Software Piracy in the Presence of Open Source Alternatives

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Abstract

We develop a model to investigate the manner in which the pricing, profitability and protection strategies of the seller of a proprietary digital good respond to changing market conditions. Specifically, we investigate how the optimal strategy of a seller of proprietary software (such as Microsoft Office) is impacted by product piracy and the presence of Open Source Software alternatives (such as Open Office). Our results, based on an analytical model, show that the losses incurred by sellers of legitimate goods on account of high quality pirated goods are amplified by the level of network externalities. Therefore, for products characterized by high network externalities (such as software), it is crucial for sellers to try to maintain a large perceived quality gap between their product and illegal copies. We also find that the appearance of an OSS alternative leads the incumbent producer to reduce both the price of the legitimate product as well as the level of piracy control. Further, although high quality pirated goods are detrimental to profits in the absence of OSS, they may actually limit seller's losses and the need to adjust prices and protection strategies due to the introduction of an OSS alternative. Thus, a firm such as Microsoft may find it easier to compete with OSS in the presence of product piracy. Finally, the seller is less affected (i.e., has to make smaller strategic adjustments to prices and piracy control) by the appearance of an OSS alternative when the consumers' valuations of the proprietary software and the OSS are strongly correlated (i.e., when the OSS alternative is a close substitute for the original).

Key words: software piracy, piracy protection, network externalities, Open Source, Microsoft

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1. Introduction

The pervasiveness of product piracy is often depicted as one of the most serious threats to firms that produce digital goods such as software, movies and music (Chellappa and Shivendu 2005, Jain 2008, Prasad and Mahajan 2003, Hashim et al, 2014). The digital goods industry has tried to fight piracy in various ways, including publicizing its damages, educating the public on copyright law, engaging in legal actions against copyright offenders, and using protective technological systems like Digital Rights Management (Raghu et al., 2009). Consistent with this view, the academic literature that has incorporated technology-based piracy protection as a firm decision variable has found that profits can increase with the level of protection (Conner and Rumelt 1991; Sundararajan 2004).

However, despite its potentially harmful effects, some producers can also benefit from consumer piracy. For example, Conner and Rumelt (1991) and Jain (2008) demonstrate, in monopoly and duopoly settings respectively, that producers may benefit from tolerating piracy in the presence of network externalities. This is because piracy increases the externality benefits that accrue to legal buyers and also reduces price competition by removing the low willingness to pay consumers from the market. Similarly, Givon, Mahajan and Muller (1995) found that piracy had a very strong influence on the legal diffusion of software, as pirates were estimated to generate four-fifths of new software buyers. Gayer and Shy (2003) analyzed the markets for digital products and concluded that if network externalities are strong enough, a publisher may gain from distributing a lower quality version of its product. Accordingly, investing in piracy control measures may not necessarily be an optimal strategy for digital products.

Another variable that impacts the way in which piracy affects the industry is the quality differential between the original and illegal copies. In some contexts, such as digital music, this differential may be very small, while in others, such as software, it tends to be very significant. Although most of the theoretical models of piracy assume perfect substitutability between copies and the original product, it is clear that the existence of a quality differential impacts the sellers' optimal strategies and profit levels. In particular, Sundararajan (2004) has shown that increases in the quality of the pirated good cause the producer to optimally reduce prices.

Moreover, the emergence of Open Source software (OSS) alternatives creates significant new complications for software producers. Currently, OSS is available in virtually all software categories. Examples include Linux (operating system), Apache (web server), Mozilla Firefox (web browser), Mozilla Thunderbird (e-mail), RapidMiner (data mining), Open Office (office package) and ADempiere (ERP Applications). The literature on the topic (von Krogh and von Hippel 2006; Hann et al., 2013) has analyzed the motivation for producing OSS software, participating in OSS communities and the competition between OSS and proprietary software (Lakhani and Von Hippel 2003, Bagozzi and Dholakia 2006, Lerner and Tirole 2005, Casadesus-Masanell and Ghemawat 2006). In particular, Casadesus-Masanell and Ghemawat (2006) considered a dynamic mixed duopoly model to study the impact of Linux on Microsoft's strategies towards Windows and on the market equilibrium. Among other results, the authors find that the appearance of Linux lowers profits for Microsoft, but that the incumbent is likely to sustain its leadership position by dropping its prices relative to monopoly levels. Although the authors briefly discuss the introduction of piracy in their model, they assumed the piracy rate to be small and exogenous, rather than being endogenously determined by market conditions and/or by Microsoft's piracy control strategy. Powerful incumbents like Microsoft find themselves caught between zero (or very low) price OSS competitors and digital pirates, thereby forcing them to reconsider the trade-offs between their price setting and copyright protection strategies. Products like Linux and Open Office have the potential to become strong competitors in their markets and "whether or not this will severely impact Microsoft remains to be seen, but expect Microsoft to react aggressively – and probably effectively" (Baker, 2009). Therefore the extent to which OSS impacts the strategies of the sellers of proprietary software and market equilibrium in the presence of product piracy remains an open and important question.

Because OSS is either free or available at a cost substantially lower than comparable proprietary software applications, both consumers' willingness to pay for proprietary software and their propensity to pirate could be significantly reduced in an OSS environment. Intuitively, although the availability of OSS may threaten the market share of legitimate software, its presence also allows potential and existing pirates to consider legal alternatives to proprietary software. The availability of such OSS alternatives may therefore limit the potential of piracy controls to convert pirates into buyers and ultimately reduce the firms' incentives to protect its products.

In order to address these issues, this paper develops an analytical model to study how the pricing, profitability and protection strategies of the seller of a proprietary good respond to changing market conditions. To the best of our knowledge, no theoretical work has thus far investigated how the optimal strategy of a seller of proprietary software (in particular, its piracy control strategy) and the market equilibrium is impacted by varying quality of pirated goods in the presence of an OSS alternative.

Table 1 summarizes the main assumptions regarding key variables in the five theoretical papers that are the most closely related to our work. By focusing on the assumptions that these papers have in common with our model, we highlight the specific contributions of our paper in assessing the impact of piracy on legitimate demand. Specifically, our contributions stem from examining the strategy of a digital goods producer when (a) piracy protection, prices and the demand for legitimate and pirated goods are treated as endogenous, (b) the cost of implementing piracy controls may vary across software products, (c) the quality of the pirated goods is not fixed, (d) product demand is dependent on network externalities, (e) the cost of pirating varies across consumers, and finally (f) a viable OSS alternative exists for consumers. In addition, it is worth noting that our work represents the first attempt to model the impact of OSS on the demand for both legitimate and pirated goods. This is an important contribution given the increasing importance, availability and usage of OSS.

Table 1: Assumptions regarding key variables in relevant theoretical work

	Conner & Rumelt (1991)	Jain (2008)	Sundararajan (2004)	Shy and Thisse (1999)	Casadesus_Masanell & Ghemawat (2006)	This Paper
Piracy Protection	Exogenous	**Endogenous**	**Endogenous**	Exogenous	Not Considered	**Endogenous**
Protection Cost	Costless	Almost Zero	Costless	Costless	Not Considered	**Varying**
Quality of Pirated Good	Fixed: Perfect Substitute	**Varying: Imperfect Substitute**	**Varying: Imperfect Substitute**	Not considered	Not Considered	**Varying: Imperfect Substitute**
Consumers' Pirating Costs	Fixed	Fixed	Fixed (free)	Fixed	Not Considered	**Varying**
Network Externalities	**Yes**	**Yes**	No	**Yes**	**Yes**	**Yes**
Demand Estimation	Exogenous	Exogenous	**Endogenous**	**Endogenous**	**Endogenous**	**Endogenous**
Open Source Alternatives	No	No	No	No	**Yes**	**Yes**
Market Structure	Monopoly	Duopoly	Monopoly	Duopoly	**Mixed Oligopoly**	**Mixed Oligopoly**
Model Dynamics	**Static**	**Static**	**Static**	**Static**	Dynamic	**Static**

Note: **Highlighted items** reflect issues that have been incorporated in this paper. The Table points out that some but not all of these factors have been addressed in the other papers.

Our main results are as follows. First, in sharp contrast to most of the existing work on piracy and network externalities, we show that there are realistic conditions under which a firm may want to increase piracy protection in response to increasing network externalities. Second, we show that the losses incurred by sellers of legitimate goods on account of high quality pirated goods are amplified by the level of network externalities. Therefore, the need to maintain a large perceived quality gap between the firm's legitimate product and illegal copies becomes even more pressing for product categories that are characterized by high network externalities (such as software). Third, we find that the appearance of an OSS alternative leads the incumbent to reduce both the price of the legitimate product and its level of piracy control. Further, although high quality pirated goods are detrimental to profits, they may actually limit the seller's losses due to the introduction of an OSS alternative, as well as its need to respond to such introduction by adjusting its price and protection strategies. Finally, the seller is less affected (i.e., bears a smaller profit reduction and has to make smaller strategic adjustments to prices and piracy control) by the appearance of an OSS alternative when the consumers' valuations of the proprietary software and the OSS are strongly correlated (i.e., when the OSS alternative is a close substitute for the original).

The rest of the paper is organized as follows. Section 2 presents the theoretical models for software piracy in the absence of OSS. Section 3 presents the models with varying piracy costs and OSS alternative. Section 4 presents the findings from numerically simulating the extended models. Finally, Section 5 concludes with a discussion of the implications and directions for future research.

2 Software Piracy Model with Endogenous Demand

We begin our analysis by describing the model in the absence of an OSS alternative (Section 2.1) and investigate how the firm's optimal strategies, demand level and profits vary with the levels of network externalities and quality of the pirated good (Section 2.2). This is followed, in Section 3, by an analysis of the impact of the appearance of an OSS alternative on the optimal strategy of the legitimate goods producer, who now has to deal with both a pirated product as well as a free (or nearly free) but legal alternative. The complexity of this model necessitated a simulation analysis since it was not possible to obtain closed form solutions for the optimization problem. This analysis is contained in Section 4.

2.1 The Model

Consider a market for an information good where the consumers' "intrinsic" valuations for the good (that is, abstracting from benefits that may be drawn from the fact that other consumers also use the same product) is distributed uniformly over $X \in [0, \theta_X]$. The utility from using the information good is determined by the intrinsic value of the product to the consumer (X), the size of the externality benefit derived when using the product and its price. Consumers have the option of purchasing a legitimate copy of the good at a price (p) or acquiring a pirated copy, in which case, the cost of pirating is dependent on the piracy controls imposed by the producer. The market penetration of the information good is the sum of the demands for the legitimate (ψ_{leg}) and the pirated (ψ_{pir}) copies. The legitimate goods producer chooses a piracy control level L and the individual consumer's cost of pirating is proportional to this investment level ($c.L$). We first solve the model under the usual assumption that consumers have a fixed cost of pirating. We later relax this assumption to model a market where the consumer's cost of pirating is a random variable[1].

A consumer buying a legitimate copy or acquiring a pirated copy extracts value that is dependent on the network externality factor, α, and the market penetration of the information good ($\psi_{leg} + \psi_{pir}$). Since the quality of the pirated copy may be inferior to that of the legitimate good, the value extracted by the consumer of a pirated copy is reduced by a quality factor, $q \in [0,1]$. We assume that the poor quality of a copy affects not just its intrinsic value component but also the potential externality benefits that can be drawn from using it. For example, users of pirated copies may be unable to get updates and face reduced functionalities (such as disabled features and persistent warning messages). While lack of updates may reduce intrinsic value, restricted features can affect both intrinsic value and externality benefits. While an increase in the quality of the pirated good can benefit the pirate directly, legitimate users benefit indirectly due to the network externality generated by the pirates' demand.

The utility for a random consumer in this setting is described below **(Model 1)**:

$$U_i = \begin{cases} X_i + \alpha(\psi_{leg} + \psi_{pir}) - p & \textit{Buy a legitimate copy} \\ q[X_i + \alpha(\psi_{leg} + \psi_{pir})] - cL & \textit{Acquire a pirated copy} \\ 0 & \textit{Do Nothing (buy neither)} \end{cases} \qquad (1)$$

[1] Given the complexity of the demand equations, it is not possible to obtain closed form solutions to the optimization problem when c is a random variable.

Consumers choose to buy, pirate or do without depending on their valuation for the good (X) relative to two thresholds (X_1 and X_2). The marginal consumer who is indifferent between buying and pirating is given by,

$$X_1 = \frac{[p - cL - (1-q)\alpha(\psi_{leg} + \psi_{pir})]}{(1-q)} \tag{2}$$

Similarly, the marginal consumer who is indifferent between pirating and doing nothing is given by,

$$X_2 = \frac{[cL - q\alpha(\psi_{leg} + \psi_{pir})]}{q} \tag{3}$$

Thus, the demand functions for the three segments (where ψ_{doN} represents the Do Nothing segment) are:

$$\psi_{leg} = \left[\frac{(1-\alpha)(cL - pq) + (q - cL)(1-q)}{q(1-q)(1-\alpha)}\right] \quad \psi_{pir} = \frac{pq - cL}{q(1-q)} \quad \psi_{doN} = \frac{cL - q\alpha}{q(1-\alpha)} \tag{4}$$

The profit function for the information good producer is the revenue generated from the demand for legitimate purchases and the costs incurred in producing the information good. Without loss of generality, we include only the cost of investments in piracy controls in the profit function. The cost is assumed to be a convex function of the piracy control level and the producer's profit is defined by $\pi = p\psi_{leg} - \beta L^2$.

Using the producer's profit function, we can derive the optimal price, p^* and optimal piracy control level, L^*. Apart from the non-negativity constraints on p^* and L^*, from (4) we see that the constraints to ensure that the "Do Nothing" and piracy segments are non-negative are, respectively: $L \geq \frac{\alpha q}{c}$ and $L \leq \frac{pq}{c}$.

Taken together, these constraints lead to four distinct solutions. Each of these cases, along with their implications, is discussed below.

CASE A (*legitimate buyers only*): When both constraints are binding, both the pirate and do without segments are eliminated (substituting $L = \frac{\alpha q}{c}$ and $L = \frac{pq}{c}$ in (4) above). In this case, $p^* = \alpha;\ L^* = \frac{\alpha q}{c}$. Intuitively, the price increases with externality benefits and piracy control levels are set such that they nullify all the externality benefits to the pirates. The optimal profit level is given by: $\pi_A^* = \alpha - \frac{q^2\alpha^2\beta}{c}$, which is decreasing in q and β and increasing in *c*.

CASE B ($q + \alpha \le 1$) (*legitimate buyers and pirates only*): This case is generated when the first constraint is binding, i.e., $L^* = \frac{\alpha q}{c}$. This implies that only the *do without* segment is eliminated. Substituting the values of p^* and L^* in ψ_{pir} (Equation 4), yields the feasibility condition ($q + \alpha \le 1$) in order for pirate demand to be positive. The optimal price is given by $p^* = \frac{(1-q+\alpha)}{2}$ and substituting this optimal value of p in (1) shows that the utility from buying is $\left[X_i - \frac{(1-q)}{2} + \frac{\alpha}{2}\right]$ and pirating is qX_i. Optimal profit is given by: $\pi_B^* = \frac{(1-q+\alpha)^2}{4(1-q)} - \frac{q^2\alpha^2\beta}{c}$.

It is easily shown that the profits under this case are strictly higher than that of the case when only a population of legal buyers exists (i.e, $\pi_B^* > \pi_A^*$). Therefore, CASE B dominates CASE A whenever it is a feasible solution i.e., $\pi_B^* - \pi_A^* = \frac{(1-q+\alpha)^2}{4(1-q)} - \alpha \ge 0$. This suggests that firms' incentive to tolerate piracy is determined by the combination of q and α values; as externality benefits (α) increase, the threshold for pirated goods quality (q) at which the firm will move to eliminate piracy decreases progressively.

CASE C (*legitimate buyers and do nothing segment only*): This case is operational when the second constraint is binding, i.e., $L = \frac{pq}{c}$. This implies that piracy demand is eliminated. In this case, optimal price and piracy controls are:

$$p^* = \left[\frac{c^2}{2(c^2 + q^2\beta(1-\alpha))}\right] \quad L^* = \left[\frac{cq}{2(c^2 + q^2\beta(1-\alpha))}\right] \tag{5}$$

This is a feasible solution if $\beta \le \frac{c^2(1-2\alpha)}{2q^2\alpha(1-\alpha)}$ and shows that both p^* and L^* are (a) increasing in α and (b) decreasing in the cost of implementing piracy controls (β). It is interesting to note that at the limit of this feasibility condition, the optimal solution for both p and L reverts to that of Case A (i.e., the entire do nothing segment converts to legitimate buyers).

Case D (*All three segments exist*): When both constraints are non-binding, optimal price and piracy control are as follows:

$$p^* = \left[\frac{2\beta q^2(1-\alpha)(1-q)^2}{4\beta q^2(1-q)(1-\alpha)^2 - c^2(q-\alpha)^2}\right] \qquad L^* = \left[\frac{cq(q-\alpha)(1-q)}{4\beta q^2(1-q)(1-\alpha)^2 - c^2(q-\alpha)^2}\right] \tag{6}$$

This is a feasible solution if $4\beta q^2(1-q)(1-\alpha)^2 - c^2(q-\alpha)^2 > 0$, and $q \ge \alpha$.

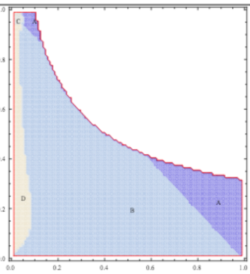
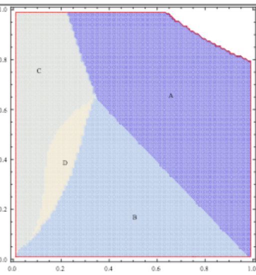
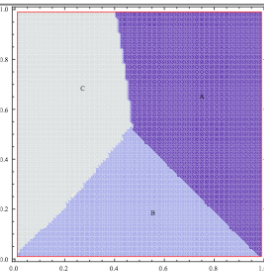
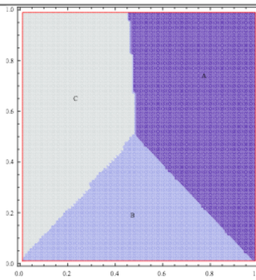
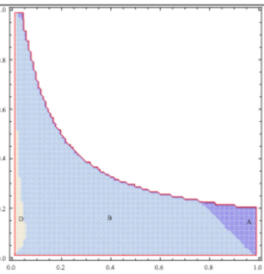
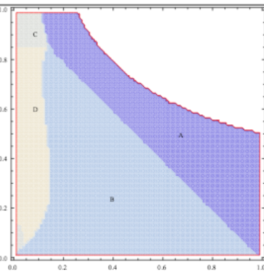
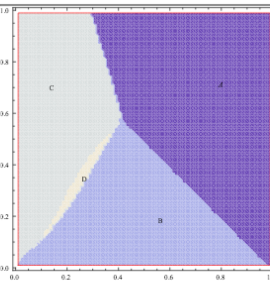
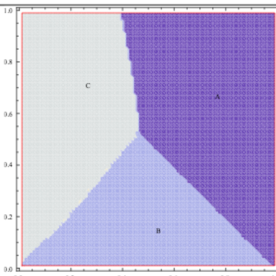
Note that optimal price and piracy controls are a function of the cost of implementing piracy controls, β, only in Cases C and D (i.e., when do nothing segment exists). In cases A and B, price and piracy control levels are independent of the cost of piracy prevention. The implication of this is that when the market is fully covered (i.e., without the do nothing segment) producers are not constrained by costs of implementing piracy controls.

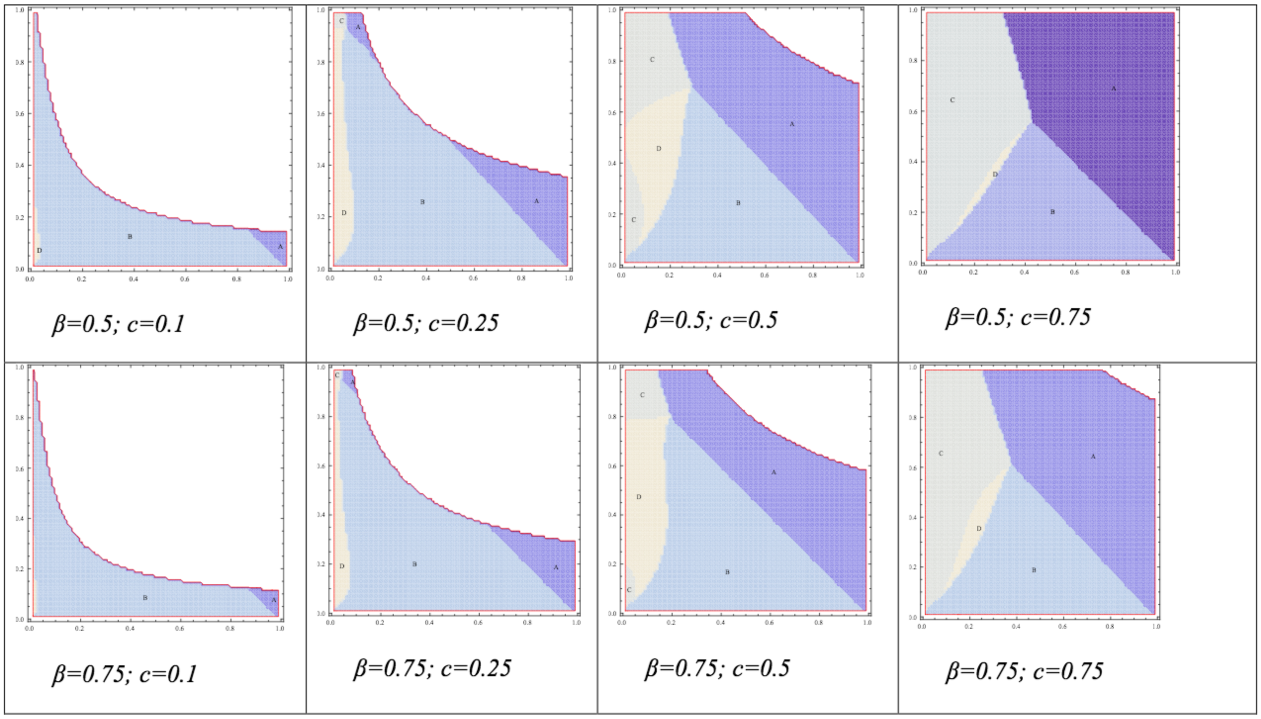
The comparative statics for the four cases described above (cases A-D) are provided in Table 2. Cases where the comparative statics sign could not be determined unambiguously (or were conditional on specific parameter values) are denoted with a ± sign.

2.2. Dominance Regions

In Figure 1 we systematically examine the emergence of the four Cases for various combinations of parameter values. Each graph is a contour plot involving pirated good quality and network externality. The contour plots are drawn for combinations of β and piracy cost, c. The first point to note is that Case D (all three segments exist) seldom emerges as a dominant solution even over a very large range of parameter values. Specifically, as the absolute value of β decreases and the ratio ($\frac{c}{\beta}$) increases (i.e., consumer cost of pirating are relatively higher than the piracy control costs of the producer), the region pertaining to Case D approaches zero. This result is due to the fact that there are strong incentives for the producer to eliminate the do without and/or the pirate segments through price and piracy control manipulations. In particular, with increases in network externalities the producer adopts a combination of price and piracy control that ensures that all consumers with positive valuation have access to the product, even though some of them may well be pirates. In addition, Case C (piracy eliminated) tends to dominate at low α and high q, while case B (do without segment eliminated) dominates at low levels of q. Finally, when q and α are high enough, case A tends to dominate, unless the model has no feasible solution, as indicated by the blank regions in the graphs.

Figure 1: Demand regions under different parameter combinations. [x-axis: α; y-axis: q]

			
β=0.1; c=0.1	β=0.1; c=0.25	β=0.1; c=0.5	β=0.1; c=0.75
			
β=0.25; c=0.1	β=0.25; c=0.25	β=0.25; c=0.5	β=0.25; c=0.75



β=0.5; c=0.1 | β=0.5; c=0.25 | β=0.5; c=0.5 | β=0.5; c=0.75

β=0.75; c=0.1 | β=0.75; c=0.25 | β=0.75; c=0.5 | β=0.75; c=0.75

Note: Each solution region is denoted by A, B, C and D. These correspond to the four Cases of solutions for Model 1. Each row of the graph corresponds to a fixed value of β, with increasing value of c in each column. The range of β and c we tested for is (0.1-0.75).

The comparative statics results provide the rationale for the observed dominance regions. If the quality of the pirated good is very low, it will not pose a significant threat to the firm and consequently piracy will be tolerated through a low level of protection. If furthermore externalities are high enough, then it will be very important for the firm to eliminate the do without segment, which can be achieved through a combination of a high price and a low to moderate level of protection. Assume now that q is high. In this case piracy is a serious threat to the firm and therefore the level of protection will have to be high. However, under a high level of externalities, discouraging piracy will potentially have the very negative effect of driving some pirates out of the market, because that will in turn reduce product value for legal consumers. The firm will be able to avoid this through a combination of high protection and low to moderate prices, which will be successful in eliminating both the piracy and do without segments, unless there is no feasible solution. Such infeasible cases, corresponding to the blank regions in the graphs, arise mainly when the consumer cost of pirating c is lower than the cost of piracy controls β. For example, figure 2b, (c=0.25, β=0.75), shows that for products characterized by low network externalities, it is possible for the producer to participate in the market (i.e., generate positive profits), even in the presence of high quality pirated goods (i.e., high q). However, as network externalities increase, the producer's market participation is eliminated for progressively lower values of q *(that is*, the infeasibility region becomes larger). Basically this means that for high levels of q and α, the firm is unable to charge a positive price and to protect its good and consequently is eliminated from the market.

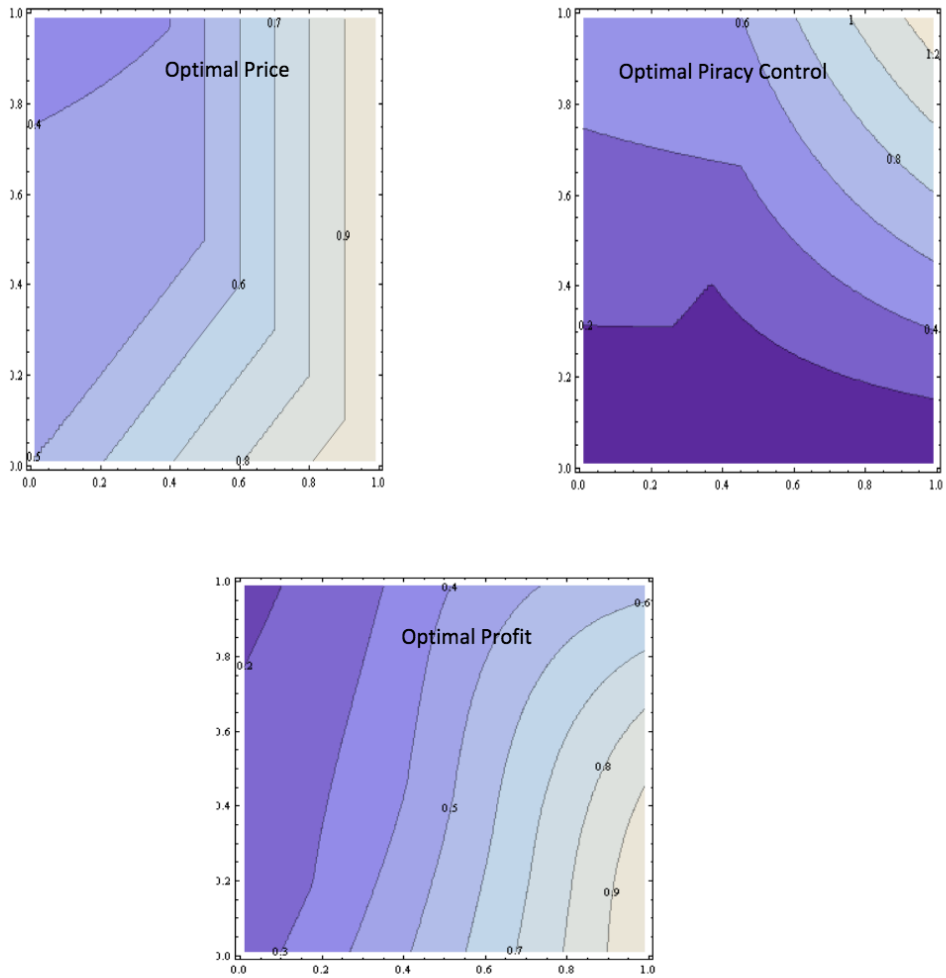
2.3 *Model Results*

Table 2 shows that the sign and magnitude of the effects of q and α on the endogenous variables vary with the region of dominance, which in turn depends on combination of parameter values (α, q, c and β). Interestingly, as pointed out in the previous section, our analysis of the dominance regions indicated that Case D (where all three segments exist) is almost never dominant. Therefore, we concentrate our discussion on cases A to C. Figure 1 illustrates the joint impact of exogenous parameters on optimal price, piracy control and profits.

Table 2: Comparative Statics for Model 1

CASE	*Effect of α*	*Effect of q*
CASE A (legitimate buyers only)	**P**: (+); **L**: (+); **Profit**: (+ if $c^2 > 2q^2\alpha\beta$)	**P**: 0; **L**: (+); **Profit**: (-)
CASE B (legitimate buyers and pirates only)	**P**: (+); **L**: (+); **Profit**: (+) if $c^2>(4\alpha\beta q^2(1-q))/(1-q+\alpha)$; $\psi_{leg}:(+);\ \psi_{pir}:(-)$	**P**: (-); **L**: (+); **Profit**: (- ; if $q+\alpha\leq 1$) $\psi_{leg}:(+);\ \psi_{pir}:(-)$
CASE C (legitimate buyers and do nothing segment only)	**P**: (+); **L**: (+); **Profit**: (+); $\psi_{leg}:(+);$	**P**: (-); **L**: (+); **Profit**: (-); $\psi_{leg}:(+);$
CASE D (All three segments exist)	**P**: (±); **L**:(±); **Profit**: (±); $\psi_{leg}:\pm;\ \psi_{pir}:\pm$	**P**: (±); L: (+);**Profit**: (±); $\psi_{leg}:\pm;\ \psi_{pir}:\pm$

Figure 2: Optimal Price and Piracy Controls (lighter shades indicate higher value) [x-axis: α; y-axis: q] (c=0.75, β=0.25, $X \in [0,1]$)



The main implications of our model, as evidenced in Table 2 and Figure 2, are described below.

Implication 1: ***In response to an increase in the level of externalities, the firm tends to increase both price and piracy control***.

This result is evident from Figure 2 and Table 2. The underlying intuition for this is the following: higher network externalities bring added value to legal consumers and pirates. Consequently, the firm captures that value by raising prices. It is interesting to note from Figure 2 that the firm finds it optimal to do so even when the quality of the pirated good is low. However, such a price rise could have the negative effect of driving some legal buyers out of the market or of transforming them into pirates. The former danger is avoided by limiting the price increase to the point where the marginal buyer becomes indifferent between buying and doing without. The drawback of a potential increase in piracy, on the other hand, is avoided by raising piracy controls. As a result of such an optimal adjustment by the firm, legal demand will tend to increase (or remain constant in Case A). As for profits, the overall effect is ambiguous (since the increased cost of protection may not be fully compensated by the added revenues).

It is worth noting that our result is in sharp contrast with that of Conner & Rumelt (1991), who showed that there is a threshold level of network externalities above which profits decrease monotonically with protection (implying zero protection with high externalities). The rationale of their model is that protection moves some pirates into the buying camp but it also pushes some pirates out of the user base. If externalities are high, the latter effect is very detrimental and therefore the firm chooses not to protect. However, this reasoning is predicated on two very specific conditions: (a) both demand and price are exogenous and (b) all three demand segments exist. In contrast, by treating both price and piracy control as endogenous, our model implies that at high levels of externality the firm will choose that combination of these instruments which allows it to eliminate the do without segment and possibly also the pirate segment. In other words, by not assuming the existence of all segments, we find that our results fall into cases B, A or C, for which the optimal level of piracy control increases with network externalities.

Implication 2: ***In response to an increase in the quality of pirated goods, the firm tends to increase piracy control***

An increase in q increases the attractiveness of piracy and therefore poses a threat to the firm. The comparative statics results of Table 2 show that the firm will respond to such a threat by increasing piracy controls. However, this move has the potentially negative effect of driving some pirates out of the market. Therefore, the firm tries to avoid the conversion of pirates into "do nothing" by dropping prices. This is similar to the effect reported in Sundararajan (2004). The overall effect on legal demand is positive (Cases B or C) or zero (in Case A). In the former cases, the added demand counteracts lower prices and higher costs of piracy control, for most parameter combinations, profits tend to decline significantly as a result of an increase in q. This highlights the importance for the seller of the proprietary good of trying to maintain a large quality gap between its product and illegal copies. As discussed in Implication 1 above, this becomes even more crucial for high network externality products because producers are forced to raise prices even in the presence of relatively low quality pirated goods.

3. Introduction of varying piracy costs and Open Source Alternatives (OSS)

We enhance Model 1 by sequentially introducing two new complications in the analysis. We first model varying piracy costs and next model a scenario with an open source alternative in the choice set.

3.1. Varying Piracy Costs

We maintain a monopoly setting but relax the assumption that all consumers have the same cost of pirating (we refer to this as **Model 2)**. More specifically we assume that the cost of pirating per unit of piracy is a uniform random variable with c $\in$ [0. 1]. The distribution of c is assumed to be independent of the distribution of the consumers' valuation of the good (X). Since c is a random variable, the regions for the different segments are different.

(1) A consumer would buy the legitimate product if $x \geq p-\alpha(\psi_{leg}+\psi_{pir})$ [Line (1)]

AND $(1-q)x+cL \geq p-(1-q)\alpha(\psi_{leg}+\psi_{pir})$ [Line (3)] (7)

(2) A consumer would pirate if $qx-cL \geq -q\alpha(\psi_{leg}+\psi_{pir})$ [Line (2)] AND

$(1-q)x+cL < p-(1-q)\alpha(\psi_{leg}+\psi_{pir})$ [Line (3)] (8)

(3) A consumer would choose to do without if $x < p-\alpha(\psi_{leg}+\psi_{pir})$ [Line (1)] AND

$qx-cL < -q\alpha(\psi_{leg}+\psi_{pir})$ [Line (2)] (9)

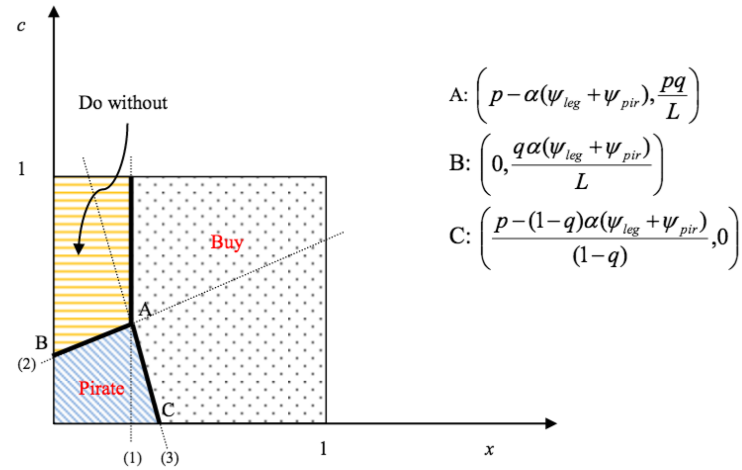
For given values of p and L, the regions for the three outcomes are shown in Figure 3 below. The three line segments correspond to the lines identified in the three conditions stated above in Equations 7, 8 and 9. Given the complexity of the demand equations, we could not obtain closed form solutions to the optimization problem.

From Figure 3, we observe that do nothing segment can be eliminated when $p=\alpha$. At this point, piracy region increases with q and α. Thus, the implications of increase in pirated good quality and network externality remain similar in this case. To determine the general closed form solutions for optimal strategies, we would need to determine the expressions for the areas represented by the three regions. The legitimate demand for the case shown in Figure 3 is a complex polynomial of L as shown below.

$$\psi_{leg} = (1-p) + \frac{(pq)^2}{2L(q-1)} + \frac{L(\alpha-1)}{q\alpha} - \frac{\sqrt{(L^4(q-1)^4(\alpha-1)^2(L^2(\alpha-1)^2 - 2L(p-1)q\alpha^2 + p^2q^2\alpha^2)}}{L^2(q-1)(q-1)^2 q(\alpha-1)\alpha}$$

Given this complex demand function, the profit optimization problem is intractable and a closed form solution could not be found.

Figure 3: Demand regions with consumers distributed randomly over x and c



3.2. Model with Open Source Alternative

We now introduce an open source (non-profit seeking) alternative (OSS) in the consumers' choice set. We assume that the consumers' valuations of this new alternative (Y) are uniformly distributed over $Y \in [0, \theta_Y]$ with $\theta_Y < \theta_X$. Therefore, OSS has a lower mean valuation than the proprietary good due to its perceived lower quality [$q_2 = \frac{E(Y)}{E(X)} = \frac{\theta_Y}{\theta_X} < 1$]. Then, consumer utility in the presence of OSS may be defined as **(Model 3)**:

$$U_i = \begin{cases} X_i + \alpha \ \psi_{leg} + \psi_{pir} \ - p_1 \ : \text{Buy a Legitimate Copy} \\ q_1 \left[X_i + \alpha \ \psi_{leg} + \psi_{pir} \ \right] - c_i L : \text{Acquire a Pirated Copy} \\ Y_i + q_2 \ \alpha \ \psi_{OS} - p_2 : \text{Acquire OSS} \\ 0 : \text{Do Nothing} \end{cases} \qquad (10)$$

Open-source consumers also benefit from network externalities (α) and we assume that the overall externality benefit depends on the mean quality of OSS alternatives (q_2). Consistent with the assumption previously made for pirated copies, this means that, for any given user-base, a lower quality product will generate smaller externality benefits for its consumers. We also note that a base level of externality benefit would accrue from the use of any available product in a software market. However, producers can confer unique externality benefits for users of a specific product. From this perspective, the externality benefits in our model can be considered as the incremental benefit over and above the base level conferred to all users of commercial and open source products. Under the mixed duopoly setting of Model 3, OSS is sold at a price p_2, which may be zero or a relatively small positive value to reflect service costs that may be associated with its use.

A consumer would opt to do without if $q_2 x < p_2 - q_2 \alpha \psi_0$ [Line (1)] AND

$q_1 x - cL < -q_1 \alpha(\psi_{leg} + \psi_{pir})$ [Line (2)] AND $x < p_1 - \alpha(\psi_{leg} + \psi_{pir})$ [Line (3)] (11)

A consumer would opt for the open source alternative if $q_2 x \geq p_2 - q_2 \alpha \psi_0$ [Line (1)]

AND $(q_2 - q_1)x + cL \geq p_2 + q_1 \alpha(\psi_{leg} + \psi_{pir}) - q_2 \alpha \psi_0$ [Line (4)] AND

$(1 - q_2)x < p_1 - p_2 - \alpha(\psi_{leg} + \psi_{pir}) + q_2 \alpha \psi_0$ [Line (5)] (12)

A consumer would buy the legitimate product if $x \geq p_1 - \alpha(\psi_{leg} + \psi_{pir})$ [Line (3)] AND

$$(1-q_2)x \geq p_1 - p_2 - \alpha(\psi_{leg} + \psi_{pir}) + q_2\alpha\psi_0$$ [Line (5)] AND

$$x(1-q_1) + cL \geq p_1 - (1-q_1)\alpha(\psi_{leg} + \psi_{pir})$$ [Line (6)] (13)

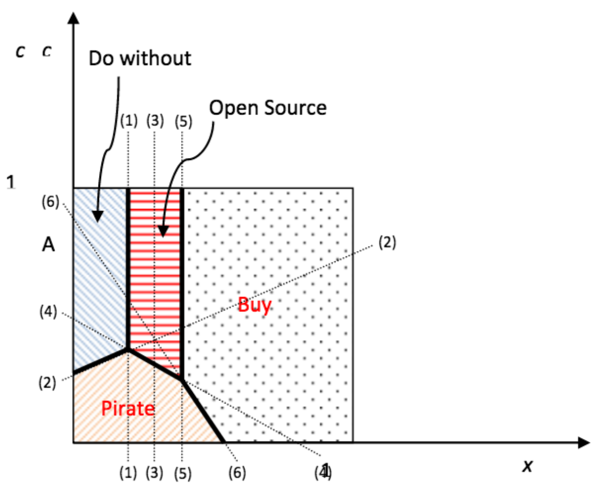
A consumer would pirate if $q_1 x - cL \geq -q_1\alpha(\psi_{leg} + \psi_{pir})$ [Line (2)] AND

$$(q_2 - q_1)x + cL < p_2 + q_1\alpha(\psi_{leg} + \psi_{pir}) - q_2\alpha\psi_0$$ [Line (4)] AND

$$x(1-q_1) + cL < p_1 - (1-q_1)\alpha(\psi_{leg} + \psi_{pir})$$ [Line (6)] (14)

For given values of p and L, a possible arrangement of the regions for the four outcomes are shown in Figure 4 below. The six lines correspond to the lines identified in the conditions stated above in Equations 11-14.

Figure 4: Possible demand segments for Model 3



4. Numerical Simulations

Since closed form solutions to Models 2 (varying piracy costs) and 3 (open source alternative) are intractable, we conducted extensive numerical simulations. In order to simulate Model 3, we generated random samples of 1000 consumers, whose individual values of X_i and c_i (i=1,2,3,…..1000) were randomly drawn from independent, uniform distributions in the [0-1] and [0-0.5] intervals respectively. The consumers' valuations for the open-source good (Y_i) were also assumed to be uniformly distributed with a lower mean [$E(Y)=\theta_Y/2$] and a correlation with X_i of [$Corr(X,Y)$]. Thus, Model 3 has three additional parameters relative to models 1 and 2: $E(Y)$, $Corr(X,Y)$ and p_2.

We began each simulation by initializing the model parameters q, α, β, $E(Y)$, $Corr(X,Y)$ and p_2. To begin with, we systematically varied the values of p and L within a pre-specified grid. Then, based on the demand curves, we estimated the number of consumers who would buy the proprietary good, pirate, choose OSS or do without the product for each (p, L) combination, as well as the corresponding profit levels. Following this, we selected the profit maximizing (p, L) combination and computed the equilibrium values of the demands and profit. Given the optimal level of L, the willingness to pay (WTP) of each consumer was computed as the price that leaves the consumer indifferent between buying the proprietary good and the best alternative (which may be pirating, using open-source or doing without). Finally, we set new combinations of parameter values and once again solved the model numerically in order to obtain the profit maximizing values of the endogenous variables. By varying the combinations of parameter values systematically in this manner, we obtained the optimal solutions across 1080 different runs. Model 2 was simulated following a similar procedure, but since three of the parameters are absent from the model the number of simulations (corresponding to all parameter combinations) is significantly lower.

In order to understand the impact of market conditions on firm strategy, demand and profits, we pooled the data from the two models and regressed the equilibrium values of the endogenous variables on: i) the basic parameters from Model 1 (levels of quality, network externalities and cost of piracy control) ii) an interaction term ($q*\alpha$) between quality and externalities (since we concluded in the previous section that the effects of pirated goods quality on the seller of the proprietary good are mediated by externalities) iii) a dummy variable (D_{OSS}) that takes the value of 1 when the *OSS* alternative is present in the market and zero otherwise iv) interaction effects between D_{OSS} and all model parameters.

4.1. Model Validation

To validate the model, we also simulated Model 1, where we could compare the simulation results to the analytical model solutions (No Open Source and fixed c as in Section 2). We verified that the solutions from the simulation model were very close to that of the analytical solution. The following parameter values were used: $\alpha= (0.2, 0.4, 0.6, 0.8, 1)$; $q_1= (0.2, 0.4, 0.6, 0.8, 0.95, 0.99)$; $\beta = (0.1, 0.25, 0.5)$; $E(Y)= (0.1, 0.3)$,which implies $q_2= 0.2, 0.6)$; $Corr(X,Y)= (0, 0.5, 1)$; $P_2=(0, 0.2)$. Therefore we have 1080 (5*6*3*2*3*2) possible combinations of parameter values.

To ensure that the simulation program accurately estimates near optimal values, we compared the numerical results obtained from the closed form solutions of the base model (Model 1) with that of the simulation program. The random samples drawn from the simulation program at various parameter values yield close to optimal solutions. A sample of these results is shown in the Table 3 below. In general, simulation results align with the analytical results and more importantly, we observe that the direction of change in optimal values is, in general, the same in the two models.

Table 3: Comparison of Analytical Model and Simulation Results

α	q	p^*	p^* (sim.)	L^*	L^* (sim.)	ψ_{Leg}	ψ_{Leg} (sim.)	ψ_{pir}	ψ_{pir} (sim.)	$\psi_{do\text{-}nothing}$	$\psi_{do\text{-}nothing}$ (sim.)	Profit	Profit (sim.)
0.2	0.6	0.443	**0.5**	0.355	**0.4**	0.696	**0.656**	0.000	**0**	0.304	**0.344**	0.277	**0.288**
0.2	0.8	0.407	**0.46**	0.434	**0.5**	0.741	**0.702**	0.000	**0**	0.259	**0.298**	0.255	**0.260**
0.2	0.99	0.371	**0.36**	0.489	**0.48**	0.787	**0.831**	0.000	**0**	0.213	**0.169**	0.232	**0.242**
0.4	0.2	0.500	**0.56**	0.053	**0.1**	0.625	**0.812**	0.375	**0.188**	0.000	**0**	0.312	**0.452**
0.4	0.4	0.500	**0.5**	0.213	**0.22**	0.833	**0.867**	0.167	**0.129**	0.000	**0.004**	0.405	**0.421**
0.4	0.6	0.456	**0.5**	0.365	**0.4**	0.906	**0.873**	0.000	**0**	0.094	**0.127**	0.380	**0.397**
0.4	0.8	0.400	**0.5**	0.427	**0.54**	1.000	**0.873**	0.000	**0**	0.000	**0.127**	0.354	**0.364**
0.4	0.99	0.400	**0.42**	0.528	**0.56**	1.000	**0.983**	0.000	**0**	0.000	**0.017**	0.330	**0.334**
0.6	0.2	0.600	**0.72**	0.107	**0.16**	0.750	**0.873**	0.250	**0.127**	0.000	**0**	0.447	**0.622**
0.6	0.4	0.500	**0.62**	0.213	**0.32**	0.833	**0.979**	0.167	**0.021**	0.000	**0**	0.405	**0.581**
0.6	0.6	0.600	**0.62**	0.480	**0.5**	1.000	**0.98**	0.000	**0**	0.000	**0.02**	0.542	**0.545**

Table 4 reports the results of estimating those relationships with a logistic functional form, which was found to fit the data well[2]. Note that *E(Y)*, p_2 and *corr(X,Y)* can only enter the estimated equation through such interactions, since they are only defined in the presence of OSS (i.e. when D_{OSS}=1).

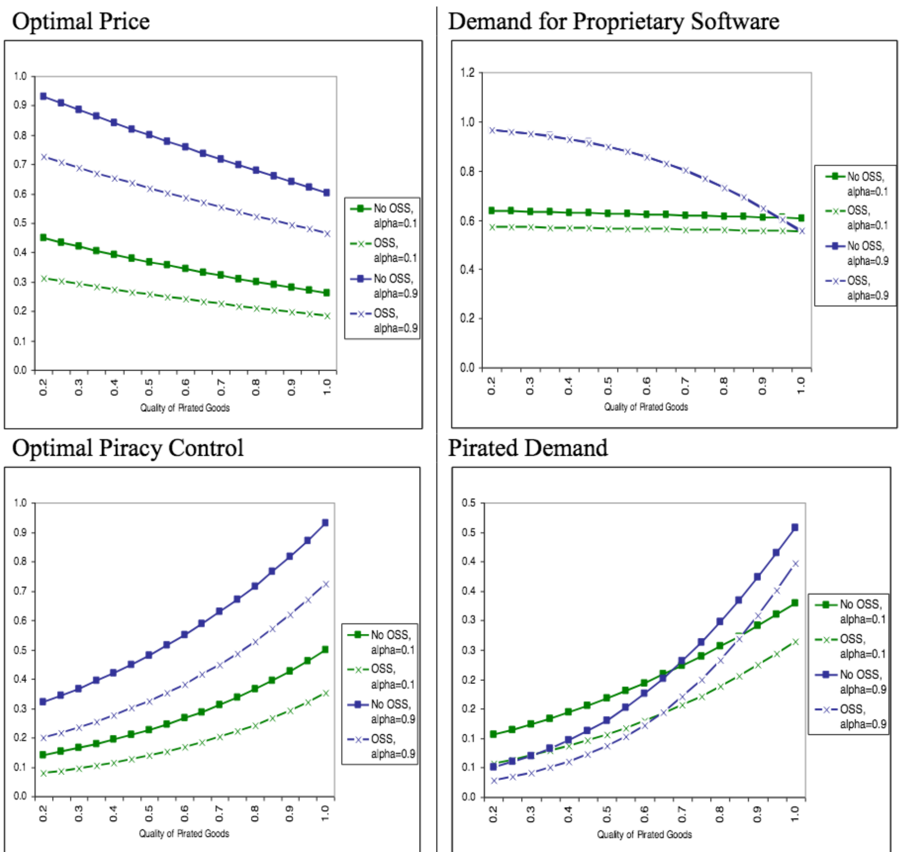
Table 4: Results of non linear regression analysis

	Dependent Variable						
	P	*L*	ψ_{leg}	ψ_{pir}	ψ_{OS}	π	*WTP*
q	-.790***	1.644***	.313*	1.574***	-1.301***	-.983***	-.814***
	(.103)	(.120)	(.176)	(.165)	(.090)	(.152)	(.142)
α	1.262***	1.104***	4.456***	-1.408***	-3.875***	3.706***	3.146***
	(.137)	(.107)	(.183)	(.152)	(.216)	(.176)	(.183)
β	-.937***	-2.791***	.050	.440**	-.574***	-1.011***	-1.580***
	(.160)	(.215)	(.257)	(.201)	(.118)	(.210)	(.218)
D_{OSS}	-.229***	-.449***	-.293**	-.536***	-	-.452***	-.493***
	(.085)	(.1047)	(.147)	(.152)		(.117)	(.118)
$q*\alpha$	.003	-.281**	-4.748***	2.084***	-.511	-2.852***	-1.864***
	(.095)	(.111)	(.157)	(.146)	(.403)	(.172)	(.157)
$D_{OSS}*q$	.060	.014	.068	.438***	-	.331***	.272**
	(.090)	(.055)	(.176)	(.024)		(.142)	(.137)
$D_{OSS}*\alpha$	.062	.116	.300**	.080	-	.046	.087
	(.078)	(.074)	(.143)	(.104)		(.118)	(.117)
$D_{OSS}*\beta$	.134	.031	-.055	.082	-	.210	.378*
	(.154)	(.197)	(.267)	(.211)		(.217)	(.222)
$D_{OSS}*p_2$	.807***	.820***	.447***	.867***	-7.776***	1.094***	1.455***
	(.090)	(.082)	(.121)	(.106)	(.259)	(.104)	(.109)
$D_{OSS}*E(Y)$	-1.194***	-1.011***	-.406***	-1.109***	5.143***	-1.478***	-1.940***
	(.106)	(.087)	(.122)	(.107)	(.219)	(.107)	(.116)
$D_{OSS}*Corr(X,Y)$	.216***	.213***	.236***	.188***	-1.281***	.309***	.275***
	(.023)	(.020)	(.030)	(.026)	(.053)	(.026)	(.026)
Const	-1.224***	-4.308***	.134	-2.464***	-.061	-.857***	-.261**
	(.257)	(.815)	(.142)	(.150)	(.081)	(.117)	(.122)
K	2.433***	13.713	1	1	1	1.030***	1.502***
	(.468)	(10.811)				(.026)	(.040)
N	1170	1170	1170	1170	1080	1170	1170
R^2	.970	.954	.989	.948	.867	.974	.977

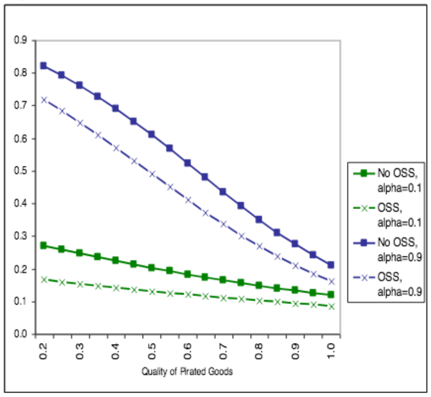
[2] For example, the estimated equation for optimal price was $P = K/\left(1+e^{-\gamma Z}\right)$ where Z is the vector of regressors described above, *K* is a parameter and γ is a vector of parameters to be estimated. Since demands vary between zero and one, we set *K*=1 in estimating the percentages of consumers who buy pirate and use OSS.

In order to illustrate our main results we also show in Figure 5 how the fitted values of the endogenous variables vary with the quality of the pirated good. We do this for two extreme levels of network externalities (α=0.1, α=0.9) and also for the "OSS absent" and "OSS present" scenarios.

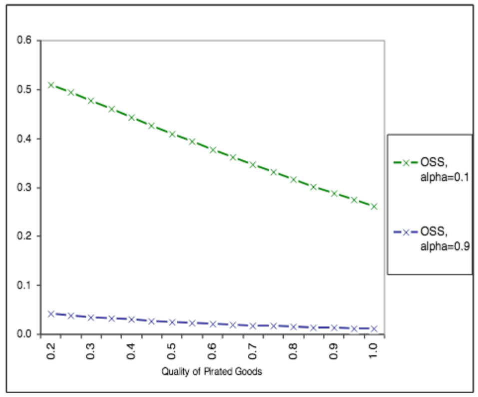
Figure 5 Estimated levels of endogenous variables as a function of the quality of pirated goods



Optimal Profit



Demand for OSS



Our results confirm the findings of the previous section. For example, Table 4 shows that price (P), piracy controls (L), legal demand (ψ_{leg}) and profits (π) are positively and significantly related to network externalities (in accordance with Implication 1). Similarly, the quality of the pirated goods has a positive effect on piracy control and a negative effect on prices and on profits (consistent with Implication 2). Interestingly, while optimal prices are relatively more sensitive to network externalities than they are to the quality of pirated goods, the opposite is true for the level of piracy control. Not surprisingly, the impact of covariates on the mean WTP for the proprietary good is very similar to that on optimal price. Finally the large and negative interaction parameter estimate of the profit equation confirms that increases in the quality of the pirated goods are more detrimental for the firm at high externality levels (consistent with Implications 1 and 2). Next, we investigate the impact of the appearance of an OSS alternative in the market (relative to the "No OSS" case).

Implication 3: ***The existence of open-source software in the market reduces the consumers' WTP for proprietary software and causes the incumbent not just to charge lower prices but to also be more tolerant towards piracy.***

The significant parameter estimates of D_{OSS} and its interaction terms show that this result is conditional on the consumer's mean valuation of OSS being high enough and/or its price low enough (that is, on OSS being sufficiently attractive to consumers). The former effect (lower price), is in line with the findings of Casadesus-Masanell and Ghemawat (2006) and can be regarded as a consequence of lower market power. The latter effect (lower piracy control) results from the fact that under network externalities pirates become the firm's allies against the threat posed by OSS. Both of those effects are clearly visible in Figure 5 by comparing the "No OSS" and "OSS" fitted lines. Thus, while dropping price and piracy controls reduces demand and profits for the legitimate goods producer in the absence of OSS, these strategic actions mitigate the detrimental effects of OSS. Not surprisingly, the levels of piracy also tend to be lower in the presence of OSS, which suggests that the existence of a zero (or very low) price OSS alternative and the lower price of proprietary software, outweigh the stimulus that is provided to pirates by lower piracy control.

Implication 4: ***The incumbent's profit loss due to OSS tends to be smaller in the presence of higher quality pirated goods.***

The estimated parameters of $D_{OSS}*q$ suggest that the effects of OSS on the seller of the proprietary good are affected by the quality of pirated goods. More specifically, the WTP reduction and the profit loss due to OSS are smaller at high values of q, as evidenced by the positive and significant parameter of $D_{OSS}*q$ in the WTP and profit equations. The intuition for this is that when the pirated copies are high quality, pirates are less likely to switch to the new

OSS alternative and, by doing so, to further increase the attractiveness of OSS relatively to proprietary software via network externalities. Consequently, despite being very detrimental in the absence of OSS, high quality piracy mitigates the negative effects that the emergence of an open-source competitor imposes on the incumbent. This result is also clearly visible in Figure 5 with the distance between the "No OSS" and the "OSS" profit lines declining as q increases).

Implication 5: ***The impact of an OSS alternative on piracy control and the price of the legitimate good decreases with the correlation between the valuations of the legitimate good and the OSS alternative (Corr (X,Y)).***

The intuition behind this result is the following. Consider a fixed ratio between the mean consumer valuations of the two goods. A very low correlation implies that some segments of consumers will derive a higher relative benefit from OSS (some may even prefer OSS to the proprietary good in absolute terms), while the opposite will happen with other segments. Such a scenario may result from OSS having different features from the proprietary good, which may be relatively more valued by particular groups of consumers. In the latter case, the incumbent is forced to charge lower prices and to tolerate piracy to a larger extent, in order to generate higher network externality benefits for its consumers and to prevent both its customers and pirates from moving to open-source. On the other hand, if the correlation between those valuations is very high, then consumers have the same relative preference for the proprietary good and OSS (i.e., they prefer the former to the latter). Under these conditions, the seller retains a high level of monopoly power and its strategic downward adjustment in price and piracy control is quite effective in deterring most consumers from switching to OSS.

5. Discussion and Conclusions

To our knowledge, this is the first study to investigate the strategic options for dealing with product piracy in the presence of OSS alternatives. Specifically, we proposed a theoretical model to discuss the impact of OSS and other market conditions on market equilibrium and the choice of policy instruments. This was followed by an empirical test of how the quality of pirated software and the presence of an OSS alternative impacts WTP, optimal price and revenues for Microsoft Office, among the most widely used software products in the world.

Our theoretical model indicates that increases in network externalities increase both the price of the legitimate product as well as piracy controls and lead to increased profits. Thus, in contrast to most of the existing literature, we show that it may be optimal to increase piracy protection in response to increasing network externalities. In addition, our simulations reveal that the quality differential between the legal and the pirated goods is an important determinant of the firm's optimal strategies and profit levels. As demonstrated by our theoretical model, this detrimental impact of high quality piracy is amplified by network externalities. Therefore, our results highlight the importance for the legal producer of maintaining a large quality gap between its product and illegal substitutes, particularly in high externality industries, such as software. Finally, our simulations of the theoretical model also yielded important insights regarding the appearance of an OSS alternative in the market. More specifically, we find that OSS reduces the profits of the incumbent and induces him/her to drop both price and piracy control. This finding has also received some anecdotal support. According to some, one of the main reasons why Microsoft, "a company known to be almost brutal in its license-protection strategies, softened its approach to piracy" was the rise in popularity of OSS (Baker, 2009, p.1)

However, the effects of an open source alternative on the firm's strategies, sales and profits also depend on a number of other factors. In particular, we highlight the role of the quality of pirated goods in mediating the impact of OSS alternatives on the WTP, demand and profits of legitimate software. Specifically, we demonstrated that although OSS alternatives reduce the profits from legitimate software, this impact is mitigated in presence of high quality pirated goods. Thus, although a wholehearted attempt at fighting pirates is the optimal strategy in the absence of OSS, tolerating the presence of high quality pirated goods may actually be beneficial in the presence of OSS. Finally, we found that for any given mean level of quality, OSS will pose a more serious threat to the incumbent when it includes different features from the original product (i.e., when the consumers' preferences for the two products are less strongly correlated.)

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