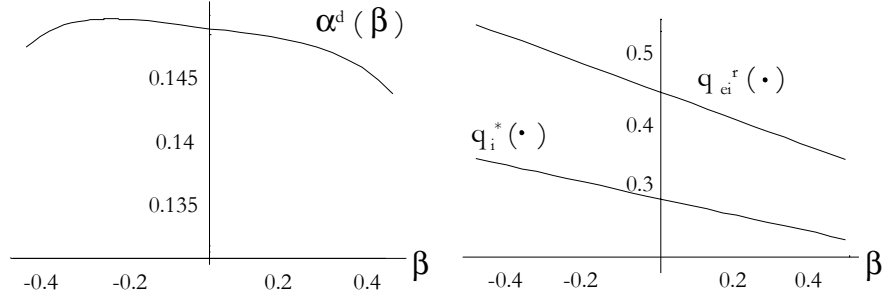

Figure 3: $\alpha^d(\beta)$ and $q_i^*(\cdot)$, $q_{e_i}^r(q_i^*(\cdot), q_j^*(\cdot), \cdot)\big|_{q_{e_j}=0}$ with $\alpha_1 = \alpha_2 = \alpha^d(\beta)$

3.5 Open Source Decisions

Finally, using the equilibrium qualities $q_i^*(\alpha_i, \alpha_j, \beta)$ let $\pi_i^{**}(\alpha_i, \alpha_j, \beta)$ denote the firms' reduced profit functions. The firms' profit maximizing open source decisions are then characterized by

$$\alpha_i^r(\alpha_j, \beta) := \arg \max_{\alpha_i} \ \pi_i^{**}(\alpha_i, \alpha_j, \beta). \tag{24}$$

Evaluating (24) yields $\alpha_i^r(\alpha_j, \beta) > \alpha_j$ for all $\alpha_j \leq \alpha^d(\beta)$. Confining the analysis to $\alpha_i, \alpha_j > \alpha^d(\beta)$ shows that $\pi_i^{**}(\alpha_i, \alpha_j, \beta)$ has a unique maximum in α_i. Hence, $\alpha_i^r(\alpha_j, \beta)$ is uniquely defined for $\alpha_j > \alpha^d(\beta)$.

Figure 4 depicts $\alpha_i^r(\alpha_j, \beta)$ and the corresponding equilibrium qualities $q_i^*(\cdot)$ for $\beta = -0.25$.
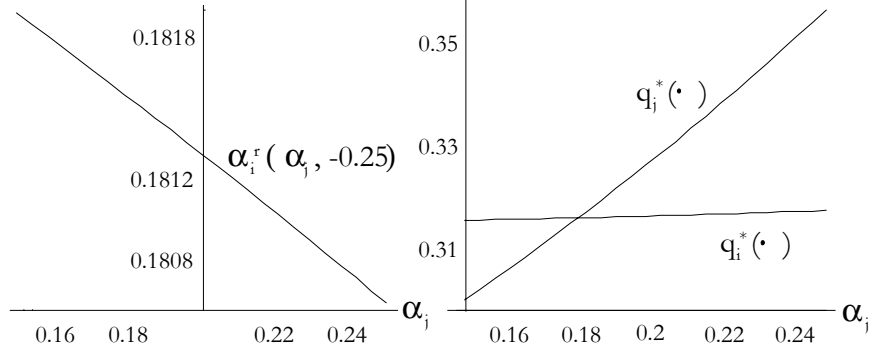
Figure 4: Firm i's optimal open source decision $\alpha_i^r(\alpha_j, \beta)$ and equilibrium qualities $q_i^*(\cdot)$ for $\beta = -0.25$.

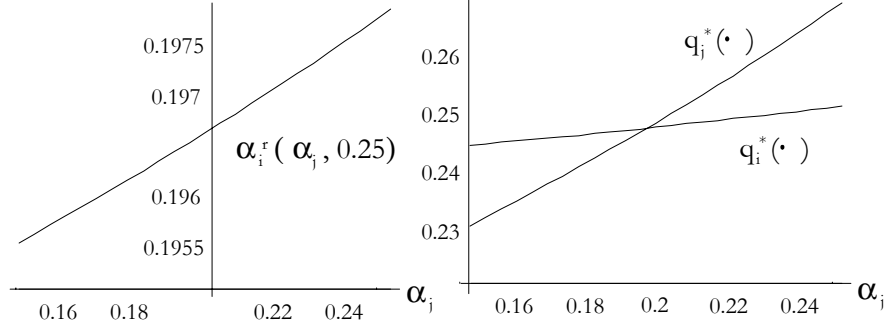Figure 5 shows $\alpha_i^r(\alpha_j, \beta)$ and $q_i^*(\cdot)$ for $\beta = 0.25$.

Figure 5: Firm i's optimal open source decision $\alpha_i^r(\alpha_j, \beta)$ and equilibrium qualities $q_i^*(\cdot)$ for $\beta = 0.25$.

Analyzing the firms' mutual best responses $\alpha_1^r(\alpha_2, \beta)$ and $\alpha_2^r(\alpha_1, \beta)$ have a unique fixed point. Therefore, we get

Result 5 *There exists a unique pure strategy equilibrium* $\alpha_1^*(\beta)$, $\alpha_2^*(\beta)$ *which satisfies*

$$\alpha^*(\beta) := \alpha_1^*(\beta) = \alpha_2^*(\beta) > \alpha^d(\beta). \tag{25}$$

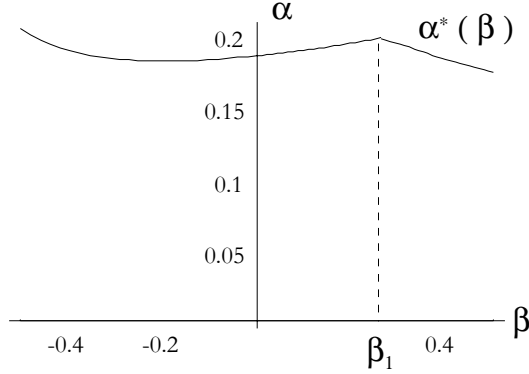Figure 6 shows the graph of $\alpha^*(\beta)$.

Figure 6: Equilibrium open source decisions $\alpha^*(\beta)$.

The kink at $\beta_1 = 0.263$ is due to the fact that the firms' equilibrium prices $p_i^*(\cdot)$ satisfy (see (10))

$$p_i^*(\cdot) = \begin{cases} \frac{1}{2}\left[\sqrt{q_i} + \beta\Theta_j^*\right] & \text{for } \beta \leq \beta_1 \\ \sqrt{q_i^*(\cdot)} - \sqrt{\alpha^d(\beta)q_j^*(\cdot)} & \text{for } \beta \geq \beta_1 \, . \end{cases}$$

With software programs that are relatively strong complements the firms' open source decisions do not only force them to choose entry deterring qualities. They also imply that the firms' prices are bounded by consumers' alternative to use the open source software instead of buying the firms' (commercial) software programs.

While figures 4 and 5 already indicate that the firms' open source decisions tend to be strategic substitutes (complements) if their programs are substitutes (complements), we now analyze this strategic interdependence more carefully. For this purpose it suffices to consider the open source decisions that would maximize the firms' joint profits, i.e.,

$$\alpha^C(\beta) := \arg\max_{\alpha} \sum_{i=1}^{2} \pi_i^{**}(\alpha, \alpha, \beta).$$

Comparing $\alpha^C(\beta)$ with $\alpha^*(\beta)$ (see Figure 7) we find that as long as the programs are strong substitutes, i.e., as long as $\beta < -0.11$ holds, the joint profit maximization open source decision is lower than $\alpha^*(\beta)$. Thus, the firms' open source decisions are strategic substitutes for all $\beta < -0.11$. For $\beta > -0.11$ the firms' open source decisions are strategic complements, i.e., $\alpha^C(\beta) > \alpha^*(\beta)$.
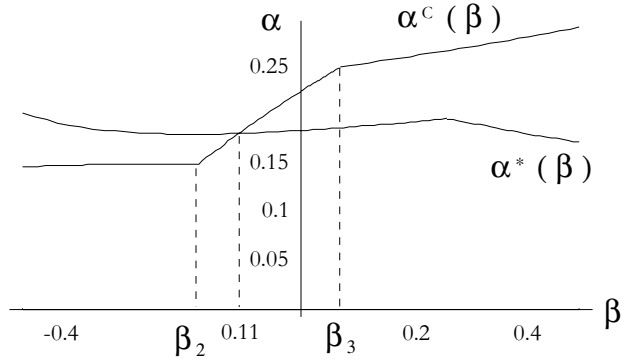
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Figure 7: Equilibrium open source decisions $\alpha^*(\beta)$ and optimal cooperative decisions $\alpha^C(\beta)$.

Furthermore, with $\beta < \beta_2 = -0.184$ we have $\alpha^C(\beta) = \alpha^d(\beta)$. That is, while increasing α above $\alpha^d(\beta)$ would reduce the firms' costs, the firms would also be forced to increase their qualities in order to deter entry. With software programs that are strong substitutes this second effect is negative and dominates the positive effects from cost reductions. On the other hand, the higher β the lower the negative effects due to increased qualities. Therefore, $\alpha^C(\beta) > \alpha^d(\beta)$ and $\alpha^{C\prime}(\beta) > 0$ for all $\beta > \beta_2$. Note that $\alpha^{C\prime}(\beta) > 0$ also holds if the equilibrium prices are restricted by the consumers' alternative to use the open source software. While $\beta > \beta_3 = 0.07$ implies $p_i^*(\cdot) = \sqrt{q_i^*(\cdot)} - \sqrt{\alpha^d(\beta)q_j^*(\cdot)}$, we still have $\alpha^{C\prime}(\beta) > 0$.

4   Conclusion

We started with the assumption that open source reduces the coding costs of software firms developing new or qualitatively enhanced programs. The users' incentives to detect bugs and the incentives of programers to signal their coding abilities by contributing to open source are two reasons why software firms may benefit from publishing parts of their software as open source. Given these cost reducing effects we analyzed how firms determine the degree up to which they publish their software as open source. We set up a model with only two firms and potential competition from new entrants. Considering positive spillovers due to open source it turned out that the firms' open source decisions balance the positive effects from costs reductions and the negative effects due to the tightened restrictions with respect to entry deterrence. Furthermore, since consumers may use the open source software instead of buying the commercial software pro-

grams, the firms' prices can ultimately be bounded by the restriction that the demand for their commercial programs is positive.

The strategic interdependence between the firms' open source decisions is determined by whether the firms' programs are substitutes or complements. Programs which are (strong) substitutes imply that the open source decisions are strategic substitutes, complementary programs lead to open source decisions which are strategic complements. This result is due to the fact that the firms' qualities increase in the number of software components they publish as open source. Therefore, the strategic interdependence between the firms' open source decisions mirrors the strategic interdependence between the firms' quality decisions.

The model in this paper shows that not only the obvious technical effects of open source software (e.g. cost reductions) have to be taken into account when discussing the decision of firms to publish some of the software they have developed under an open source license. Rather, strategic considerations taking into account actual and potential competitors affect this decision as well. These might help to explain certain issues involved in the open source activities of firms better than an analysis that purely focuses on the technical effects of OSS.

One of these issues is the question, why we see a lot of open source activity by firms in the field of operating systems such as Linux and not so much for many other types of software. The model, illustrated by figure 6, suggests that this may be due to the strong competition among operating systems, especially among the different flavors of Unix. This competition drives prices down, and consumers continue to buy the commercial software (e.g. the Linux distribution) for its better quality instead of using the cheaper but qualitatively inferior open source components. Knowing this, firms can publish more of their software components as open source to benefit from the cost savings. This does not work as well if software prices are high, such as in the scenario with two complementary goods. In this situations the incentives for consumers to use the (free) open source components alone is rather large and firms have an incentive to restrict their OSS publications.

Thus, according to the model we should observe more open source activities by firms in areas where competition is large. This would support those in the software industry who see an increasing importance of OSS as an answer to "commodification" in areas like office suites or application servers.

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