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COMPETITIVE STRATEGY OF PROPRIETARY SOFTWARE FIRMS IN AN OPEN SOURCE ENVIRONMENT

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Abstract. This paper analyzes the competitive strategy of a proprietary software (PS) firm in the presence of open source software (OSS) where the copyright holder has granted software users access and use of OSS without any obligation regarding source code disclosure and royalty payments. The OSS is developed by volunteer programmers, while the firm incurs costs to hire programmers to build the PS. The firm has a quality advantage because, first, it can provide professional technical support and promotion, and second, it is difficult for the OS community to collaborate for the production and maintenance of the OSS. The analysis is based on two scenarios: (1) the OSS is available free of charge; (2) the OSS is distributed by fringe vendors who can provide OSS quality upgrades. We find that both types of software can coexist in equilibrium. Furthermore, despite the fact that PS enjoys a quality advantage, it will optimally set a lower quality than OSS. The comparative statics show that a change in each market parameter can lead the firm to simultaneously increase (or decrease) both the PS price and quality. We consequently evaluate the impact on the firm's profit and consumer surplus.

1. Introduction

Open source software (OSS) has become the main challenger of dominant proprietary software (PS). Successful OSS including Linux, Apache, and Sendmail are leaders in their respective market segments. At present, there are many OS alternatives to costly PS either free of charge or low cost by OSS vendors. The implications of OSS development can be illustrated in the following statement from an internal email written by Steve Ballmer, CEO of Microsoft in 2003: "Non-commercial software products in general, and Linux in particular, present a competitive challenge for us and for our entire industry, and they require our concentrated focus and attention."

In practice, the number of OSS vendors has increased dramatically in recent years. According to International Data Corporation (2017), the market share of global server operating system Red Hat Enterprise Linux is 32.7%, second only to Microsoft with 49.6%

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of market share.[1] PS firms continue to invest and innovate to adapt to a changing industry. Microsoft determined to increase the prices of software and related products in 2018.[2] Thus, one central question is how does a PS firm, such as Microsoft, take advantage or use strategic approaches to manage open source challenges?

Indeed, free-of-charge OSS has certain shortcomings. First, it is relatively difficult for the OS community to collaborate on the production and maintenance of OSS. Second, free-of-charge OSS often has poor technical support and highly technical user interfaces. Third, OSS awareness and promotion are limited, especially if the OSS is introduced later in the software industry. These reasons could reduce incentives for consumers to adopt an OSS. From a dynamic perspective, the OSS quality disadvantage could be lessened through open source development, including government policy support, better governance of OS projects, and provision of supported services by OSS vendors. This would then put increasing competitive pressure on PS firms.

The contribution of programmers in the OS community is also an interesting economic phenomenon. While a programmer can be employed and paid by a firm, he/she also has an incentive to work as a volunteer to signal his/her talent to receive non-pecuniary rewards (ego gratification, peer recognition, personnel learning, and enjoyment from programming). Due to this heterogeneous preference, it becomes more costly for PS firms to hire programmers in the labor market. On the contrary, the licensor of OSS would make the source code available to licensees at zero price.[3] Thus, a volunteer programmer has the right to choose a project that he/she wants to work on, and importantly, he/she can start a new project using an existing code as its base, which is known as code forking. Although forking can increase the variety of OSS programs, it can reduce the OSS's perceived quality due to a lack of coordination of the OS community as previously explained.[4]

[1] In 2010, the market shares of Red Hat and Microsoft were 21.2% and 73.9%, respectively.
[2] See Microsoft's announcement at https://www.microsoft.com/microsoft-365/partners/news/article/announcing-price-adjustments-for-on-premises-and-cloud-products
[3] See Rosen (2004) and Leveque and Ménière (2007) for a more comprehensive analysis of OSS licenses.
[4] Forking can be seen as a catalyst for innovation and potentially better quality OS software (see Nyman and Lindman (2013) for a further discussion on forking).

The objective of this paper is to provide a simple theoretical model to analyze the competitive strategy of a monopolistic PS firm in an open source environment. More specifically, the programmers have heterogeneous preferences when deciding to work for the firm or the OS community in the labor market. In the product market, software is differentiated in both quality and price dimensions. Additionally, as discussed previously, the firm has a quality advantage in developing software relative to the OS community. In the baseline model, the OSS is available free of charge, while in the extension model, consumers have to pay a fee to OSS vendors who provide them with supported services. The competitive pressure on the PS firm can be represented by the exogenous market parameters including low quality advantage, high degree of software substitutability, and high (or low) OSS quality (respective of the price).

Thus, both markets are interconnected and imperfect, and the objective of the PS firm is to maximize profit in this context. More specifically, we first show that both types of software can coexist in equilibrium, and the firm optimally chooses to build low-quality software relative to the OSS level. Because the software industry is rapidly changing, we are interested in examining the impact of small deviations in the exogenous parameters on the equilibrium values. In particular, we show that if the OSS becomes more attractive from a consumer's viewpoint, that is, when the PS firm quality advantage is lower, this will reduce the wage rate and the PS price. Conversely, if software becomes more substitutable, the firm will want to build higher quality software and set a higher price. In both cases, the firm's profit is lower, but consumer surplus is higher. Furthermore, in the presence of competitive OSS fringe vendors, the PS price, wage rate, and firm's profit are also relatively lower while consumer surplus is relatively higher.

1.1. **Related literature.** There is well-established literature related to competing with open source software. Bitzer and Schroder (2006) examined the innovation impact of OSS entry in the software market. In their model, firms compete in technology. In this context, the evolution of the market structure from a monopoly to a duopoly exerts a positive effect on innovation. Lin (2007) proposed a model of duopolistic competition between OSS and

PS in which users are heterogeneous in terms of skills and experience. The author showed that the market may tip to the OSS if it provides significant benefits to users who can develop customized tools and applications using the OSS. Gaudeul (2007) considered that both programmers and consumers are heterogeneous: users have different valuations of software features and programmers are differentiated in terms of programming costs. The author focused on the competition between OSS and PS when the OS community faces imperfect coordination between its programmers. In equilibrium, both types of software will always coexist, and low-income users and highly skilled programmers opt for an OSS, and the others adopt a PS. According to Zhu and Zhou (2011), the PS firm can adopt a lock-in strategy that creates a switching cost for consumers. The authors studied the firm's incentive and provided implications for social welfare. This paper contributes to the existing literature by providing a framework to analyze competition in the software market when software is differentiated in both quality and price dimensions, and competition in the labor market when programmers have heterogenous preferences. Moreover, there is an exogenous parameter to capture the quality advantage of the PS firm due to different coordination of programmers and the provision of technical support and promotion, which is a crucial departure from previous research. Furthermore, as open source software continuously evolves, we provide various competition scenarios to examine how a change in each market parameter could affect the firm and consumer surplus.

Few researchers implemented a dynamic approach to study OSS development and market competition. More specifically, Casadesus-Masanell and Ghemawat (2003) introduced a mixed duopoly model to analyze the competition between Linux and Microsoft in a dynamic setting. Linux is characterized by a strong demand-side effect and Windows by a larger initial installed base. The authors showed that, if Microsoft keeps its initial advantage in terms of installed base and uses its market power to set its price strategically, Linux will never become the market leader. The result of the competition would be the coexistence of the two, or Linux software exits the market unless the cost difference between the two software platforms increases significantly or strategic buyers such as public institutions and large corporations commit themselves to developing Linux. Athey and Ellison

(2014) studied open source movements with a focus on software quality and reciprocal altruism incentives of programmers who used OSS to publish their own improvements. They also analyzed the optimal pricing strategy of PS firm. Our model differs from these studies as follows. First, our model is static, and we analyze the impact of competitive pressure on the PS firm via comparative statics. Second, for simplicity, we do not consider that a programmer participating in a software project cannot be a software user. Then, we assess the PS firm's strategy in both the software and labor markets by simultaneously adjusting software prices and wage rates. Regarding the latter, our research is similar to Mustonen (2003) who studied the constraints of PS compared to OSS. Our paper differs from Mustonen (2003) in the model's heterogeneity of programmers. In Mustonen (2003), the programmers had different skill levels, and high-skilled programmers were volunteers because the firm set a too low wage. Conversely, in the model developed in the current study, the programmers have heterogeneous tastes regarding working for either the firm or the OS community. To focus on this type of heterogeneity, we assume that the programmers have identical skills and the software quality depends on their joint efforts. Thus, our definition of software quality is a general indicator. In Kumar *et al.* (2011), software quality was represented by both functionality and usability aspects. To account for the fact that the OSS has a technical interface or poor technical support, we assume that in the process of software building by the volunteer programmers, the free-of-charge OSS has a quality disadvantage because the OS projects lack standardized processes or have weak coordination.

Our results show that the PS firm optimally chooses to build inferior quality software relative to the OSS. This result is consistent with the previous studies. More precisely, while Kuan (2001) and Bessen (2006) focused on the users' need to improve OSS quality, Johnson (2006) analyzed the possibility of collusive behaviors of the programmers at the firm and in the OS environment. Furthermore, Raymond (2001) argued that OSS development leads to superior software because of the visibility feature. We depart from this approach and consider that OSS development is exogenous to the firm's choice. Then we analyze the PS firm's optimal strategy. We show that the firm is not interested in building superior quality PS because this would increase its cost and price. However, OS development could increase competitive pressure, and therefore the firm has to improve the PS quality when software is more substitutable.

Other topics in this paper were also explored in recent research. Bitzer (2004) focused on the horizontal differentiation between Linux and Microsoft operating systems. In our paper, software is both horizontally and vertically differentiated, and we investigate the firm's optimal choice of PS quality and price. Llanes and Elejalde (2013) studied the co-existence of PS and OSS. This paper's focus is on embedded systems in electronic devices with a primary good and a complementary private good as in the case of embedded systems in electronic devices. Niedermayer (2013) provided an analysis on investment incentive for platforms and applications due to different platform governance structures. Additionally, code forking was intensively studied in Robles and González-Barahona (2012). Our research departs from this analysis to consider that code forking represents the duplication or overlapping efforts of programmers, which reduces OSS quality. Broad economic issues related to OSS development and particularly programmers' incentives to work for the OS community were highlighted in Lerner and Tirole (2002, 2005). Because the labor market is imperfect, we develop a model of oligopsony to account for the heterogeneous preferences of programmers (see Bhaskar *et al.*, 2002, for a general presentation). In our model, there is only one PS firm hiring programmers, while the alternative for the programmers is to join the OS community.

The paper is organized as follows. In Section 2, we analyze the baseline model whereby the OSS is provided free of charge in the software market. In Section 3, we analyze competition with the entry of OSS competitive fringe vendors. Section 4 provides a brief conclusion. Throughout this paper, we report the main results; the Appendix provides detailed proofs.

2. The PS firm's competitive strategy

2.1. The baseline model. The model consists of two markets (labor and product), three types of market players (the firm, programmers, and consumers), and two products (PS and OSS). In the labor market, a programmer decides to work for either the PS firm or the OS community. In the product market, OSS and PS are imperfect substitutes from a consumer's viewpoint. The OSS is available free of charge, while the PS price is determined by the monopolistic PS firm. Furthermore, software quality represents the connection between the two markets. In particular, the PS quality is proportional to the number of programmers hired by the firm, while the OSS quality partially depends on the joint efforts of volunteer programmers. We first analyze the PS firm's optimal choice of wage rate and the PS price in this context. Then we compute the equilibrium values and provide comparative statics.

The stylized model is illustrated in Figure 1.

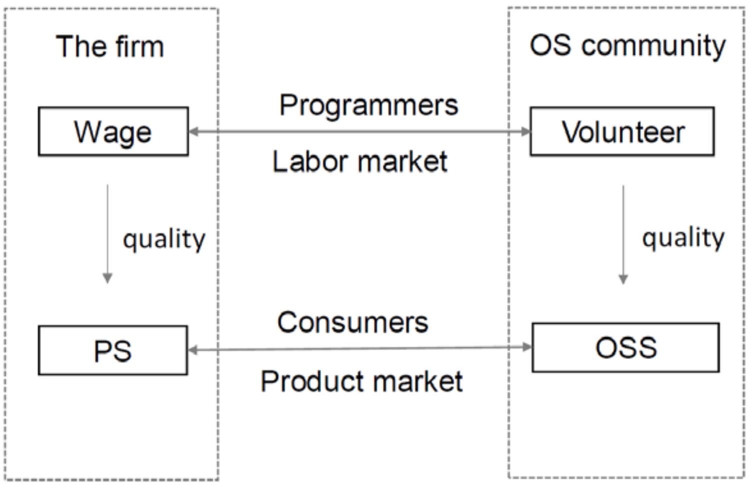

FIGURE 1. The baseline model

Programmers. We consider that a programmer can either be employed by the firm, or a volunteer in the OS community, or be unemployed. The firm offers a wage rate, denoted as $w > 0$, while the OS community provides non-pecuniary rewards,[5] normalized to 1.

In addition, assume that there is a unit mass of programmers with preferences distributed uniformly along the Hotelling line $(0, 1)$. The PS firm is located at 0, while the OS

[5] The latter includes the signaling incentive (see Lerner and Tirole (2005) for a formal analysis). Essentially, in a technical discipline such as software programming, the best for a programmer to signal his/her talent is through good code. However, it is not easy for others to assess a programmer's talent in standardized metrics, or it simply requires a significant amount of time. Thus, the programmer has an incentive to show his/her work in open source where OSS users can judge him/her on the value of his/her code (see Weber (2004) for a general discussion).

community is located at 1. We let parameter t capture the unit transportation cost of developing the software or "*mismatch*". Thus, $t\eta$ and $t(1-\eta)$ represent the coding cost for the programmer located at η, if he/she is hired by the firm and if he/she is a volunteer, respectively.

Assumption A1. The degree of heterogeneity is sufficiently high, that is $t > 1$.

Intuitively, because the value of t is high enough, there are unemployed programmers who are sufficiently far from both the PS firm and the OS community. An unemployed programmer derives net utility equal to 0. This assumption implies that the firm is unable to affect the participation of the volunteer programmers in the OS community by adjusting the wage rate.[6] In summary, the programmer located at η would decide as follows:

$$\begin{cases} u^F = w - t\eta \text{ if he/she is hired by the firm} \\ u^O = 1 - t(1-\eta) \text{ if he/she is a volunteer} \\ u^U = 0 \text{ if he/she is unemployed} \end{cases} \tag{1}$$

Now, assume that there are $(1-\widehat{\eta})$ volunteer programmers in the labor market. The programmer located at $\widehat{\eta}$ is indifferent between joining the OS community or being unemployed, that is $u^F = u^U$. In this case, we have:

$$1 - t(1-\widehat{\eta}) = 0 \tag{2}$$

or,

$$\widehat{\eta} = \frac{t-1}{t} \tag{3}$$

Assumption $A1$ is to ensure that $0 < \widehat{\eta} < 1$. In other words, the indifferent programmer between working for the OSS community or not should be addressed in the Hotelling line $(0, 1)$.

Similarly, the programmer located η^* who is indifferent between the firm and unemployment solves $u^O = u^U$, or we have:

$$w - t\eta^* = 0 \tag{4}$$

[6] In practice, a firm's demand for programmers could be relatively small compared to the supply. Additionally, it might be too costly for the firm to hire programmers who prefer to work for the OS community.

Thus, the number of programmers hired by the firm is as follows:

$$\eta^* = \frac{w}{t} \tag{5}$$

We need to have $\widehat{\eta} > \eta^*$ so that there are unemployed programmers in the labor market. We will verify this condition after deriving the equilibrium values. Furthermore, (5) demonstrates that if the firm wants to hire an additional programmer, it has to offer a higher wage rate not only to the new programmer but also to all of the existing programmers.[7]

Figure 2 shows the programmers' choice.

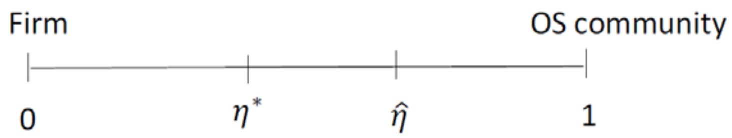

FIGURE 2. A programmer's decision

For tractability, we also assume that the programmers have identical productivity. This assumption allows us to focus on the heterogeneity of the programmers' preferences, which is useful for formulating an approximation of software quality in the subsequent analysis.

Software quality and cost. Generally speaking, software development is a process that includes contributions of programmers and coordinates those contributions. Thus, we consider that software quality is generated by adding up the contributions of programmers to a joint product. Because the programmers have identical skills, this implies that the number of programmers determines the software quality.[8] Then, α and $\widehat{\alpha}$ denoted the quality of the PS and OSS, respectively. In addition, it is defined that $\alpha = \eta^*$. Intuitively, if the firm decides to set a higher wage rate, it can hire more programmers, leading to higher PS quality. In other words, we can interpret w as the investment incentive in the PS quality enhancement representing the firm's strategic choice.

[7]In (5), the ratio $\frac{1}{t}$ can be interpreted as the labor supply elasticity.

[8]The quality defined here is a simplified aggregate indicator because software development can be compared along many perspectives, including leadership, mutual learning, and private labor efforts (see Giuri *et al.,* 2010, for an empirical study on the project's performance and team production) and engineering dimensions such as security, performance, and usability (for example, Lerner and Tirole, 2002, Kuan, 2001, Kumar *et al.,* 2011).

To measure the OSS quality, we also consider a few important OSS features as follows. First, volunteer programmers often have diverse interests and expertise, while the PS firm can better manage its programmers' efforts. In other words, there is a relatively higher level of coordination between the programmers hired by the firm than between those in the OS community. Second, the firm can provide software technical support and promotion. Thus, we assume that the OS community has a relative disadvantage in building software compared to the firm, represented by ψ where $0 < \psi < 1$. To this end, the OSS quality is $\widehat{\alpha} = 1 - \widehat{\eta} - \psi$.

In summary:

$$\begin{cases} \alpha = \eta^* = \frac{w}{t} \\ \widehat{\alpha} = 1 - \widehat{\eta} - \psi = \frac{1}{t} \ - \psi \end{cases} \tag{6}$$

We observe from (6) that the PS quality increases with the wage rate set by the firm (that is, w),), but decreases with the programmers' heterogeneity, that is, parameter t. However, the OSS quality is exogenous depending on t and ψ. The higher these parameters' values, the lower the OSS quality. In addition, $\widehat{\alpha} > 0$ if $\psi t < 1$ or $\psi < \frac{1}{t}$.

The firm's cost to develop the PS is simply the total wages paid to the hired programmers as follows

$$C(w) = w\eta^* \tag{7}$$

Consumers. There is a unit mass of software users deciding whether to buy one unit of PS or OSS. For convenience, we use a Hotelling model to capture the software market's imperfections as in Figure 3.

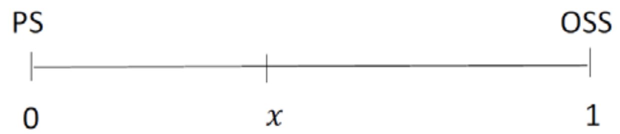

FIGURE 3. A software user's decision

A software user located at x derives gross utility V_{PS} or V_{OSS} if he/she adopts the PS or OSS, respectively. Consumers obviously prefer high-quality software, thus, for simplicity, we assume that the gross utility is equal to the software quality, that is, $V_{PS} = \alpha$ or $V_{OSS} = \widehat{\alpha}$. In addition, h denotes unit transportation cost.

Assumption A2. Software horizontal differentiation is sufficiently high, that is $h > 1$.

Thus, the assumption of high differentiation implies less software substitutability, representing the heterogeneous tastes of the software users. We restrict the value of $h > 1$ to ensure the equilibrium values are positive in the subsequent analysis.

Regarding software price, p denotes the PS price which is determined by the firm. For simplicity, we consider that the copyright holder gives consumers a license to freely copy and use the OSS. Then, assuming that the market is fully covered, the decision of the consumer located at x is as follows:

$$U = \begin{cases} \alpha - p - hx \text{ if he/she adopts the PS} \\ \widehat{\alpha} - h(1-x) \text{ if he/she adopts the OSS} \end{cases} \tag{8}$$

The indifferent user located at x^* solves

$$\alpha - p - hx^* = \widehat{\alpha} - h(1-x^*) \tag{9}$$

Thus, the firm's demand is

$$x^*(p,w) = \frac{1}{2} + \frac{\alpha - \widehat{\alpha} - p}{2h} \tag{10}$$

From (10), the demand for the PS is positively affected by its quality (that is, α), but negatively affected by the PS price (that is, p), the OSS quality (that is, $\widehat{\alpha}$), and the level of horizontal differentiation (that is, h). Furthermore, the impact on the PS demand of an increase in the PS quality is the same as that of a decrease in the PS price. For notation convenience, we drop the subscript $*$ of the PS quantity.

The firm. For simplicity, we assume there is no fixed or marginal cost of production. Thus, the PS firm's profit function is

$$\pi(p, w) = px(p, w) - C(w) \tag{11}$$

Replacing (6), (7) and (10) into (11), and rearranging, the firm profit becomes

$$\pi(p, w) = \frac{[(h + \psi - p)t + w - 1]\, p}{2ht} - \frac{w^2}{t} \tag{12}$$

Of note, the firm behaves as a monopolist when it sets the PS price because the OSS price and quality are exogenously determined. Furthermore, the firm sets the optimal PS price and quality using the wage rate to maximize profits. Thus, the first-order conditions for profit maximization are as follows:

$$\frac{\partial \pi}{\partial p} = \frac{(h + \psi - 2p)t + w - 1}{2ht} = 0 \tag{13}$$

and

$$\frac{\partial \pi}{\partial w} = \frac{p - 4hw}{2ht} = 0 \tag{14}$$

The FOC with respect to w in (14) is directly dependent only on the firm's choice of PS price and the degree of differentiation (that is, h). Solving simultaneously for the FOCs in (14) and (13), we obtain the following proposition.

Proposition 1. *There exists a unique Nash equilibrium, as follows:*

$$p^E = \frac{4h\,[(h + \psi)t - 1]}{8ht - 1} \tag{15}$$

$$w^E = \frac{p^E}{4h} \tag{16}$$

From (15), we observe that the equilibrium wage rate is increasing in the PS price, but decreasing in the degree of software differentiation. Furthermore, under assumptions $A1$ and $A2$, the firm optimally sets the positive PS price and wage, that is, $p^E > 0$ and $w^E > 0$. In the Appendix, we prove that this candidate equilibrium is a maximal one.

Furthermore, plugging the equilibrium PS price and wage rate back into (5), (10) and (11), the equilibrium software quality, demand, and firm's profit are:

$$\alpha^E = \frac{p^E}{4ht} \text{ and } x^E = \frac{p^E}{2h} \tag{17}$$

$$\pi^E = \frac{[(h+\psi)t-1]\, p^E}{4ht} \tag{18}$$

Under assumptions $A1$ and $A2$, that is, $h > 1$ and $t > 1$, the equilibrium values in (17) and (18) are positive.

Consumer surplus is

$$CS = \int_0^{x^E} (\alpha - p - hx)dx + \int_{x^E}^{1} [\widehat{\alpha} - h(1-x)]\, dx \tag{19}$$

Thus, we obtain:

$$CS^E = \frac{8ht^3\psi^2 - 2(56h^2t^2 - 8ht + 1)t\psi - 56h^3t^3 + 128h^2t^2 - 25ht + 2}{2t(8ht-1)^2} \tag{20}$$

The equilibrium consumer surplus is positive, that is, $CS^E > 0$ under the following condition:

*Assumption A*3. The value of ψ is sufficiently small, that is, $\psi \preceq \widehat{\psi}$ where:

$$\widehat{\psi} = \frac{56t^2h^2 - 8ht - \sqrt{3584h^4t^4 - 1920h^3t^3 + 376h^2t^2 - 32ht + 1)} + 1}{8ht^2} \tag{21}$$

By plotting,[9] we observe that the maximum of $\widehat{\psi}$ is approximately 0.52 when $t = h = 1$.

Finally, we verify that under our assumptions, the OSS quality is exogenous, that is, $\widehat{\eta} > \eta^*$.

We have thus established the following proposition.

Proposition 2. *In equilibrium, the wage rate is lower than the non-pecuniary rewards, that is,* $w^E < 1$, *and the PS quality is lower than the OSS quality, that is,* $\alpha^E < \widehat{\alpha}$.

Proposition 2 indicates that because the software is differentiated both horizontally and vertically, and the firm can determine the PS quality, the firm optimally chooses the low cost and price strategy despite the fact that it has a quality advantage. Intuitively, we observe that if the firm slightly increases the wage rate, this would increase both the PS

[9]See the Appendix for the figure.

quality and price with the coefficients of $\frac{1}{t}(< 1)$ and $4h(> 1)$, respectively, as shown in (5) and (16). This then leads to lower demand for the PS as shown (10). Furthermore, the firm's cost of improving the PS quality is strictly convex of the wage rate. Thus, this, together with the demand reduction, reduces the firm's incentive to raise the wage rate to develop high-quality software.

This finding is quite consistent with the empirical evidence found in Kuan (2001), and the claims on the OSS's superior quality, for example, in Johnson (2006), Bessen (2006), and Raymond (2001). In other words, in the context of the exogenous development of open source software described in this paper, the PS firm optimally builds low-quality PS relative to that of OSS to maximize profits. We will examine the PS firm's strategy to manage increasing competitive pressure by the OSS development in the next subsection.

2.2. **Comparative static analysis.** In the face of rapid changes in the software industry, the first challenge of open source is that the OSS and PS could become more or less substitutable from a consumer's viewpoint. Additionally, government policies supporting open source could be implemented to improve coordination of volunteer programmers or promote and raise the public's awareness of the OSS. In other words, this policy can improve the OSS quality disadvantage in this model. Therefore, we evaluate the impact of a small deviation on the quality advantage parameter (that is, ψ) and the degree of software differentiation (that is, h) on the PS firm's behavior and subsequently profit and consumer surplus.

2.2.1. ***Impact of quality advantage.*** A higher level of the firm's quality advantage (that is, parameter ψ) could clearly bring the firm a higher profit and vice versa. The remaining important question is how this change will affect the firm's optimal choices of software quality, price, and consumer surplus.

From (15) and (16), the results from a slight decrease in ψ would increase the firm's strategic variables as follows.

Proposition 3. *If ψ slightly decreases, the firm reduces both the PS price and quality and obtains lower profits. In this case, consumer surplus is higher.*

This proposition implies that government policies to increase the adoption of OSS, a large range of support services in the OS community, a more user-friendly OSS interface, or more efficient coordination of volunteer programmers would give the firm incentive to develop lower quality PS by offering a lower wage rate because $\frac{\partial w^E}{\partial \psi} > 0$. This lowers the firm's costs and consequently the PS price because $\frac{\partial p^E}{\partial \psi} < 0$.

Furthermore, a lower quality advantage could harm the PS firm but benefit software users. We show that the firm's profit and quantity are lower when the consumer surplus is higher for a slight decrease in ψ, that is, $\frac{\partial \pi^E}{\partial \psi} > 0$, $\frac{\partial x^E}{\partial \psi} > 0$ and $\frac{\partial CS^E}{\partial \psi} < 0$. Of note, the consumer surplus could be higher despite a lower PS quality because PS users prefer lower PS prices and the improved OSS quality for those who adopt the OSS.

2.2.2. ***Impacts of software substitution.*** Standard economic arguments assert that higher degrees of substitutability give consumers more choice, intensifying competition and reducing the software price and firm's profit. This then lowers the firm's ability to maintain labor wages or costs. Conversely, when software is more comparable from a consumer's viewpoint, the PS firm may be interested in improving the PS quality to capture a greater market share. In other words, because the PS and OSS are differentiated vertically and horizontally, the impact of a slight change in the degree of substitutability is *a priori* ambiguous.

From (15), (16), (18), we state the impact of a slight change in h on the firm and consumer surplus in the following proposition:

Proposition 4. *When software becomes less horizontally differentiated, that is, h is lower, the firm will want to increase the wage rate and PS price. In this case, the firm's profit is lower while the consumer surplus is higher.*

The intuitions behind this result are as follows. Because the PS quality is inferior, when the software becomes less differentiated, the firm will want to increase the PS quality, thereby decreasing the software quality difference and increasing the PS price. This explains why the free-of-charge OSS could not replace the PS when software becomes more comparable from a consumer's viewpoint. We also show that, on the one hand, OS development reduces the firm's profit, that is, $\frac{\partial \pi^E}{\partial h} > 0$. On the other hand, it could provide an opportunity for the PS firm to raise its market share, that is, $\frac{\partial x^E}{\partial h} < 0$. This is because consumers value software based on both price and quality dimensions. Finally, the consumer surplus is higher, that is, $\frac{\partial CS^E}{\partial h} < 0$. This implies that the gain from higher software quality could outweigh the loss from higher software prices in this situation.

3. Competition with OSS vendors

We now consider other challenges facing the PS firm in an open source environment, which is the entry of OSS vendors.[10] For the sake of simplicity, we consider that the vendors do not own the intellectual property rights to the OSS. Rather, the OSS vendors only sell supported services, such as product customization, problem solving, or best practices, for OSS users at a positive price. Thus, both the OSS's supported services and price level could put further competitive pressure on the PS firm. Then, we assume that the free-of-charge OSS is no longer available in the software market. We analyze the impacts of a change in competitive pressure caused by the OSS fringe vendors on the firm's strategy, profit, and consumer surplus.

More specifically, suppose that there is a continuum of small OSS vendors called the competitive fringe. The fringe vendors can offer a set of technical support and customization services to increase the utility of OSS users. Because the fringe firms have no market power, the increased utility and price are exogenous, as denoted by m and $\widehat{p}$, respectively. m is the OSS quality upgrade provided by the OSS fringe vendors. Furthermore, we assume that $\widehat{p} < m$ to ensure that the software users always prefer the paid OSS to the free-of-charge OSS. This implies that the paid OSS has higher quality than the free-of-charge OSS as shown in the baseline model.

In this context, the firm's demand is modified from (10) with the presence of $\widehat{p}$ as follows:

$$x = \frac{1}{2} + \frac{\alpha - \widehat{\alpha} - p + \widehat{p}}{2h} = \frac{(h + \psi - p + \widehat{p} - m)t + w - 1}{2ht} \tag{22}$$

[10] This assumption is justified because one feature in the software industry is that an OSS vendor does not need a large amount of upfront resources compared to a PS firm.

The PS demand in (10) demonstrates that the OSS quality can be higher than in the baseline model if $\widehat{p} > m$. Additionally, the impact of a slight increase in m on the PS demand is equal to that of a slight decrease in $\widehat{p}$. Finally, because we assume that $\widehat{p}$ and $\widehat{\alpha}$ are exogenous, the firm has to take into account the new demand functions provided in (22) for maximizing profit.

In particular, the firm's profit function is

$$\pi(p, w) = \frac{[(h + \psi - p + \widehat{p} - m)t + w - 1]\, p}{2ht} - \frac{w^2}{t} \tag{23}$$

Compared with the profit function in (12), *ceteris paribus*,the firm's profit is lower at a lower OSS price, higher OSS quality, and higher benefit of the volunteer programmers. The analytical method is analogous to the baseline model. We simultaneously solve the FOCs for profit maximization and obtain the optimal price and wage subscripted with N as follows:

$$p^N = p^E + \frac{(\widehat{p} - m)t}{8ht - 1} \tag{24}$$

$$w^N = \frac{p^N}{4h} \tag{25}$$

Of note, these equilibrium values are the same as those in the baseline model if $\widehat{p} = m$. To put it differently, the baseline model is a special case of the general situation when $\widehat{p} = m = 0$. Because $\widehat{p} < m$, we find that $p^N < p^E$ and $w^N < w^E$. Thus, in equilibrium, the paid OSS quality is higher than the PS quality.

In addition, $p^N > 0$ and $w^N > 0$ only if the OSS price is sufficiently high compared to the OSS quality upgrade, that is:

$$\widehat{p} > m - h - \psi + \frac{1}{t} \tag{26}$$

The following proposition states the equilibrium properties.

Proposition 5. *In the face of OSS fringe vendors, the firm decreases both the wages and PS price. Consequently, while the firm's profit is lower, the consumer surplus is higher relative to those in the baseline model.*

Intuitively, the impact of the entry of OSS fringe vendors is similar to the case when the OSS quality disadvantage is lower in the baseline model. In particular, from (22), we observe that the PS demand is increasing in the OSS price (that is, $\widehat{p}$) and decreasing in the OSS quality (that is, m). Because $m - \widehat{p} > 0$, the net effect of the OSS competitive fringe on the PS demand is negative. Thus, the firm has to decrease both the wage rate and PS price and obtains lower profit. Regarding consumer surplus, while consumers suffer from a lower level of PS quality, they benefit from the lower PS price and higher OSS quality. Thus, this proposition indicates that the aggregate impact of the OSS competitive fringe vendors on consumers is positive.

4. Conclusion

We observe in practice that the open source environment is rapidly changing, putting competitive pressure on the PS firm with many possible dimensions. Thus, our paper takes the view that OSS development is exogenous from the PS firm's viewpoint and then analyzes its optimal strategy. We build a simple theoretical model accounting for various important features of the software industry including the imperfections in the labor and software markets, the quality advantage of the firm in software development, the presence of OSS vendors. In particular, we attempt to characterize the firm's optimal wage setting and software pricing when software is differentiated both horizontally and vertically. Then we evaluate the impact of a change in the market structures.

First, we find that the firm strategically chooses to build the PS with inferior quality compared to the OSS. Second, if the OSS quality disadvantage is lower, or the OSS becomes more attractive from a consumer's viewpoint, then the firm would decrease both the PS price and quality. Conversely, if software becomes more substitutable, the firm will increase both the price and quality. In both situations, the firm's profit is lower while the consumer surplus is higher. Finally, the impact of the entry of OSS competitive fringe vendors is similar to the case when the quality advantage is lower, that is, the firm would reduce the wage rate and PS price, thereby deriving lower profit.

From a dynamic viewpoint, the firm would have incentives for a reputation for high-quality production. In a static framework, we also show that it would not be in the firm's interest to reduce the PS quality if the OSS becomes increasingly substitutable. Finally, this paper ignores a few other important features including the network effects, active role of OSS vendors, different quality dimensions and competition scenarios, and empirical evidence, which we leave for future research.

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APPENDIX. This Appendix provides the proofs.

Proof of Proposition 1.

First, the SOCs are guaranteed because the Hessian matrix is negative as follows:

$$\begin{aligned}\frac{\partial^2\pi}{\partial w^2} &= -\frac{2}{t} < 0; \frac{\partial^2\pi}{\partial p^2} = -\frac{1}{h} < 0\\ \frac{\partial^2\pi}{\partial w\partial p} &= \frac{1}{2ht}\\ \frac{\partial^2\pi}{\partial w^2}\frac{\partial^2\pi}{\partial p^2} - \frac{\partial^2\pi}{\partial w\partial p} &= \frac{8ht+1}{4h^2t^2} > 0\end{aligned}$$

Proof of Proposition 2.

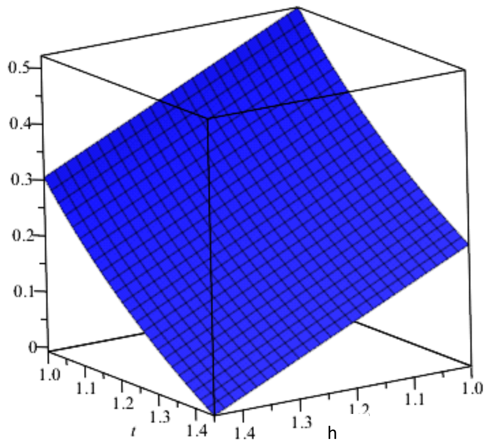
We can compare that:

$$w^E - 1 = -\frac{(7h-\psi)t}{8ht-1} < 0 \tag{27}$$

$$\Delta\alpha = \alpha^E - \widehat{\alpha} = \frac{(8\psi t - 7)h}{8ht-1} \tag{28}$$

Thus, the condition for $\Delta\alpha < 0$ is that $\psi < \frac{7}{8t}$. This condition holds under assumptions $A3$, that is, $\psi < \widehat{\psi}$, and from (21), $\widehat{\psi} < \frac{7}{8t}$.

Furthermore, we plot $\widehat{\psi}$ indicated in (21) in the (t, h) space, as follows.



Proof of Proposition 3.

$$\begin{cases} \frac{\partial w^E}{\partial \psi} = \frac{t}{8ht-1} > 0; \frac{\partial p^E}{\partial \psi} = 4h\frac{\partial w^E}{\partial \psi} > 0 \\ \frac{\partial x^E}{\partial \psi} = 2\frac{\partial w^E}{\partial \psi} > 0 \\ \frac{\partial \pi^E}{\partial \psi} = \frac{2[(h+\psi)-1]}{8ht-1} > 0 \\ \frac{\partial CS^E}{\partial \psi} = \frac{8ht^2\psi - 56h^2t^2 - 8ht + 1}{(8ht-1)^2} \end{cases}$$

Thus,

$$\frac{\partial CS^E}{\partial \psi} \lesseqgtr 0 \quad \text{if} \quad \psi \lesseqgtr \psi_1 = \frac{56h^2t^2 - 8ht + 1}{8ht^2}.$$

Furthermore,

$$\psi_1 - \widehat{\psi} = \frac{\sqrt{3584h^4t^4 - 1920h^3t^3 + 376h^2t^2 - 32ht + 1)}}{8ht^2} > 0.$$

Thus, because of assumption $A3$, we obtain $\psi < \psi_1$ or $\frac{\partial CS^E}{\partial \psi} < 0$.

Proof of Proposition 4.

Under assumptions $A1$, $A2$, $A3$, we find that:

$$\begin{cases} \frac{\partial w^E}{\partial h} = \frac{t(7-8t\psi)}{(8ht-1)^2} < 0; \frac{\partial p^E}{\partial h} = \frac{4(8h^2t^2-2ht-t\psi+1)}{(8ht-1)^2} < 0 \\ \frac{\partial x^E}{\partial h} = 2\frac{\partial w^E}{\partial h} < 0 \\ \frac{\partial \pi^E}{\partial h} = \frac{2(ht+t\psi-1)(4ht-4t\psi+3)}{(8ht-1)^2} > 0 \\ \frac{\partial CS^E}{\partial h} = -\frac{(64ht^3+8t^2)\psi^2+\left[448h^3t^3-168h^2t^2-(96ht^2+16t)\psi\right]+56ht+7}{(8ht-1)^3} < 0 \end{cases}$$

Proof of Proposition 5.

Replacing (24) and (25) in (22) and (6), we obtain the PS demand and quality as follows:

$$q^N = \frac{2\left[(h+\psi-m+\widehat{p})t-1\right]}{8ht-1}$$

$$x^N = \frac{(h+\psi-m+\widehat{p})t-1}{(8ht-1)t}$$

Thus, computing the firm's profit and consumer surplus is straightforward as follows:

$$\pi^N = \pi^E + \frac{(\widehat{p}-m)\{2\left[(h+\psi)t-1\right]+(\widehat{p}-m)\}}{8ht-1}$$

To prove that $\pi^N < \pi^E$, we need to prove that $2\left[(h+\psi)t-1\right]+(\widehat{p}-m) > 0$ or $\widehat{p} > p_1 = m-2\left[(h+\psi)t-1\right]$.

This is always true because it is easy to show that $p_1 < \widehat{p}^* = m-h-\psi+\frac{1}{t}$.

We compute the equilibrium consumer surplus and obtain:

$$CS^N = CS^E + (m-\widehat{p})\frac{\left[8\left(7ht-t\psi-1\right)ht+4(m-\widehat{p})ht^2+1\right]t}{(8ht-1)^2}$$

Thus, because $m > \widehat{p}$, and under assumptions $A1, A2, A3$, $CS^N > CS^E$.

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