Generating Value through Open Source: Software Service Market Regulation and Licensing Policy

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March, 2017

Forthcoming in *Information Systems Research*

Abstract

In the software industry, commercial open-source software vendors have recognized that providing services to help businesses derive greater value in the implementation of open-source based systems can be a profitable business model. Moreover, society greatly benefits when software originators choose an open-source development strategy, as their products become widely available, readily customizable, and open to community contributions. In this study, we present an economic model to study how software licensing attributes affect a software originator's decisions, aiming to provide policy makers with insights into how welfare-improving open-source outcomes can be incentivized. We show that when a competing contributor is apt at reaping the benefits of software development investment, a less restrictive open source license (e.g., BSD style) can improve welfare. On the other hand, when the originator is better at leveraging investment and service costs are high, a more restrictive license (e.g., GPL style) can be best for social welfare, even when a contributor can cost efficiently develop the software.

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1 Introduction

Open-source software (OSS) has assumed an increasing role in the operations of businesses and governments. Surveying organizations with either 500 or more employees or revenues in excess of $500 million, the Linux Foundation found that the use of Linux for mission-critical workloads has increased from 60% in 2010 to 73% in 2012 (Linux Foundation 2013). Broadly speaking, businesses indicate that the improved qualities of OSS over the years have now made OSS preferable to proprietary alternatives in many implementation contexts (Noyes 2014). In the public sector, the US Department of Defense has advocated OSS by formalizing their position in the plan, Open Technology Development, which makes openness a priority for both internally developed and externally acquired software (Herz et al. 2006). The UK government recently also indicated a clear preference for OSS in their Government Service Design Manual (Glick 2013). Increasingly, governments have realized that migration to OSS enables a shift in IT "spend" from proprietary products to professional services (Herz et al. 2006).

OSS quality benefits from the efforts and investments of both originators and others who contribute to its development. As an executive of the YMCA states, "*Open source software maintains its high quality by empowering a large number of users from diverse backgrounds with unique perspectives to make frequent updates to improve the value and flexibility of the code*" (Paulnock 2016). Development efforts to improve OSS quality are typically distributed across various, but necessary activities. Ibrahim Haddad, head of the open source innovation group at Samsung Research America suggests that OSS allows Samsung "*to concentrate on aspects of product development where the company can actually distinguish itself*" (King 2014). In a similar vein, Red Hat's CEO James Whitehurst indicates, "*So the innovation, or the original feature development, happens in the open source community. But all of the downstream sustaining engineering, the patching, all of that's what we do*" (Vanian 2016). The open nature of OSS is a mechanism that empowers contributors to significantly increase software quality through updates, patches, and new features, by distributing the cost of development across all contributors who directly benefit from the software's existence (Lakshminarayanan 2014, Columbus 2016). Many of these strategic contributors leverage their investments and established expertise by offering professional services.

In fact, the provision of value-added services has been the primary source of revenue for commercial OSS.[1] Today, Red Hat generates over $1 billion in revenues for subscription-based support services driven mostly by its two flagship products: Red Hat Enterprise Linux and JBoss (McMillan 2012). Cloudera, who provides an open-source distribution of Apache Hadoop called CDH, invests heavily in the open-source projects composing CDH and similarly relies on the services market to generate revenues. Cloudera recently was backed by Intel with a $740 million investment to support its revenue goals (Cohan 2013, Clark 2014).

[1] See, e.g., August et al. (2013) for a discussion of integration, support, and consulting services.

These examples underscore how high-quality software alone often does not benefit an organization unless it is sufficiently integrated with business processes to generate value. For organizations to achieve such higher value-added implementations, they require services and it is the firms who have developed extensive expertise that are in the best position to help, as is the case for Red Hat and Cloudera in their respective markets. While there are many firms who could also provide basic support and services for Linux and Apache Hadoop, the quality associated with obtaining services from firms such as Red Hat and Cloudera is considerably higher due to their substantial investments in developing this expertise.

With the services market, firms have an economically viable business model that can justify investments in the development of OSS, even though the software itself is essentially available for free. For a software originator, an important advantage of pursuing an open-source path is that the quality of its OSS product leverages effort investments from the community, which in turn increases the value derived by its consumers on service contracts. However, some contributors to OSS can also be motivated to invest in development in an effort to gain expertise and compete for these service contracts.[2] Thus, a software originator going open source faces a trade-off between an increase in quality of software and services by leveraging community contributions and an increase in services market competition from these extrinsically-motivated contributors as well as the many providers of basic services packages. Examples of strategic contributors who invest effort and compete for OSS service contracts include: Shadow-Soft (JBoss), Synolia (SugarCRM), Bista Solutions (OpenERP), and Hortonworks (Hadoop)[3]. On the other hand, a software originator could simply pursue a more traditional, proprietary approach where it does not directly benefit from the efforts of third-party developers because of the closedness of the source code, but it can generate revenues by selling copies of the software at a positive price.

From a social perspective, however, there are several benefits associated with a software originator choosing the open-source path. First, the broader participation in software development that characterizes OSS can boost quality significantly while keeping development costs relatively low, distributed costs being more efficiently incurred (Holmstrom and Milgrom 1991). Second, when active contributors to OSS invest in development and expertise, there is greater competition in the services market which can also be beneficial to consumers. Third, in contrast to proprietary software, an originator of OSS does not (practically) have the ability to charge for the software itself, given that it is open and freely downloadable. This additional pricing power retained by a proprietary originator has a negative effect on both consumer surplus and the incentives of potential service providers. Taken altogether, there can be gainful opportunities to substantially increase social welfare if open-source outcomes are encouraged to prevail in certain software

[2]In some cases, contributors to OSS can be large, cost-efficient firms such as HP and IBM. HP has over 2,500 developers working on OSS (Hewlett-Packard 2007), and similarly IBM dedicates vast resources to OSS because their global services divisions generate $58 billion in revenue which exceeds revenues from their software and hardware businesses (IBM 2012).

[3]The originator in the case of Hadoop is now chief architect of Cloudera which competes in the same space.

markets. On the other hand, because of the increased competition it faces in the services market, an originator may have a reduced incentive to invest in development since its return on investment can now be lower. Its reduced investment can lead to lower quality solutions brought to market if not adequately compensated by increased contributions from the community. Therefore, despite the promising benefits associated with OSS, it is critical to understand how the strategic interactions between an OSS originator and contributor ultimately determine market outcomes.

In this paper, our goal is to present insights into how regulation and policy can provide incentives to help stimulate open-source outcomes. The primary factor we focus on in this study is *OSS licensing*. By OSS licensing, we refer to the terms and conditions that govern an OSS product, generally specifying the rules by which an end-user or developer of the software can use, modify, and/or redistribute the software. OSS licenses vary significantly in their level of restrictiveness. The most common broad forms of licensing are GNU GPL (General Public License) and BSD (Berkeley Software Distribution), with GPL being possibly the most popular license employed (Fishman 2004). GPL is based on the notion of "copyleft", which requires that derivative works of the software also adopt the GPL license. Under this license, all code others develop based on the originator's software must be made publicly available, including for the use of the originator. Thus, a GPL-style license is a relatively more restrictive license and gives the originator higher direct benefit from a contributor's efforts. An example of this case is Red Hat's obligatory acceptance of the GPL (Hillesley 2008).

On the other hand, BSD-style licenses are very permissive, placing minimal restrictions on software use and redistribution (Rusin 2008). Under such licenses, contributors are not required to make their code developed based on the originator's code available to the public, instead permitting contributors to retain the rights to their modifications and improvements. Thus, BSD-style licenses are less restrictive, and the originator's benefit from others' contributions is limited relative to that under GPL. PostgreSQL and the Apache Software Foundation are two prominent adopters of this style of license (Montague 2008). A number of other licenses lie between these two extremes such as GNU LGPL (*Lesser* GPL), which eases restrictions on software that only links to binaries of GPL licensed code (Rusin 2008). JBoss, for instance, is licensed under the GNU LGPL (see JBoss 2008).

There are advantages and disadvantages for different licenses. For example, Stewart et al. (2006) explore the impact of OSS license choice on user interest by considering users' perception of the costs and benefits of using the software as well as perceived risks related to legal uncertainties and enforceability. Lerner and Tirole (2005b) point to "hijacking" by commercial software contributors/vendors, i.e., outside contributors utilizing the open software code to develop (and potentially undermine) commercial software for profit under unrestrictive licenses. Among many other factors, our focus in this paper is on the economic incentives. More restrictive licenses provide an advantage to OSS originators who can benefit from subsequent contributors' developments. On the other hand, less restrictive licenses can provide stronger incentives for these contributors to actually make these developments (Fishman 2004). However, because of the strategic nature of contributions, the way licensing affects investments in equilibrium can be difficult to ascertain. Given that commercial firms increasingly invest in and contribute to OSS products, our goal is exploring and focusing on those issues related to the economic incentives to contribute to an OSS project.

In that we study open-source software as motivated by the services market, the level of *service costs* is relevant to the analysis. By service costs, we refer to the variable costs incurred by firms when providing services to customers of the software. These costs can vary considerably depending on the class of software in question. For example, an enterprise resource planning (ERP) or customer relationship management (CRM) system integration would require high service costs because it is typically a time-consuming project involving extensive customization (Hitt et al. 2002). On the other hand, supporting a MySQL implementation as part of an application server stack would involve lower service costs, and providing training and support for productivity tools such as OpenOffice would be even less costly to the provider.

In this paper, we formulate a model to study how service costs and OSS licensing attributes affect a software originator's decision to pursue an open-source development strategy. To develop the originator's choice problem, our model captures the economic incentives of open-source contributors who also compete in the services market and whose strategic effort investment can be seen as both complementary and competitive. Using this model, we study the effects of licensing on the incentives of both the originator and subsequent contributor to invest in the development of OSS. Because whether open-source or proprietary outcomes are realized can greatly impact the total value generated by software to society, we examine welfare considerations in this complex production and service environment and study policy implications for regulators.

The rest of this paper is organized as follows. Section 2 discusses the relevant literature. In Section 3, we formally present the model. Section 4 presents the equilibrium consumer market structure and prices, and studies the originator's selection of open-source license restrictiveness and its implications on welfare and policy. Section 6 offers our concluding remarks. All proofs and technical equilibrium derivations are given in the Online Supplement.

2 Literature Review

The primary contribution of this paper is its examination of how [*i*] *open-source software licensing* impacts the incentives of [*ii*] *profit-motivated OSS contributors* operating in the services market, thereby affecting an OSS originator's [*iii*] *decision to pursue a proprietary or OSS strategy*. Our paper is the first to integrate these three facets into a single model that facilitates an understanding of the role of OSS licensing in enterprise software markets which tend to be driven by services. August et al. (2013) is the first paper to study the source code decision while including contributors with *extrinsic* motivations in the services market who make endogenous investments toward the development of the OSS product and attainment of service-related expertise (i.e., facets [*ii*] and [*iii*]). Therefore, we build upon August et al. (2013) to formally examine how OSS licensing (facet [*i*]) interacts with participants' investments in OSS and subsequently characterize varying parameter regions under which permissive and restrictive licensing schemes can ultimately be beneficial to social welfare.

August et al. (2013) provides a discussion of literature related to facets [*ii*] and [*iii*]. For a deeper exploration of these two facets, we direct the reader to that discussion as well as the following papers: those that model extrinsically motivated OSS firms (see, e.g., Sen 2007, Kumar et al. 2011, August et al. 2013) stem from a broader literature on the economic incentives of open-source developers (see, e.g., Lerner and Tirole 2002, Hars and Ou 2002, Lerner and Tirole 2005a, von Krogh and von Hippel 2006, Roberts et al. 2006, Iansiti and Richards 2006, Mehra et al. 2011, Mehra and Mookerjee 2012, Von Krogh et al. 2012). There is also a growing body of work that studies competition between open-source and proprietary firms (see, e.g., Gaudeul 2004a, Bessen 2006, Casadesus-Masanell and Ghemawat 2006, Sen 2007, Lee and Mendelson 2008, Casadesus-Masanell and Llanes 2011, Cheng et al. 2011, Zhu and Zhou 2012, August et al. 2014). The strategic choice between developing open-source and proprietary software has gathered significant attention in the literature as well (see, e.g., Lerner and Tirole 2005b, Lerner et al. 2006, Haruvy et al. 2008, August et al. 2013, Wen et al. 2016). In particular, August et al. (2013) find that if an originator is sufficiently efficient in development, the licensing decision mainly depends on her ability to harness the contributor's development to improve quality: if the originator is adept at improving the quality of her software/service package by utilizing the contributor's development, then an OSS strategy is optimal, otherwise the originator is better off keeping the software proprietary. They also show that increased contributor efficiency can unexpectedly decrease welfare. This result can manifest when the contributor is highly efficient because if the originator opens up the source code, the originator can be squeezed out of the services market as the contributor uses his development efficiency and strategic pricing to open up a large gap between the overall attractiveness of his offering and that of the originator. In such circumstances, the originator may instead choose a proprietary strategy, which results in lower software and service quality and decreased welfare.

Turning attention to the integration of facet [*i*], when an open-source approach is preferred to a proprietary one, an important question is how restrictive should the open-source license be. West (2003) argues that competing forces of adoption and appropriability make firms choose among proprietary, open source, and hybrid licensing strategies. Hawkins (2004) identifies the primary costs associated with proprietary and open-source development and, through a series of examples, demonstrates when it is optimal to open the code and the conditions under which viral licensing is preferred to public-style licensing. Gaudeul (2004b) concludes that when developer wages are high and costs are low, GPL is preferred although the existence of GPL can hurt social welfare. Asundi et al. (2012) show that firms may choose to release open-source versions of their software products under competition because by doing so they can increase the value of their closed-source product due to enhancements. Sen et al. (2011) model open-source license choice for a project leader when the license affects the incentives of subsequent developers. They find that leaders should adopt less restrictive licenses when significant effort of subsequent developers is required to create derivative works. On the other hand, a more restrictive license is preferred when the effort required is smaller.

There is a rich stream of literature that empirically examines licensing of OSS. Lerner and Tirole (2005b) build a simple model to examine the licensing decision, and empirically find that restrictive licenses like GPL would be unlikely candidates for OSS that runs in proprietary environments. Stewart et al. (2006) study how both licensing and organizational sponsorship influence the success of open-source projects. They find that projects with a non-market sponsor and a nonrestrictive license tend to garner the most user interest, which they demonstrate positively affects development activity. More recent studies examine the relationships between OSS licensing and developer motivations and attitudes (Sen et al. 2009), developer membership and activity characterization (Colazo and Fang 2009), and social influence (Vir Singh and Phelps 2013).

Our paper complements this literature on OSS licensing by theoretically exploring how different licenses affect an originator firm's decision on whether to choose an open-source strategy or proprietary strategy, and how the social value associated with software can be increased by advocating particular licenses. Selecting an open-source strategy has two effects: a complementarity effect and a strategic effect. The complementarity effect stems from the benefits associated with contributions from the community. These benefits can help increase the quality of both the base product as well as the services offered in the market by the originator. The strategic effect stems from strategic contributors who invest effort into the OSS with the intention of competing against the originator for service contracts. The core contribution of our paper is that we are able to characterize the influence of license restrictiveness on development incentives and ultimately on the originator's preferred source code strategy across different economic regimes. In our model, the answer to the licensing question ultimately relates to how licensing impacts the originator's ability to generate revenues in the services market. License restrictiveness sways the investment incentives of contributors which, in turn, modifies the pricing landscape for services. Since our model captures sequential endogenous investment choices and Nash equilibrium pricing strategies for services, it enables us to formally study the influence of cost structure, OSS licenses and preferences on source code strategy.

3 Model

Our model builds on the one presented in August et al. (2013): A software *originator* (o) chooses a source code strategy and price, and how much to invest in a software product she has created. Her first decision in the sequence, ρ, is to choose whether to license the product as a proprietary product (P) or an open-source one (O), i.e., $\rho \in \{P, O\}$. Once this decision has been made, her next decision is how much to invest in effort and development of the software, $e_o \geq 0$, where these improvements to the software product and services incur a convex cost of effort $C_o(e_o) \triangleq \beta_o e_o^2/2$. After the initial investment and development by the originator firm, a follower firm, the *contributor* (c), can also choose to invest $e_c \geq 0$ in the software, with the hope of profiting from providing services associated with the software product, incurring a cost of effort is $C_c(e_c) \triangleq \beta_c e_c^2/2$.[4]

After obtaining the software, in order to effectively operate it and derive value, a customer needs integration and support services. To the customer, the total quality of the software including services depends on the effort invested by the originator and contributor. There is a continuum of consumers defined by the consumer type parameter θ, which is uniformly distributed on $\Theta = [0, 1]$. Consumer type θ indicates the customer's sensitivity to the quality of the software package, including services. A consumer can choose either the originator or contributor to provide the necessary services. In addition, we extend August et al. (2013) to give consumers the option to obtain a base level of service from either a competitive services market or self service, which we denote by b. The base level of service is important to consider because its presence not only captures a significant way that many low-end users obtain open-source integration services, but it also substantially shapes the strategic interaction between the originator and the contributor. A type θ consumer derives value θQ_k if she chooses to obtain services from provider $k \in \{o, c, b\}$, where Q_k is the total quality of the software solution.

The development efforts of the originator and the contributor have two effects. First, they improve the total base quality of the software solution itself, Q_g. We model the effect of the originator and contributor investments on the base software quality as $Q_g \triangleq g_o e_o + g_c e_c$ where $g_o, g_c > 0$ are multipliers capturing the relative impact of each player's effort. The parameters g_o and g_c in our model are associated with the private provision of public good in that they reflect the extent to which private efforts expended build quality into the freely available base product.[5] Public goods tend to be undersupplied by voluntary contributions because of the free-rider problem (Groves and Ledyard 1977). Non-altruistic motivations are

[4]In some contexts, the contributor can be the individual developers who are not profit seeking. We have also considered this case in a later section and analytically shown that profits, social welfare and consumer surplus increase as OSS licensing becomes more restrictive, which is similar to the cases discussed in panels (c) and (d) of Figure 7. Please see the Online Supplement for detailed analysis. We thank an anonymous reviewer for this suggestion.

[5]Typically, the base OSS product is both non-rival and non-excludable, consistent with the nature of a public good (Samuelson 1954).

central to the discussion of the private provision of public goods (Andreoni 1988). In this vein, our work captures how the base OSS product hinges on incentives of the contributing participants to distinguish themselves as experts in the value-added software services market, which we next discuss.

The second effect lies on the quality of firm-specific integration and support services, Q_s. This effect also has two components: First, as a firm invests resources and effort on a software product, it builds expertise and competency in providing integration and services. This boosts the quality of the total software solution the firm provides to customers. Second, a firm's service quality can also be positively impacted by other firms' investments which yield publicly available OSS service support components, utility contributions, and information. Therefore, in general, a firm that spends effort in building expertise may benefit from efforts and investments of all developers. Hence we model the effect of originator and contributor's investments on their respective service qualities as $Q_{so} \triangleq s_{oo}e_o + s_{oc}e_c$ and $Q_{sc} \triangleq s_{co}e_o + s_{cc}e_c$. We employ an additive model. By doing so, we do not assume any complementary but will instead formally demonstrate that originator and contributor efforts can be strategic complements or strategic substitutes (Bulow et al. 1985) in equilibrium. In the broader literature, quality is frequently modeled as a linear function of effort or investment of producers (see, e.g., Radner et al. 1986, Moldovanu and Sela 2001, Kuan 2001, Varian 2004). In many cases, this is a simplifying assumption that is made for tractability and model transparency, without sacrificing the core variable relationships and insights from the model.

The parameters s_{oo}^O and s_{cc}^O represent the accumulation of knowledge, experience and expertise. Dutton and Thomas (1984), building on Levy (1965), aptly categorize learning into two types: autonomous and induced. Autonomous learning refers to the improvements that automatically result from sustained production over a long period of time (Dutton and Thomas 1984. Induced learning refers to specific investments or efforts made by the firm toward improvement. Models of autonomous learning often use cumulative production as a proxy of experience or knowledge (see, e.g., Spence 1981, Fine 1986). Models of induced learning use cumulative investments instead as a proxy (see, e.g., Arrow 1962, Dorroh et al. 1994). Li and Rajagopalan (1998) model both types of learning on productivity and quality in a production environment. The OSS literature reflects the expertise of service providers gained by efforts invested into OSS (i.e., induced learning) in a similar manner. For example, Sen (2007) models the expertise of a support services vendor as reducing the variable cost associated with usability, with quality levels being held fixed. August et al. (2013) model services expertise as an increase in quality for a fixed variable cost, further capturing the service provider's incentives to invest efforts. We similarly capture the impact of induced learning on quality for the strategic players in our model with s_{oo}^O and s_{cc}^O.

The parameters s_{co}^O and s_{oc}^O capture the cross complementarities of strategic project participants as determined by licensing and the governance structures of the OSS project. Such complementarities can exist among firms contributing to OSS production. Specifically, OSS licensing can significantly influence the extent to which an originator can leverage a contributor's efforts towards the originator's total quality. For example, restrictive licenses that require a contributor to fully document and contribute any new functionality back to the OSS project and governance structures that require a contributor to provide unit tests, use cases, and other information can altogether enhance the originator's quality level in the marketplace. This is particularly true for service-related utilities including system administration tools. In a similar fashion, the contributor can also benefit from the originator's efforts to the extent that the governance structures are shaped to empower contributor's in the services market. In Section 4.3, we explore the impact of license restrictiveness on software outcomes.

The magnitudes of coefficients s_{ij} and g_k quantify the relative importance of common quality factors versus firm-specific ones to consumers, which is largely determined by the particular software product market and can change under proprietary and open-source regimes and critically depends on the restrictiveness of the open-source license. When the software is proprietary, it is not open to outside contributions, hence the contributor cannot add to the base software quality nor can the originator benefit from the contributor's efforts and investment, i.e., $g_c^P = 0$ and $s_{oc}^P = 0$. Furthermore, since there is no major factor that would necessarily change how the originator benefits from its own effort between proprietary and open-source cases, we also assume $s_{oo}^P = s_{oo}^O$. Finally, when the consumer obtains a base level of service, i.e., when $k = b$, she does not receive the quality premium associated with obtaining service from an agent who has committed significant resources toward the development of the software and gained expertise. We normalize this quality component to zero, i.e., $Q_{sb} = 0$. The total quality of the software solution, when a customer obtains service from provider $k \in \{o, c, b\}$ is $Q_k = Q_g + Q_{sk}$.

Consumers' usage decisions are made in the last stage, at which point the policy, effort levels, and prices are fixed. If the product is licensed as proprietary, the originator sets a price for the product p^P and a price for her services p_o^P, while a contributor only sets a price for his services offering p_c^P. Under an open-source strategy, the pricing of integration and services still occurs, with the originator and contributor setting their service prices at p_o^O and p_c^O respectively, but the product price is zero (i.e., $p^O = 0$). We denote the marginal cost of providing services with $c > 0$. Under a software license strategy $j \in \{P, O\}$ (Proprietary or Open Source), denote the price charged by a competitive integrator as p_{ci}^j. Then, the unit profit for that integrator is $\pi_{ci}^j = p_{ci}^j - c$. That is, each competitive integrator makes a revenue of p_{ci}^j at a cost of c for an integration service. Under either licensing scenario, the competitive integrators are not differentiated from each other in service quality.[6] Since their services are undifferentiated from one another and there are

[6]By "competitive integrator", we mean any IT human resource who is able to provide basic services on the OSS product but importantly is not involved in the development of the product and its direction (and therefore has not built the extensive expertise that comes from OSS project involvement). A competitive integrator can include (i) small companies that offer basic IT services such as Open Source Architect, a small business in Nevada that provides JBoss consulting services and (ii) individuals hired in house who have basic knowledge of an OSS product. It can even be the case that a large IT consulting company sends out resources for paid help on technologies that they do not possess expert level knowledge of; this being an

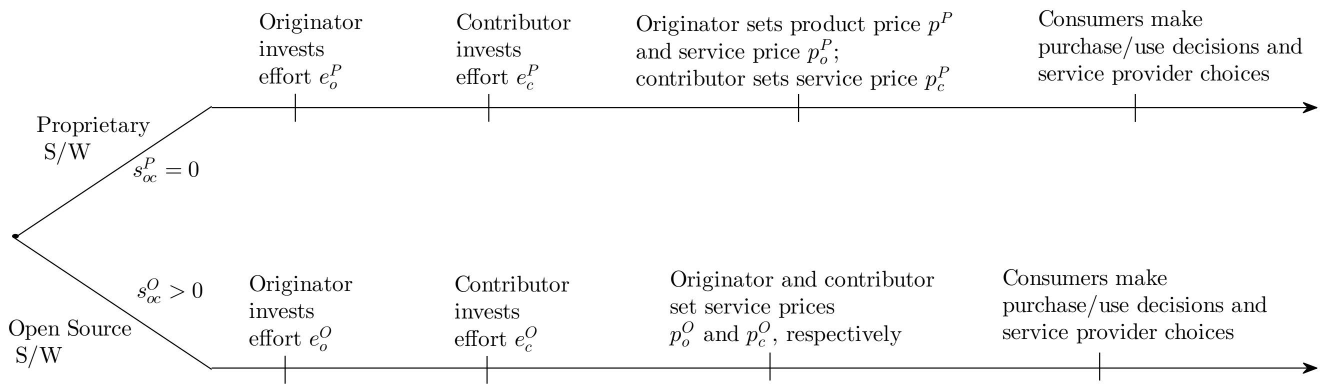

Figure 1: The model timeline in a tree format.

many of them, the competitive integrators engage in perfect price competition, and hence their services are competitively priced at the marginal cost, i.e., $p_b = c$.

In the proprietary case, a consumer with type θ can choose not to use the software product, purchase the product and obtain competitive services, purchase both the product and services from the originator, or purchase the product from the originator and contract with the contributor for services. Her net payoff from each action is given by

$$V^P(\theta) \triangleq \begin{cases} Q_o^P\theta - p^P - p_o^P & \text{if} \quad \text{purchased the software, and contracted service with the originator}\,; \\ Q_c^P\theta - p^P - p_c^P & \text{if} \quad \text{purchased the software, and contracted service with the contributor}\,; \\ Q_b^P\theta - p^P - c & \text{if} \quad \text{purchased the software, and contracted service with a competitive integrator}\,; \\ 0 & \text{if} \quad \text{not purchased}\,. \end{cases} \tag{1}$$

In the open-source case, the price of the software itself is zero, and the net payoff for a consumer with type θ is

$$V^O(\theta) \triangleq \begin{cases} Q_o^O\theta - p_o^O & \text{if} \quad \text{contracted service with the originator}\,; \\ Q_c^O\theta - p_c^O & \text{if} \quad \text{contracted service with the contributor}\,; \\ Q_b^O\theta - c & \text{if} \quad \text{contracted service with a competitive integrator}\,; \\ 0 & \text{if} \quad \text{not used}\,. \end{cases} \tag{2}$$

In summary, the model timeline is as given in Figure 1.

Two industry structures commonly observed in practice can be characterized by specific relationships between fundamental parameters of the model. A *strong originator* would be characterized by high β_c and s_{oc}^O ($\beta_o \ll \beta_c$ and $s_{co}^O \ll s_{oc}^O$), i.e., the originator is relatively more cost efficient and can strongly leverage the effort exerted by any subsequent contributor. These conditions reflect that the originator has better resources for both developing the software at a lower cost and harnessing the contributions of others, in

unfortunately common occurrence in practice (Markon and Crites 2013).

comparison to the outside contributor.[7] On the other hand, a *strong contributor* would be characterized by low β_c and s^O_{oc} ($\beta_c \ll \beta_o$ and $s^O_{oc} \ll s^O_{co}$), i.e., the contributor has the resources to be adept at developing the software at a lower cost as well as leveraging the effort invested in the project by others toward its own benefit. This often happens when the main outside contributor is a bigger and more powerful firm than the originator.[8] These labels will refer to these mathematical conditions and be used in Section 4.3.

4 Licensing Policy Analysis

In this section, we give an overview of the equilibrium derivation for the two licensing strategies, Proprietary (Section 4.1) and Open-Source (Section 4.2). The technical derivations are given in full detail in the Online Supplement.

4.1 Proprietary Licensing Equilibrium Characterization

The analysis of the equilibrium is by backward induction. Given the effort levels, e^P_o and e^P_c, and prices, p^P, p^P_o and p^P_c, as fixed, each consumer of type $\theta \in \Theta$ chooses an action that maximizes her net payoff given in (1) which reflects the choices she has for obtaining services. Lemma EC.2 in the Online Supplement presents the structure of the consumer market equilibrium in the final stage.

After the effort levels and hence the service quality levels are set, projecting the customers' responses to the prices as described above, the originator and the contributor set their prices. The originator sets p^P and p^P_o to maximize her final stage profit function. Her corresponding optimization problem can be formulated as

$$\max_{p^P, p^P_o} \quad \breve{\Pi}^P_o(p^P, p^P_o \,|\, p^P_c, e^P_o, e^P_c) \triangleq p^P \int_\Theta \mathbf{1}_u(\theta) d\theta + \left(p^P_o - c\right) \int_\Theta \mathbf{1}_o(\theta) d\theta \,. \tag{3}$$

The contributor's profit maximization problem at this stage is

$$\max_{p^P_c} \quad \breve{\Pi}^P_c(p^P_c \,|\, p^P, p^P_o, e^P_o, e^P_c) \triangleq \left(p^P_c - c\right) \int_\Theta \mathbf{1}_c(\theta) d\theta \,. \tag{4}$$

[7] Such cases usually happen when the originator is a relatively big and established firm compared to the major outside contributors. One open source project that fits well with this characterization is JBoss application server. The JBoss project was started in 1999 and quickly became a force in the middleware market with an entirely services-based business model (Kerstetter 2004). JBoss Inc. harnessed the open source developer community well, becoming the leading services provider of the open source product and maintaining tight control over the project's evolution.

[8] An example for this case is the Apache Software Foundation (ASF) project, *Geronimo*. Geronimo is an open source application server that was founded by members of the ASF. One company that offers services related to many ASF open source projects including Geronimo is Covalent Technologies, which employs some of the founders of Geronimo. However, IBM dedicates a significant amount of resources to the Geronimo project due to its own acquisition of Gluecode and interest in providing services to the lower tier of the application server market, and IBM is the most prominent development leader for the project. In this case, the contributor (IBM) is the more cost-efficient entity who can strongly leverage the originator's effort, while the originator tends to provide services to a smaller market.

Solving (3) and (4) simultaneously gives rise to Nash equilibrium product and service prices. The following lemma summarizes the equilibrium outcome in the pricing stage.[9]

Lemma 1 *Let e_o^P and e_c^P be fixed, and $\max(Q_o, Q_c) \geq c$. The equilibrium prices, p^P, p_o^P and p_c^P, satisfy:*

Region I: If $Q_c > Q_o > Q_b$ and $Q_o \leq 3c$, then

$$p^P = \frac{Q_c(Q_c - c)}{3Q_c - Q_o}\,, \quad p_o^P = \frac{(Q_o + Q_c)c - (Q_c - Q_o)^2}{3Q_c - Q_o}\,, \quad p_c^P = \frac{Q_c(Q_c - Q_o + 2c)}{3Q_c - Q_o}\,, \tag{5}$$

and only the originator and the contributor are active in the services market.

Region II: If $Q_c > Q_o > Q_b$ and $Q_o > 3c$, then

$$p^P = \frac{2Q_c + Q_o - 3c}{6}\,, \quad p_o^P = c - \frac{Q_c - Q_o}{3}\,, \quad p_c^P = c + \frac{Q_c - Q_o}{3}\,, \tag{6}$$

and only the originator and the contributor are active in the services market.

Region III: If $Q_o \geq Q_c \geq Q_b$, then

$$p^P = \frac{Q_o - c}{2}\,, \quad p_o^P = c\,, \quad p_c^P = c\,, \tag{7}$$

and only the originator is active in the services market.

Lemma 1 states that for any given effort levels, under a proprietary license, in equilibrium, competitive integrators are pushed out of the services market, and only the firms who invest in building expertise in the software are active in selling services. The competitive integrators, who have not invested and hence are not differentiated in quality, provide service at the base quality level at the unit price equaling to marginal cost c. In comparison, larger firms who invested and improved their service quality can charge prices higher than the marginal service cost since their quality levels generate additional value for the customers. If the high quality options are priced sufficiently low, it can be the case that no customer finds it preferable to procure service from the competitive integrators, as better quality service at a good price is available. Given this, in certain cases, the originator and the contributor firms may choose in equilibrium to lower their prices so much that there is zero demand for purchasing services from the competitive integrators. Such equilibrium outcomes, called limit pricing, are common in models of price competition (please see, e.g., Bain 1949, Modigliani 1958, Gabszewicz and Thisse 1979, Tunca and Wu 2013). In particular, and different from prior studies on software competition, Lemma 1 demonstrates that for the proprietary license case, limit pricing is likely to occur because the originator has additional pricing power when base software and value-added services are priced separately. The originator charges both a price p^P for the product

[9]For simplicity in exposition and to avoid trivialities, in Lemmas 1 and 2 we focus only on the parameter regions that are relevant to the full game equilibrium.

and a price for her services p_o^P, while a contributor only sets a price for his services offering p_c^P. Because the contributor is a strategic player, he can invest effort to differentiate the quality of his offering and be active in the market. However, the competitive integrators do not invest effort toward differentiation. Therefore, an originator can utilize the additional price lever, p^P, effectively as a limit price to push them out of the market while still using its service price, p_o^P, to extract surplus. As stated in Regions I and II, if the contributor has a higher service quality, then the originator and the contributor share the services market. However, if the originator has a higher quality (Region III), she can use her flexibility to price the product itself as well as the software services she provides to push the contributor out of the market and become a monopolist.

At the investment stage, taking the equilibrium price formation given in Lemma 1 into account, the contributor chooses an effort level, $e_c^P(e_o^P)$, that maximizes his total profit function, $\Pi_c^P(e_c^P|e_o^P) = \breve{\Pi}_c^P(e_c^P|e_o^P) - C_c(e_c^P)$, where $\breve{\Pi}_c^P$ is as given in (4) after observing the originator's effort investment level. Considering this optimal contributor effort characterization, $e_c^P(e_o^P)$, the originator sets an effort level to maximize her own total profits, $\Pi_o^P(e_o^P) = \breve{\Pi}_o^P(e_o^P) - C_o(e_o^P)$, where $\breve{\Pi}_o^P$ is as given in (3). Formally, let $\vec{p} = (p^P, p_o^P, p_c^P)$, which reflects the equilibrium prices as functions of effort levels. The originator solves

$$
\begin{aligned}
\max_{e_0^P \geq 0} \quad & \Pi_o^P(e_o^P) = p^P \int_\Theta \mathbf{1}_u(\theta, \vec{p}, e_o^P, e_c^P(e_o^P))d\theta + \left(p_o^P - c\right) \int_\Theta \mathbf{1}_o(\theta, \vec{p}, e_o^P, e_c^P(e_o^P))d\theta - \beta_o(e_o^P)^2/2 \\
\text{s.t.} \quad & \vec{p} \text{ solves (3) and (4) given } e_o^P, e_c^P(e_o^P) \text{ as characterized in Lemma 1;} \\
\text{and} \quad & e_c^P(e_o^P) = \underset{e_c^P \geq 0}{\operatorname{argmax}}\, \Pi_c^P(e_c^P|e_o^P) = \underset{e_c^P \geq 0}{\operatorname{argmax}} \left\{ \left(p_c^P - c\right) \int_\Theta \mathbf{1}_c(\theta, \vec{p}, e_o^P, e_c^P)d\theta - \beta_c(e_c^P)^2/2 \right\} \\
& \qquad\qquad \text{s.t. } \vec{p} \text{ solves (3) and (4) given } e_o^P, e_c^P \text{ as characterized in Lemma 1.}
\end{aligned}
\tag{8}
$$

For convenience in notation, we use Π_o^P and Π_c^P to refer to the equilibrium payoffs of the originator and the contributor under the proprietary strategy. The related equilibrium derivations are given in the Online Supplement.[10] In the resulting equilibrium, the originator and the contributor may form a duopoly in the services market, or the originator may emerge as the exclusive service provider.

4.2 Open Source Licensing Equilibrium Characterization

The analysis of the equilibrium is similar to the proprietary case and again proceeds by backward induction. The main difference is that when the software is licensed as open source, the originator cannot charge a price for the software itself and both firms aim to make profits purely from service provision. Given effort levels, e_o^O and e_c^O, and service prices, p_o^O and p_c^O, each consumer of type $\theta \in \Theta$ chooses an action that maximizes her net payoff given in (2) which reflects the choices she has for obtaining services. Lemma EC.3 in the Online Supplement presents the structure of the consumer market equilibrium in the final

[10] See Lemmas 1 and EC.2 in the Online Supplement.

stage.

At the pricing stage, again projecting the consumer market equilibrium as described above and given the development effort levels e_o^O and e_c^O, the originator and the contributor's respective optimization problems are

$$\max_{p_o^O} \quad \breve{\Pi}_o^O(p_o^O \,|\, p_c^O, e_o^O, e_c^O) \triangleq \left(p_o^O - c\right) \int_\Theta \mathbf{1}_o(\theta) d\theta \,, \tag{9}$$

and

$$\max_{p_c^O} \quad \breve{\Pi}_c^O(p_c^O \,|\, p_o^O, e_o^O, e_c^O) \triangleq \left(p_c^O - c\right) \int_\Theta \mathbf{1}_c(\theta) d\theta \,. \tag{10}$$

The firms compete in the services market by solving (9) and (10), which gives rise to Nash equilibrium prices. The pricing equilibrium outcome is summarized in the next lemma.

Lemma 2 *Given $Q_i > Q_j > Q_b$ and $Q_i > c$ where i denotes the higher quality provider between the Originator (o) and Contributor (c) and j denotes the remaining one, let $\vec{Q} = (Q_i, Q_j, Q_b)$. There exist threshold values $0 \le \tau_A(\vec{Q}) \le \tau_B(\vec{Q}) \le Q_j/2 \le \tau_C(\vec{Q})$[11] such that*

Region I: If $c \le \tau_A(\vec{Q})$, then

$$p_i^O = c + \frac{2(Q_i - Q_b)(Q_i - Q_j)}{4(Q_i - Q_b) - (Q_j - Q_b)}, \qquad p_j^O = c + \frac{(Q_j - Q_b)(Q_i - Q_j)}{4(Q_i - Q_b) - (Q_j - Q_b)}, \tag{11}$$

and the originator, contributor and competitive integrators are active in the services market.

Region II: If $\tau_A(\vec{Q}) < c \le \tau_B(\vec{Q})$, then

$$p_i^O = \frac{Q_i - Q_j}{2} + \frac{c(Q_j + Q_b)}{2Q_b}, \qquad p_j^O = \frac{cQ_j}{Q_b}, \tag{12}$$

and only the originator and contributor are active in the services market.

Region III: If $\tau_B(\vec{Q}) < c \le Q_j/2$, then

$$p_i^O = \frac{Q_i(2(Q_i - Q_j) + 3c)}{4Q_i - Q_j}, \qquad p_j^O = \frac{Q_j(Q_i - Q_j) + c(2Q_i + Q_j)}{4Q_i - Q_j}, \tag{13}$$

and only the originator and contributor are active in the services market.

Region IV: If $Q_j/2 < c \le \tau_C(\vec{Q})$, then $p_i^O = \frac{cQ_i}{Q_j}$, $p_j^O = c$, and only the higher quality of the originator and contributor is active in the services market.

Region V: If $c > \tau_C(\vec{Q})$, then $p_i^O = \frac{Q_i + c}{2}$, $p_j^O = c$, and only the higher quality of the originator and contributor is active in the services market.

[11] Full characterizations of $\tau_A(\vec{Q})$, $\tau_B(\vec{Q})$, $\tau_C(\vec{Q})$ are given in the proof of Lemma 2 in the Online Supplement.

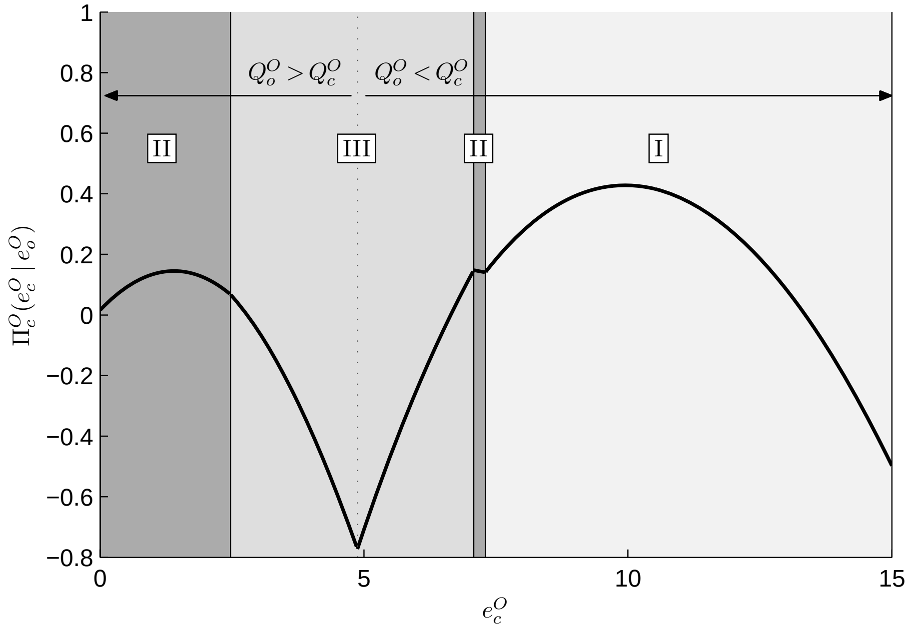

Figure 2: The nature of the contributor's profit curve. Region labels match the distinct consumer market structures identified in Lemma 2. The parameter values are $e_o^O = 2.5$, $g_o = 3$, $g_c = 3$, $s_{oo}^O = 4$, $s_{oc}^O = 1$, $s_{cc}^O = 3$, $s_{co}^O = 0.1$, $c = 2$, $\beta_o = 0.3$, and $\beta_c = 0.065$.

As can be seen in Lemma 2, under an open-source license, depending on the level of service costs, c, there can be five different market structures in the pricing equilibrium. First, if the service costs are low, i.e., in Region I, the potential net value from services in the market is high, and in equilibrium the providers can profitably target distinct consumer segments with their pricing. As a result, all three service providers (the originator, contributor, and competitive integrators) will be actively present as a three-way *oligopoly* in the market. In Regions II and III, as the service cost increases, the consumer population, for which the value from services is higher than the service costs to have net positive value for using the software, shrinks. Consequently, the originator and the contributor have to price their services closer to marginal cost c. This tight pricing squeezes the competitive integrators who provide inferior quality service at marginal cost out of the market. The market structure becomes a *duopoly* between the originator and contributor. Finally, in Regions IV and V, the service costs are so high that the profitable consumer segment becomes small. Then, in equilibrium, there is room for only one firm to operate profitably, and the higher quality one between the originator and contributor prices out the other two options and becomes a *monopoly* in the services market.

Using the equilibrium service price characterization given in Lemma 2, we can again analyze the sequential effort investment problems for both the originator and contributor. Similar to the proprietary software case, taking the effort level of the originator e_o^O as fixed, the contributor chooses $e_c^O \geq 0$ to maximize $\Pi_c^O(e_c^O|e_o^O) = \breve{\Pi}_c^O(e_c^O|e_o^O) - C_c(e_c^O)$. Taking this contributor effort best response, $e_c^O(e_o^O)$, the originator chooses $e_o^O \geq 0$ to maximize $\Pi_o^O(e_o^O) = \breve{\Pi}_o^O(e_o^O) - C_o(e_o^O)$, where $\breve{\Pi}_o^O$ and $\breve{\Pi}_c^O$ are as given in (9) and (10),

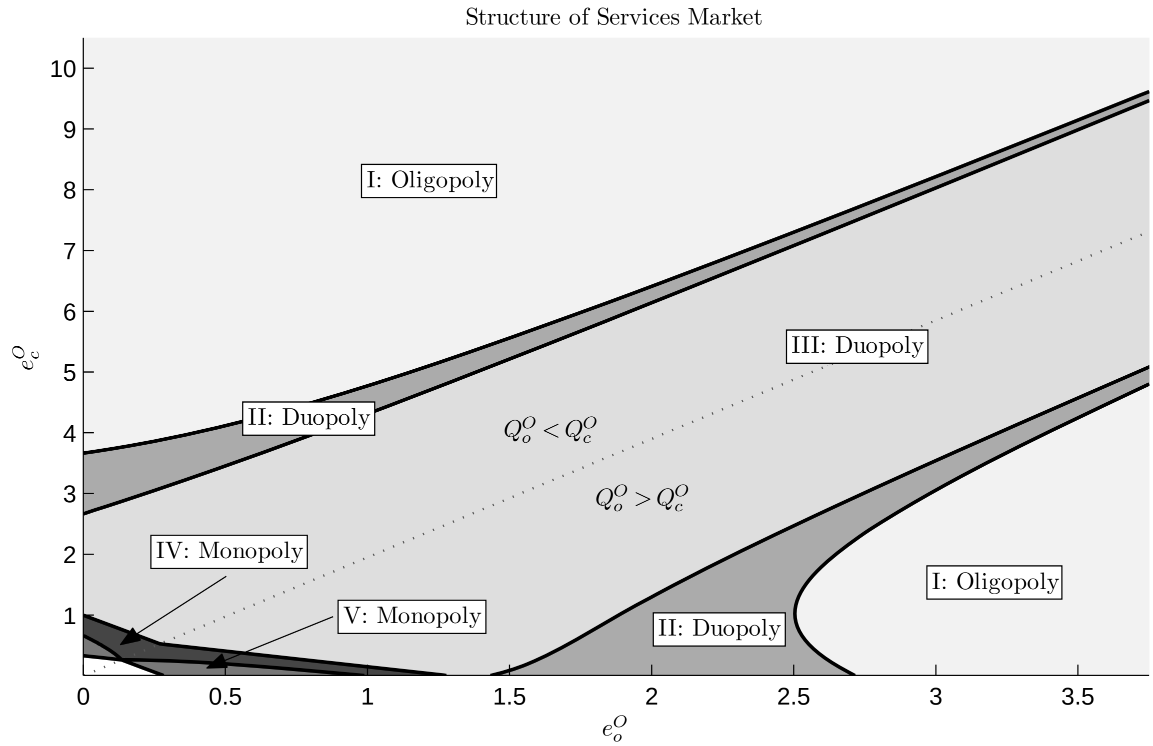

Figure 3: Market structure and firms' effort investments. Region labels indicate whether one, two, or three firms have positive market shares in the services market. The parameter values are $g_o = 3$, $g_c = 3$, $s_{oo}^O = 4$, $s_{oc}^O = 1$, $s_{cc}^O = 3$, $s_{co}^O = 0.1$, $c = 2$, $\beta_o = 0.3$, and $\beta_c = 0.065$.

respectively. Formally, let $\vec{p} = (p_o^O, p_c^O)$. The originator solves

$$\begin{aligned}
\max_{e_o^O \geq 0} \quad & \Pi_o^O(e_o^O) = \left(p_o^O - c\right) \int_\Theta \mathbf{1}_o(\theta, \vec{p}, e_o^O, e_c^O(e_o^O)) d\theta - \beta_o (e_o^O)^2/2 \\
\text{s.t.} \quad & \vec{p} \text{ solves (9) and (10) given } e_o^O, e_c^O(e_o^O) \text{ as characterized in Lemma 2;} \\
\text{and} \quad & e_c^O(e_o^O) = \operatorname*{argmax}_{e_c^O \geq 0} \Pi_c^O(e_c^O | e_o^O) = \operatorname*{argmax}_{e_c^O \geq 0} \left\{ \left(p_c^O - c\right) \int_\Theta \mathbf{1}_c(\theta, \vec{p}, e_o^O, e_c^O) d\theta - \beta_c (e_c^O)^2/2 \right\} \\
& \qquad\qquad \text{s.t. } \vec{p} \text{ solves (9) and (10) given } e_o^O, e_c^O \text{ as characterized in Lemma 2.}
\end{aligned} \tag{14}$$

Again for convenience in notation, we use Π_o^O and Π_c^O to refer to the equilibrium payoffs of the originator and contributor under the opens-source strategy.

Figures 2 and 3 illustrate the equilibrium investment decisions, e_o^O and e_c^O, for the originator and the contributor and their effects on the resolution of the rest of the game. In particular, Figure 2 depicts the contributor's decision problem by tracing how his profit function changes as a function of his development effort level e_c^O given the originator's investment level e_o^O. The market structure labels are as given in Lemma 2 for open-source licensing. Since in the figure the originator has sufficient committed investment in the software, the overall starting software quality is high even with zero investment from the contributor. Therefore, at small e_c^O, there is enough value for the consumers in the market that the originator and contributor can coexist as a duopoly (Region II) with the originator having a higher service quality.

As the contributor invests more in developing the software, after a certain point, the service qualities for the originator and the contributor become closer and price competition between the two firms intensifies, resulting in lower profits for both firms. Beyond a certain investment level e_c^O, the contributor becomes the quality leader. However, as the contributor investment level increases, the overall software quality becomes high enough that competitive integrators can have a segment of the service market; the market structure becomes a three-way oligopoly as can be seen in the figure (Region I). In this region, the contributor is the highest quality service provider and his overall profits are maximized by choosing a high investment level that induces a market structure where all three service options are actively present in equilibrium.

Figure 3 demonstrates the regions for the equilibrium service market structure. As can be seen in the figure, when both the contributor's and originator's investment levels are very low (in the lower left corner of the figure with white background), the software does not have sufficient quality to generate net value from service so there are no users of the software – the product does not make it to the market. As either the contributor's or originator's investment increases, the overall software solution starts to have net positive value. However, for small investment levels, the quality of the total software solution is low and the providers cannot charge a high price for their services. As a result, there is room for only one provider in the market–the overall quality leader–and he or she prices both the lower quality developer and the competitive integrators out of the market, becoming a monopolist for services (Regions IV and V).

On the other end of the spectrum, if one of the developer firms has significantly higher quality than the other two options (i.e., either the originator or the contributor invest heavily and one significantly more so than the other), then both providers will have sufficient value and the quality leader will achieve sufficient separation from the other firm. In this case, all three service options o, c and b can have their own distinct customer segments, actively contracting in equilibrium and the market structure will be a three-way oligopoly (Region I). In the middle, however, when the originator's and contributor's investments are close to one another, the service offerings of the two firms are close substitutes and intense price competition emerges. In that case, the equilibrium prices of the two higher quality service providers (o and c) drop low enough that the competitive integrators are priced out of the market, resulting in a duopoly (Regions II and III).

The general structure of the equilibrium regions in Figure 3 is robust. In fact, as the parameters change, the layout of the regions stay the same but the picture can sway in two main ways, which are displayed in Figure 4. First, if the originator becomes stronger by, for instance, having an improved ability to benefit from the contributor's development efforts (higher s_{oc}^O), then when the contributor invests in development at a high level (i.e., for high e_c^O levels) the two firms can push the competitive integrators out of the market more easily and achieve duopoly (Regions II and III) where the contributor is the product quality leader. As a result, for the same investment levels, Region I in the upper quadrant, (i.e., where

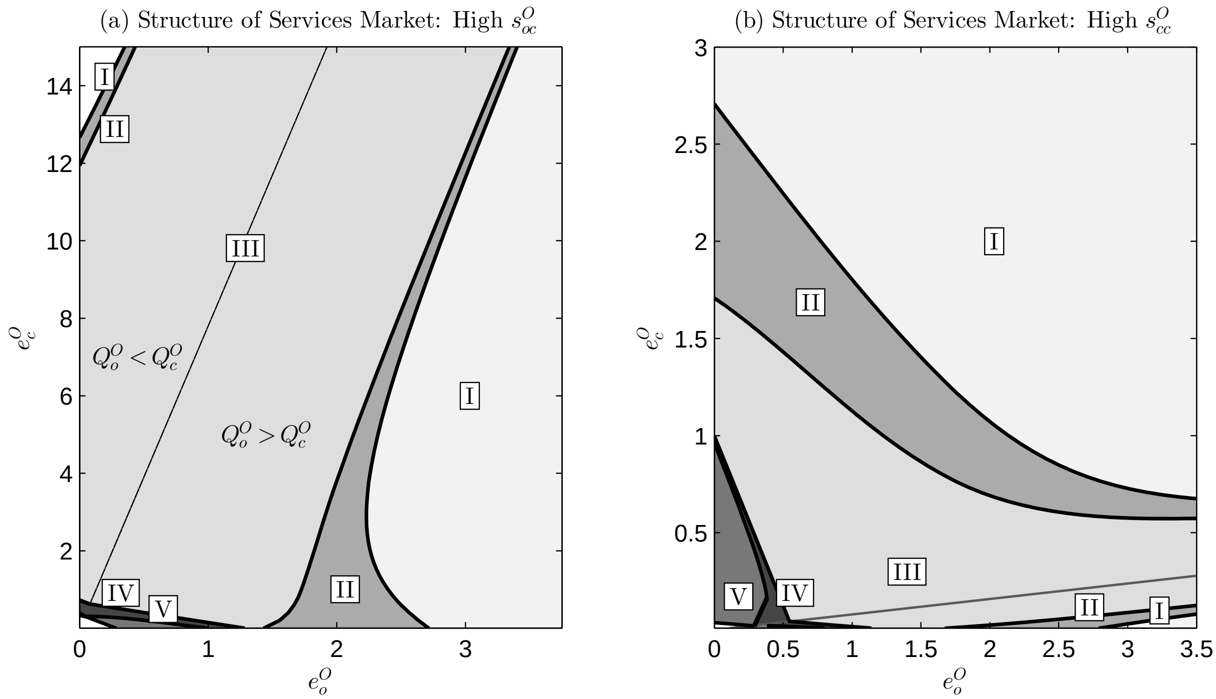

Figure 4: The parameter values are $g_o = 3$, $g_c = 3$, $s_{oo}^O = 4$, $s_{oc}^O = 2.5$ for panel (a) and $s_{oc}^O = 1$ for panel (b), $s_{cc}^O = 3$ for panel (a) and $s_{cc}^O = 50$ for panel (b), $s_{co}^O = 0.1$, $c = 2$, $\beta_o = 0.3$, and $\beta_c = 0.065$. The market structure labels, I, II, III, IV and V, are the same as those in Figure 3.

$Q_o^O < Q_c^O$) shrinks and is replaced mainly by Region III, as can be seen in panel (a) of the figure, i.e., the pattern sways counter-clockwise. On the flip side, if the contributor becomes stronger by, for instance by improved ability to benefit from his own effort (higher s_{cc}^O), then for the same investment levels the contributor quality moves up, and the competitive integrators are more easily pushed out of the market for the cases in which the originator is the quality leader. Therefore, the region where the market structure is oligopoly (Region I) shrinks for $Q_o^O > Q_c^O$. However, if the contributor is the quality leader, higher s_{cc}^O results in an increased quality gap between the contributor and the originator, which allows the lower quality competitor, namely the originator to increase his price. This increase relieves pressure on the low cost competitive integrators and allows them to survive, resulting in a three-provider oligopoly (Region I) replacing duopoly (Regions II and III) for $Q_o^O < Q_c^O$. Consequently, in this case the pattern of the market structures sways clockwise as can be seen in panel (b) of Figure 4.

4.3 Impact of Open-Source Licensing Policy

In this section, we explore the impact of license restrictiveness and project organization on profitability and social welfare and discuss under which conditions each style of license is better suited. Social welfare is the sum of consumer surplus and the profits of the firms in the market. Consumer surplus for a given licensing policy $\rho \in \{P, O\}$, CS^ρ, is

$$CS^\rho = \int_\Theta \mathbf{1}_o(Q_o\theta - p^\rho - p_o^\rho)d\theta + \int_\Theta \mathbf{1}_c(Q_c\theta - p^\rho - p_c^\rho)d\theta + \int_\Theta \mathbf{1}_b(Q_b\theta - c)d\theta\,. \tag{15}$$

Substituting into the profit expressions (3), (4), (9), and (10), social welfare then is given by

$$\begin{aligned} W^\rho &= CS^\rho + \Pi_o^\rho + \Pi_c^\rho \\ &= CS^\rho + \breve{\Pi}_o^\rho - C_o(e_o^\rho) + \breve{\Pi}_c^\rho - C_c(e_c^\rho) \\ &= \int_\Theta \mathbf{1}_o(Q_o\theta - c)d\theta - C_o(e_o^\rho) + \int_\Theta \mathbf{1}_c(Q_c\theta - c)d\theta - C_c(e_c^\rho) + \int_\Theta \mathbf{1}_b(Q_b\theta - c)d\theta\,. \end{aligned} \tag{16}$$

In our model, the parameter s_{oc}^O captures the contributor-to-originator cross complementarity of effort investment on the originator's offering and reflects the restrictiveness of the open-source license. Under more restrictive licenses, the originator can reap the benefits of the contributor's effort, and, hence, this type of license is characterized by a high value of s_{oc}^O. Under more permissive licenses, since the contributor can keep his software developments from the public, the originator benefits less from the contributor's effort. Hence, this style of license corresponds to a low value of s_{oc}^O. In practice, there are only a few categories of licenses available which vary in their strength of restrictiveness. In many cases, a new OSS project may rely on the components of existing OSS projects which significantly constrains OSS license selection for the new project. As an example, if an originator's OSS project utilizes even one component governed by the GPL, then her OSS project necessarily must also be GPL. For these reasons, we parameterize license restrictiveness and the following table gives an overview of this perspective that we will be employing in this section.

Table 1: The relative magnitude of s_{oc}^O across different licensing scenarios

Low s_{oc}^O	Medium s_{oc}^O	High s_{oc}^O
Permissive licenses	Partially Restrictive licenses	Restrictive licenses
Non-copyleft	Weak copyleft	Copyleft / reciprocal
Minimal requirements	Exceptions granted when only linking	All derivative works inherit license
Ex. BSD, MIT, Apache	Ex. LGPL, MPL	Ex. GNU GPL, GNU AGPL

We begin by exploring the potential desirability of a less restrictive license for an originator and its effect on developer effort levels, product quality, and welfare. From a software originator's point of view, a restrictive license is preferable to a permissive one in many respects. For example, a restrictive license can maximize the returns an originator receives from the developments of subsequent contributors to the project. An open question then is whether it is possible for a permissive license to actually be preferred by a software originator. The following proposition explores this question.

Proposition 1 *When a strong contributor's efforts benefit its own firm-specific quality component to a greater extent than the originator's, a less restrictive license can increase originator profits and social welfare. Technically, let* $4/9 < s_{oc}^O / s_{cc}^O < 1$*. Then there exists* $\bar{\beta} > 0$ *such that if* $\beta_c < \bar{\beta}$*, then the contributor is the quality leader, i.e.,* $Q_c > Q_o$*, and*

(i) A less restrictive license increases the quality gap, the originator's profits and social welfare, i.e., if s_{oc}^O *decreases then* $Q_c - Q_o$*,* Π^O*, and* W^O *increase;*

(ii) Define $\bar{r} = 40/(37 + \sqrt{2169})$*. If* $s_{oc}^O / s_{cc}^O < \bar{r}$*, then there exists* $\underline{\gamma} > 0$ *such that a less restrictive license decreases consumer surplus if and only if* $g_c < \underline{\gamma}$*. If* $s_{oc}^O / s_{cc}^O > \bar{r}$*, then a less restrictive license increases consumer surplus.*[12]

Proposition 1 makes an interesting observation: Despite the fact that a permissive license can limit the benefits that a software originator who chooses to go open source can reap from her product, it can still be the case that the originator selects an open approach as her licensing style. This result emerges from strategic considerations. Specifically, when the contributor is cost efficient in development, he has the potential to improve the overall quality of the product both for himself and the originator. However, if the license is too restrictive and requires the contributor to make his developed code publicly available (i.e., if s_{oc}^O is high), the originator benefits in quality and then uses it to more effectively compete against the contributor in the services market. On the other hand, if the license is less restrictive, the total quality of the contributor's offering may exceed that of the originator. Further, in such a case, as stated in part (i) of Proposition 1, a less restrictive license increases the quality difference between the contributor's and the originator's service quality levels, since it results in the originator benefiting less from the contributor's investments. Yet, even in such a case, the originator can increase her profit by differentiating from the contributor, serving a lower valuation consumer segment, and avoiding intense competition against the contributor. In this case, under a restrictive license, the complementarity effect is dominated by the strategic effect and the price competition in the services market becomes too intensive. However, under a less restrictive license, the complementarity effect dominates the strategic effect because it enables the contributor to become the quality leader which, in turn, enables the originator to benefit from contributions while providing services in a less competitive market. Hence, a less restrictive license, such as LGPL, can indeed benefit the originator's profits as stated in part (i) of Proposition 1, even though the originator sacrifices being the quality leader in equilibrium. Moreover, provided that the effects of the contributor's efforts on improving *common* quality factors are appreciable, a permissive license is not only more profitable to the originator but can also improve welfare by boosting developer efforts and improving overall software quality offered to consumers.

[12] The closed form expression of $\underline{\gamma}$ is given in the proof provided in the Online Supplement.

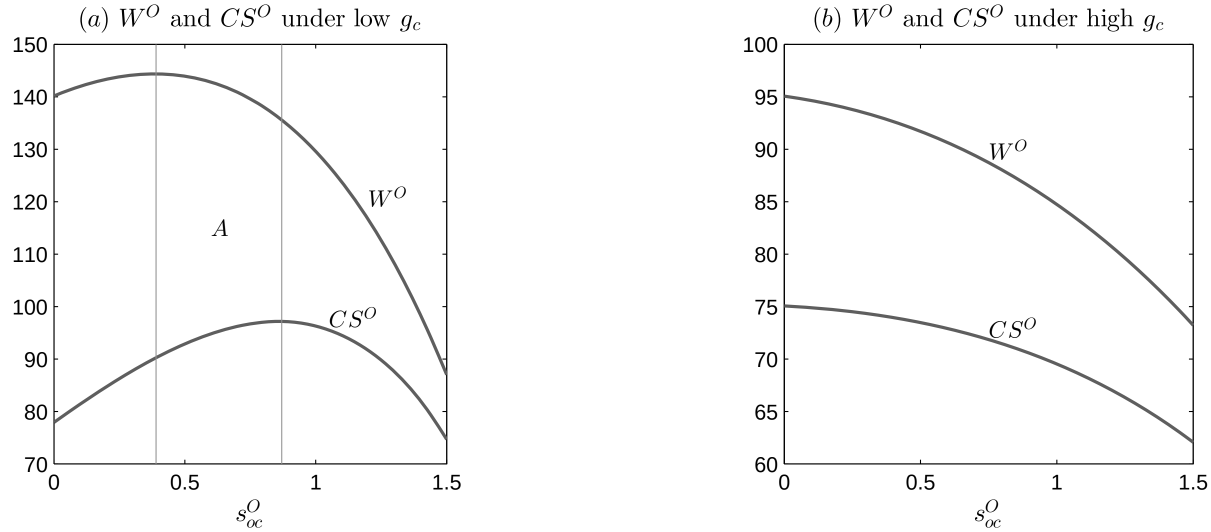

Figure 5: Social Welfare and Consumer Surplus with respect to s^O_{oc}. The parameter values for panel (a) are $g_o = 1$, $g_c = 0.1$, $s^O_{oo} = 2$, $s^O_{cc} = 2$, $s^O_{co} = 0.1$, $s^P_{co} = 0.05$, $s^P_{cc} = 0$, $c = 0.1$, $\beta_o = 0.1$, and $\beta_c = 0.002$. The parameter values for panel (b) are $g_o = 0.1$, $g_c = 1$, $s^O_{oo} = 2$, $s^O_{cc} = 2$, $s^O_{co} = 0.5$, $s^P_{co} = 0.5$, $s^P_{cc} = 0$, $c = 0.01$, $\beta_o = 0.1$, and $\beta_c = 0.006$.

It is important to note that consumer surplus does not always go hand in hand with social welfare. Part (ii) of Proposition 1 states that when the contributor's impact on the base software quality is less pronounced, choosing a less restrictive (i.e., low s^O_{oc}) license, can hurt consumer surplus despite increasing social welfare. This is because when the license becomes less restrictive and the contributor is strong, as explained above, the originator allows the contributor to become the quality leader in the services market, and in order to differentiate her service quality from that of the contributor's, she does not invest in quality improvement much. As a consequence, the service quality increases but price competition between the two firms in the services market is less intense and the consumers face higher prices. In addition, if the firm that makes the main investment (i.e., the contributor) does not have a strong impact in improving the base software quality (i.e., if g_c is small), then the originator's overall quality does not sufficiently improve to compensate for the higher prices the consumers face. Therefore, the net effect is that consumer surplus suffers. At the same time, the firm profits increase as a result of increased prices; the firm reaps the benefits of improved service quality, which can result in increased total welfare. This can also be seen in panel (a) of Figure 5. As the figure demonstrates, there is a wide range of s^O_{oc} values (marked as range A), for which decreased open-source license restrictiveness (lower s^O_{oc}) can decrease consumer surplus while increasing total welfare.

Under these conditions, when the contributor is stronger than the originator of the product, a social planner who weighs consumer surplus higher than firm profits may choose to impose regulations to strengthen open-source licensing restrictions, despite the fact that such action would reduce the overall social value generated by the software. Consistent with the mission of the FTC, it is important to address market situations like this one where a firm becomes relatively too strong and leverages its market power to leave consumers in a manner that is worse off (FTC 2017). Our work advises regulating bodies like the FTC to determine promising ways forward that help protect consumer surplus under such circumstances. One way is to advocate that OSS originators structure project governance to ensure that project contributors commit sufficient code to *common* code bases so that the impact of license restrictiveness on consumer surplus and social welfare is well aligned. In particular, if the contributor's impact on base software quality is high enough, this pushes the overall product quality up and compensates for the higher prices paid by the consumers, and both consumer surplus and social welfare can increase together with decreased open-source license restrictiveness, as stated in the proposition and can be seen in panel (b) of Figure 5.

Since permissive licenses increase the incentives for contributors to invest in software development and thus help improve software quality, one may suggest that this type of licensing is better from a policy perspective as it creates the right incentives for developers. In fact, one argument against GPL-style licenses is that such licenses restrict the freedom of contributors by forcing them to release their software developments to the public against their own interests, which can in turn hurt software development, quality and ultimately welfare. However, the strategic involvement of firms in open-source licensing is inherently complex, and, as demonstrated in the following proposition, the effect of GPL-style licensing can, in fact, be quite the opposite.

Proposition 2 *If the contributor is efficient in development, a more restrictive license can increase, the originator and contributor development investments, total software quality, originator profits, consumer surplus and social welfare. Technically, there exist* $\underline{\nu}, \bar{\nu} > 0$*, such that when* $s_{oc}^O > s_{cc}^O$*,* $\underline{\nu} < c < \bar{\nu}$*,* $g_c(4s_{oc}^O - 7s_{cc}^O) < s_{cc}^O(4s_{oc}^O - s_{cc}^O)$*, and* β_c *is sufficiently low,* $Q_o > Q_c$*, and a more restrictive license increases (i)* e_o^O *and* e_c^O*,* Q_o *and* Q_c*, and the quality gap,* $Q_o - Q_c$*; (ii)* Π_o*,* Π_c*,* CS^O*, and* W^O*.*

Proposition 2 demonstrates that, despite the arguments suggesting that GPL-style licenses conflict with contributor incentives and, hence, may hurt the value generated by the open-source project as a whole, GPL-style licensing may actually create the right incentives and improve not only originator profits but welfare as well. Further, although it forces a contributor to share the product of his efforts with the public, including the originator who is his main competitor, even the contributor can still be better off with such a restrictive license. The key here is the strategic interaction between the originator and the contributor.

The intuition for this result is best illustrated in Figure 6, which contrasts the firms' incentives under a permissive license, characterized by low s_{oc}^O (panels (a) and (b)), and a restrictive license, characterized by high s_{oc}^O (panels (c) and (d)). As demonstrated in panel (a), the originator loses money for low levels of investment since the overall quality of her package is too low to charge high enough prices to recover the

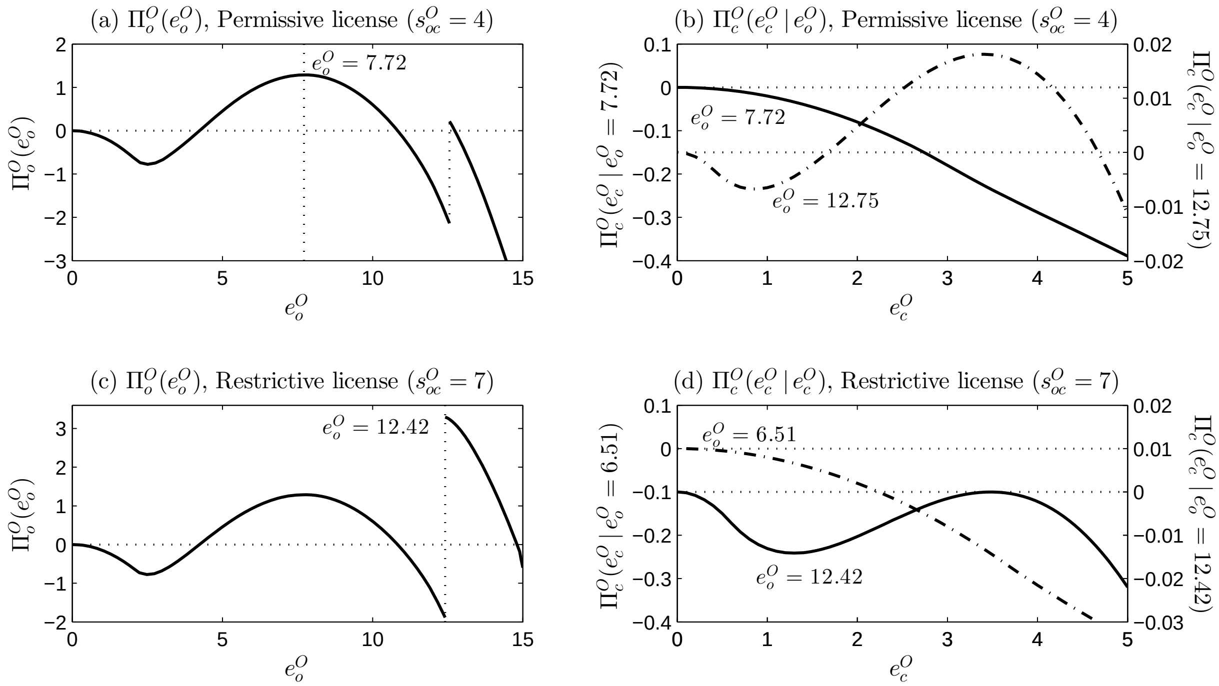

Figure 6: The impact of licensing choice on firm profits. Panels (a) and (b) illustrate the originator and contributor profit curves, respectively, under a less restrictive license ($s_{oc}^O = 4$), and panels (c) and (d) show the impact of a more restrictive license ($s_{oc}^O = 7$). The parameter values for all panels are $g_o = 3$, $g_c = 3$, $s_{oo}^O = 7$, $s_{cc}^O = 3$, $s_{co}^O = 0.10$, $s_{co}^P = 0.05$, $s_{cc}^P = 0$, $c = 21$, $\beta_o = 0.30$, and $\beta_c = 0.04$.

costs of providing service. As the originator's investment increases, she begins to make positive profits. However, until the originator's investment reaches a certain level, the contributor's profit curve is strictly decreasing in e_c^O as depicted in panel (b) at the optimal originator investment level of $e_o^O = 7.72$, for this given level of s_{oc}^O. For higher levels of originator contribution, it becomes optimal for the contributor to make positive investments as seen in panel (b) when the originator sets an investment level of $e_o^O = 12.75$. Examining the contributor's profit curves which are illustrated in panels (b) and (d), it is important to note that his profit as a function of his own effort can be bimodal. As a result, the originator's profit function can have a discontinuity which reflects the contributor's jumping up of effort when e_o^O increases past a critical level.

However, since the originator does not benefit much from the contributor's efforts in this case, she prefers to restrict her own effort level such that the contributor does not invest and stays out of the services market (i.e., the strategic effect outweighs the complementarity effect). On the other hand, under a restrictive license such as GPL, the originator can strongly benefit from the contributor's software developments (i.e., s_{oc}^O is high) while maintaining her position as the quality leader. In such a case, the originator can be better off with a high level of investment, which also induces the contributor to invest in the project, as seen in panels (c) and (d) of Figure 6. Therefore, both originator and contributor qualities increase with a more

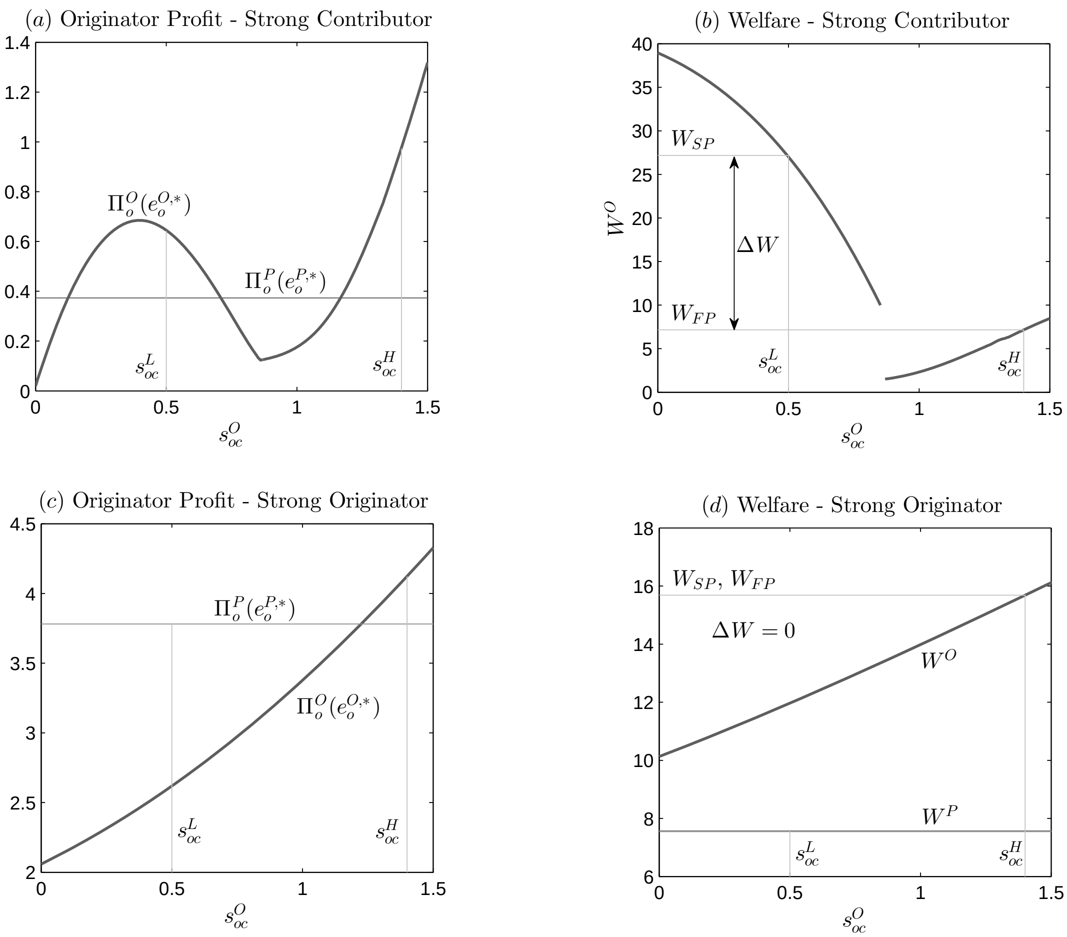

Figure 7: The impact of licensing choice on firm profits and social welfare. Panels (a) and (c) illustrate the originator's profit under open source and proprietary strategies, while panels (b) and (d) plot social welfare. The parameter values for panels (a) and (b) are $g_o = 0.1$, $g_c = 1$, $s_{oo}^O = 1$, $s_{cc}^O = 1$, $s_{co}^O = 0.5$, $s_{co}^P = 0.25$, $s_{cc}^P = 0$, $c = 0.01$, $\beta_o = 0.1$, and $\beta_c = 0.006$. Parameter values for panels (c) and (d) are $g_o = 0.1$, $g_c = 1$, $s_{oo}^O = 1$, $s_{cc}^O = 1$, $s_{co}^O = 0.1$, $s_{co}^P = 0.1$, $s_{cc}^P = 0$, $c = 0.001$, $\beta_o = 0.01$, and $\beta_c = 0.01$. Social welfare under the proprietary strategy is $W^P = 0.75$ in panel (b). In panels (b) and (d), W_{SP} denotes social welfare under the social planner, W_{FM} denotes social welfare under the free market outcome, and $\Delta W = W_{SP} - W_{FM}$.

restrictive license compared to a permissive one, as stated in part (i) of Proposition 2. Further, the quality difference is also amplified, which allows the contributor and the originator to better differentiate from each other, which in turn increases both their profits as stated in part (ii). Thus, the stronger complementarity effect helps to limit the impact of the strategic effect. Finally, the across the board increase in quality with the more restrictive license also increases consumer surplus and the overall welfare, again as stated in part (ii) of the proposition.

Figure 7 illustrates the originator's licensing choice and its impact on welfare. As can be seen in panel (a), if the license is too permissive so that the originator cannot strongly benefit from the contributor's efforts (i.e., when s_{oc}^O is low), it does not pay off for the originator to pursue an open-source strategy under this licensing, and the originator's best option is to keep the software proprietary. As the originator's returns from contributor efforts increase, i.e., as s_{oc}^O increases, a more restrictive open-source license can become the best option for her: by becoming the lower-quality service provider in the market, the originator can induce increased investment by the contributor. However, structuring more restrictive licenses to extract increased returns does not necessarily pay off. With further increases in s_{oc}^O, the quality gap between the contributor and the originator decreases, which reduces the contributor's incentives for development. Hence, such an increase in license restrictiveness can reduce originator profits as we discussed above in Proposition 1.[13] This decrease in originator profits can be seen in panel (a) of Figure 7.

In panel (b), we plot the welfare associated with an open-source outcome. In this case, the discontinuity observed stems from a significant scaling back of contributor effort due to increases in s_{oc}^O. In particular, when the originator's ability to benefit from the contributor's investment increases, beyond a certain point, the contributor is better off limiting his investment; higher investment levels tend to strongly serve the quality of the originator. Therefore, as it was similarly depicted in Figure 6, the contributor may lower his investment, e_c^O by shifting to a distant local maximizer, which discontinuously reduces the overall software and service quality, and hence results in a discontinuity on the welfare curve. At a certain point, a proprietary strategy may once again become the best strategy for a software originator. However, higher s_{oc}^O values can create incentives for the originator to invest at high levels, engendering more separation and inducing further investments by the contributor. Consequently, an open-source strategy can again obtain, and these increased license requirements that enable the originator to extract larger benefits from contributor efforts can be preferred as Proposition 2 indicates.

Moreover, as is illustrated in panel (b) of Figure 7, in the lower end of the s_{oc}^O spectrum, increasing the openness requirements of the software license may reduce welfare by inducing decreased investments by the contributor. On the other hand, in the higher end of the spectrum, imposing stricter openness requirements, as in GPL-style licenses, can benefit welfare by improving quality for all participants. To gain intuition through a simple example, note that the originator often will have a discrete set of licensing options. Suppose that the originator has two licensing options with s_{oc}^O corresponding to the two levels marked in the figure: s_{oc}^L and s_{oc}^H (low and high license restrictiveness, respectively). In the free market outcome, as can be seen in panel (a), the originator's profit is higher under the more restrictive option, s_{oc}^H, so she chooses this restrictive license option. However, as is shown in panel (b), social welfare is significantly higher under the less restrictive license option s_{oc}^L; a welfare maximizing social planner would want to enforce limitations on license restrictiveness, eliminating the restrictive option s_{oc}^H. In this case, there would be a significant welfare difference between the free-market licensing outcome and the social

[13] Also, by taking a point in this region (e.g., $s_{oc}^O = 0.60$), we can demonstrate the wide parameter range for which Proposition 1 is satisfied. Consistent with the results from Proposition 1, by slightly decreasing s_{oc}^O from 0.60, profits increase, and, as can be seen in panel (b), social welfare increases. Further, we find that these results continue to hold for any g_c satisfying $0 \leq g_c < \infty$, and β_c can be increased up to fivefold.

planner enforced outcome which is depicted in panel (b).

In contrast, when the originator is strong, the difference between the free-market outcome and the social planner's choice for licensing tends to decrease. As the originator becomes stronger compared to the contributor, her trade-off between harvesting the benefits of the contributors' investment (complementarity effect) and keeping him in check in the services market (strategic effect) weakens (i.e., the complementarity effect starts to dominate). This is because when the originator is strong relative to the contributor, she no longer needs nor relies on a large investment by the contributor. Hence, she no longer needs to incentivize the contributor to invest a significant amount to develop the software. Therefore, a restrictive license (high s_{oc}^{O}) maximizes her profit as can be seen from panel (c) of Figure 7, since benefitting from the contributor's investment helps prevent the contributor from gaining a quality advantage in the services market. Continuing with the simple example discussed above, given an option between the same two s_{oc}^{O} levels, s_{oc}^{L} and s_{oc}^{H}, in the free-market outcome, the originator would choose s_{oc}^{H}, the restrictive license. Unlike the strong contributor case however, in a setting with a strong originator, this restrictive license also maximizes welfare since it maximizes the originator's investment and the overall software and service quality, as is displayed in panel (d). Consequently, both the free market and social welfare maximizing outcomes have the same licensing choice, s_{oc}^{H}, and the difference in welfare between the two outcomes is zero.

5 Discussion of the Model, Analysis, and Limitations

5.1 Profit-Seeking Contributors

Our model is one of the first to capture the simultaneously collaborative and competitive relationship between the profit-seeking firms that invest in open-source software development, intending to profit from provision of software integration services. The profit-seeking behavior of the contributor firm and the ensuing strategic interaction plays a critical role in licensing decisions. To see this, we have analyzed a version of our model with contributors who are not profit seeking and participate in software development for other reasons such as altruism or as hobbyism. We show that with such contributors, the originator's critical strategic considerations of pricing, investment, and licensing decisions we discussed in the paper disappear. In particular, in such a case, the effect of license restrictiveness on the originator's profits would simply be monotonically increasing, and she would set the open-source license as restrictive as possible to maximize the benefits she derives from their efforts.[14] Therefore, we can conclude that the profit-seeking behavior of open-source contributors plays a critical role in open-source development investments and licensing choice.

[14] We provide this model and its analysis in Section B of the Online Supplement.

5.2 The Role of Competitive Integrators

Competitive integrators are pervasive and serve an important role in IT services markets. We include them in the model because their role in these markets significantly shapes the strategic decisions being made by the originator and contributor, particularly when contemplating different OSS licensing arrangements. In particular, their existence becomes quite impactful as the implementation cost of these services becomes higher. In such cases, it becomes more difficult to retain adequate margins in the services market because higher quality levels are necessary and investments to achieve them are quite costly. Higher licensing restrictiveness can help boost quality by leveraging the contributor's effort but ultimately it will be in the best interest of the strategic players to set prices in a manner that strategically push the competitive integrators out of the market. We demonstrate that the existence of competitive integrators pricing at cost can lead to more competitive outcomes where strategic players utilize limit pricing and GPL licenses can have a positive impact on qualities, profits and welfare. Competitive integrators are fundamental to this result.

5.3 Service Provision Costs

In our model, we assumed that service provision costs are independent of service quality. This is a reasonable assumption from the perspectives of practice and modeling. In general, when firms invest to develop software, the service quality improves from built-in expertise and better developed utilities and tools. That is, a service provider firm can charge more for the higher quality service, but it does not mean that the marginal cost of providing the service has gone up. In other words, the built-in expertise and the developed support software in this case can be considered as fixed costs, as once those are attained there is no real increase in economic costs of providing services. Further, even if there were an increase in the marginal costs of providing services, from a modeling perspective as long as there were some gains in quality through investment, the model outcome would be similar or equivalent in substance to a constant service cost model in that an increase in costs can be mathematically transformed and absorbed in the value generated by the quality increase.

5.4 Robustness and the Regions of Applicability

Our propositions and proofs use asymptotic analysis, which is standard and often used in microeconomic analysis when the analysis is complex (see, e.g., Li et al. 1987, Laffont and Tirole 1988, Pesendorfer and Swinkels 2000, and Vereshchagina and Hopenhayn 2009 among many others). Given the complexity of the setting (e.g., involvement of multiple layers of nested optimizations), it is not possible to obtain a full analytical identification of the regions under all parameter sets. However, our results are not restricted

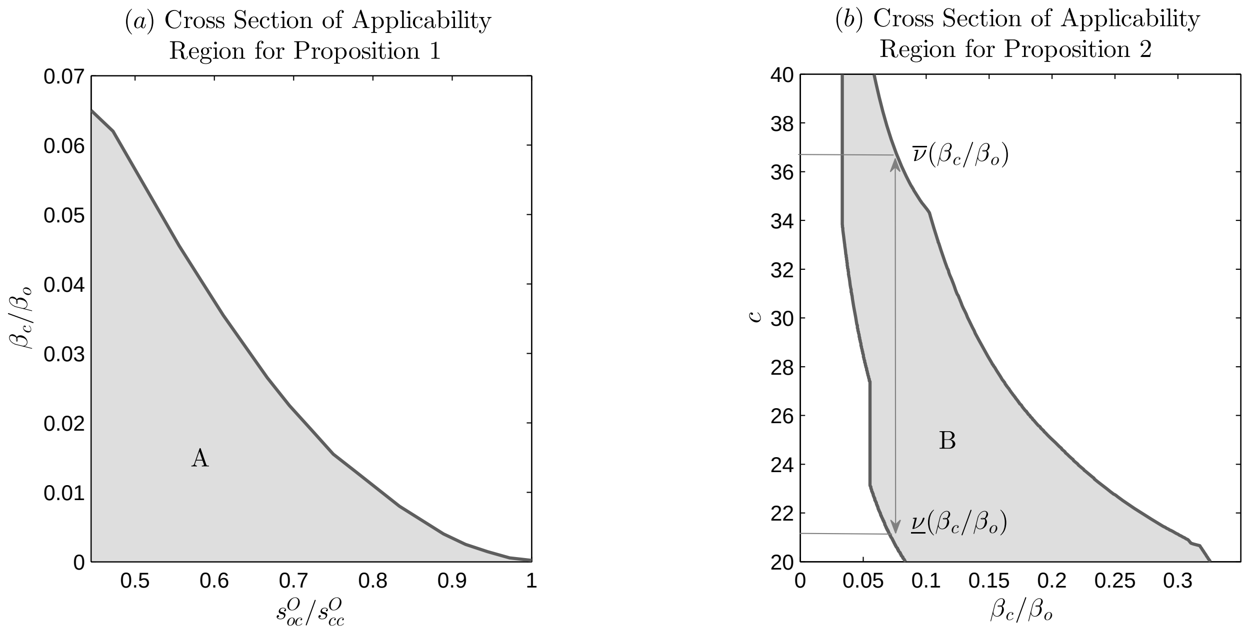

Figure 8: Numerical illustration of the region of applicability for Propositions 1 and 2. The grey shaded areas, labeled A, are delineated by the parameter bounds described in the propositions and indicate the regions where the proposition statements are satisfied. The parameter values for panel (a) are $g_o = 0.1$, $g_c = 0.1$, $s^O_{oo} = 1$, $s^O_{cc} = 1$, $s^O_{co} = 0.5$, $s^P_{co} = 0.05$, $s^P_{cc} = 0$, $\beta_o = 0.1$ and $c = 0.01$. The parameter values for panel (b) are $g_o = 3$, $g_c = 3$, $s^O_{oo} = 7$, $s^O_{cc} = 3$, $s^O_{co} = 0.10$, $s^P_{co} = 0.05$, $s^P_{cc} = 0$, $\beta_o = 0.30$, $(s^O_{oc})^L = 3.1$, and $(s^O_{oc})^H = 25$.

to limits, and instead are robust and satisfied for wide parameter regions. One can perform a sensitivity analysis and numerically identify the parameter regions where the results are valid. Panels (a) and (b) of Figure 8 demonstrates sample applicability regions for Propositions 1 and 2, respectively. As can be seen from panel (a), Proposition 1 is valid on a broad region. Fixing other parameters, under the strong contributor regime (i.e., when $\beta_c \ll \beta_o$), with any combination of β_c/β_o and s^O_{oc}/s^O_{cc} ratios in the region labeled with A, the statement of the proposition would hold. Similarly, panel (b) demonstrates an example for the upper and lower bounds of the service cost parameter c, $\underline{\nu}$ and $\bar{\nu}$ as a function of β_c/β_o as is characterized in Proposition 2. One can again observe that there is a broad parameter region (labeled B), on which the proposition statement is valid.

6 Concluding Remarks

In this note, we presented a model of OSS development that captures the incentives for firms to pursue and contribute to an open-source project, driven by a market for software services. We studied the trade-offs faced by an originating firm deciding between open and proprietary approaches for her software products. If she pursues a proprietary strategy, the firm does not benefit from the contributions of other developers dedicating resources toward creating higher quality software that carries a higher value in the consumer market. However, the firm retains the ability to generate revenues from selling copies of her product regardless of whether she provides the associated services aspect. Should a firm choose an open-source strategy, she can benefit from the positive quality effects. However, she can no longer charge purely for her software product. Her primary source for revenues, under an open-source path, lies with offering integration and support services, which is of significant value to consumers in most cases. This competitive aspect is characterized by quality competition between originating and contributing firms as they invest effort into open-source development, followed by price competition in the services market.

Given the wide range of licenses employed in the open-source domain, we studied whether restrictive or permissive licenses are better for profitability and welfare. We find that in cases where an open-source contributor is adept in reaping the benefits of his own efforts to a greater extent than the originator, requiring or favoring less restrictive licenses (e.g., BSD style) can increase both the originator's profits and welfare. However, if the originator can harness contributor efforts well and the service costs are high, a more restrictive (e.g., GPL style) license can increase developers' contributions and overall software quality.

It is worth noting that with a permissive license, the contributor could, in certain cases, have the option of opening up his contributions and benefiting the originator in the services market, effectively replicating the outcome of the restrictive license. In other words, under open-source licensing, in some cases, he can effectively increase s_{oc}^{O} if his profit increases. However, there are a couple of concerns about including this option in the current paper. First, modeling it would add yet another layer of optimization on top of the two firms' pricing and effort levels, and would make the problem much more complex, the exposition less transparent, and the solution less tractable. Second, it is likely that in many cases, facing an option of opening up his software when he is not required to do so, the contributor would likely not choose such an option that would benefit his competitor and reduce his own profit in the services marketplace. Hence, given that including this option is unlikely to change the outcome while making the analysis and the exposition significantly more complex and less transparent, and aiming to keep the paper's focus sharp, we chose not to include this option in the current paper. However, this is an interesting potential extension to the model that could be explored in a future study to deepen the understanding of license restrictiveness on the contributor firms' strategic decisions to voluntarily open their contributed code when they are not required to do so by the license set by the software originator.

With significantly increased usage and attention in the past decade, OSS is an increasingly prominent tool in today's business economic environment and promises to generate tremendous value for its users. What is even more encouraging is the evolution in recent years of service-based revenue models that provide steady revenue streams for companies that invest, develop, maintain and support this important software solution approach. Regulating bodies and policy makers, as well as companies that develop, support or use OSS, whether they are government agencies or software and trade associations should be aware of the economic dynamics of OSS and how to harness its potential value.

Acknowledgments

The authors thank Sanjeev Dewan (the senior editor), Wolf Ketter (the associate editor), and the anonymous reviewers for their helpful suggestions throughout the review process. The authors also thank seminar participants at Georgia Tech and participants at the Workshop on Information Systems Economics 2014 for their helpful comments and discussions. This material is based upon work partially supported by the National Science Foundation under Grant No. CNS-0954234.

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Online Supplement for

Generating Value through Open Source: Software Service Market Regulation and Licensing Policy

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A. Mathematical Preliminaries and Proofs of Propositions

Lemma EC.1 *Let p^P, p_o^P, p_c^P, e_o^P and e_c^P be fixed, and let i denote the higher quality provider between the Originator (o) and Contributor (c) and j be the remaining one. That is, if $Q_o \geq Q_c$ then $i = o$ and $j = c$ and vice-versa. Then, the equilibrium consumer strategy profile is characterized by three threshold values $0 \leq \theta_b \leq \theta_j \leq \theta_i \leq 1$ such that for customer θ,*

(1) if $\theta_i \leq \theta \leq 1$, then she will purchase the product and contract service with i, i.e., $\mathbf{1}_i(\theta) = 1$;

(2) if $\theta_j \leq \theta < \theta_i$, then she will purchase the product and contract service with j, i.e., $\mathbf{1}_j(\theta) = 1$;

(3) if $\theta_b \leq \theta < \theta_j$, then she will purchase the product and contract service with a competitive integrator, i.e., $\mathbf{1}_b(\theta) = 1$;

(4) if $0 \leq \theta < \theta_b$, then she will not purchase the product, i.e., $\mathbf{1}_u(\theta) = 0$,

where $\mathbf{1}_u(\theta)$ is an indicator that the type θ consumer uses/purchases the product and $\mathbf{1}_k(\theta)$ is an indicator that type θ consumer chooses to obtain the service from provider $k \in \{o, c, b\}$ as a response to effort and pricing decisions.

Proof of Lemma EC.1: Note that $\mathbf{1}_k(\theta) = 0$ for all k if and only if $\mathbf{1}_u(\theta) = 0$. From (1), for the customer of type θ to contract service with provider i, type θ customer must satisfy

$$Q_i\theta - p - p_i \geq \max\left(Q_j\theta - p - p_j,\, Q_b\theta - p - c,\, 0\right). \tag{EC.1}$$

Suppose that for some $\hat{\theta}_1 < 1$, a customer with type $\hat{\theta}_1$ contracts with provider i. Then, from (EC.1), it follows that $Q_i\hat{\theta}_1 - p - p_i \geq \max(Q_j\hat{\theta}_1 - p - p_j,\, Q_b\hat{\theta}_1 - p - c,\, 0)$. Because, by definition, $Q_i \geq Q_j \geq Q_b$, we obtain $\mathbf{1}_i(\theta) = 1$ for all $\hat{\theta}_1 \leq \theta \leq 1$. Therefore, there exists $\theta_i \in \Theta$ such that for all $\theta \in \Theta$, $\mathbf{1}_i(\theta) = 1$ if and only if $\theta \geq \theta_i$. Similarly, by (1), for $\mathbf{1}_j(\theta) = 1$, we need to have

$$Q_j\theta - p - p_j \geq \max\left(Q_i\theta - p - p_i,\, Q_b\theta - p - c,\, 0\right). \tag{EC.2}$$

Suppose that for some $\hat{\theta}_2 < \theta_i$, we have $\mathbf{1}_j(\hat{\theta}_2) = 1$. Then, by (EC.2), it follows that $Q_j\hat{\theta}_2 - p - p_j \geq \max(Q_i\hat{\theta}_2 - p - p_i,\ Q_b\hat{\theta}_2 - p - c,\ 0)$. Because $Q_j \geq Q_b$, by (EC.2), and by the characterization of θ_i, we obtain $\mathbf{1}_j(\theta) = 1$ for all $\hat{\theta}_2 \leq \theta < \theta_i$. Therefore, there exists $\theta_j \in \Theta$ such that for all $\theta \in \Theta$, $\mathbf{1}_j(\theta) = 1$ if and only if $\theta_j \leq \theta < \theta_i$. If there does not exist $\hat{\theta}_2 < \theta_i$ such that $\mathbf{1}_j(\hat{\theta}_2) = 1$, then, without loss of generality, we can set $\theta_j = \theta_i$. Next, by (1), θ must satisfy

$$Q_b\theta - p - c \geq \max\left(Q_i\theta - p - p_i,\ Q_j\theta - p - p_j,\ 0\right) \tag{EC.3}$$

as a necessary condition for $\mathbf{1}_b(\theta) = 1$, i.e., the customer with type θ purchased and contracted service with a competitive integrator. Suppose that for some $\hat{\theta}_3 < \theta_j$, we have $\mathbf{1}_b(\hat{\theta}_3) = 1$. By (EC.3), we obtain $Q_b\hat{\theta}_3 - p - c \geq \max(Q_i\hat{\theta}_3 - p - p_i,\ Q_j\hat{\theta}_3 - p - p_j,\ 0)$. Using this fact, (EC.3), and the characterizations of θ_i and θ_j, it follows that $\mathbf{1}_b(\theta) = 1$ for all $\hat{\theta}_3 \leq \theta < \theta_j$. Therefore, there exists $\theta_b \in \Theta$ such that for all $\theta \in \Theta$, $\mathbf{1}_b(\theta) = 1$ if and only if $\theta_b \leq \theta < \theta_j$. Similarly, if there does not exist $\hat{\theta}_3 < \theta_j$ such that $\mathbf{1}_b(\hat{\theta}_3) = 1$, then, without loss of generality, we can set $\theta_b = \theta_j$. Finally, suppose $\theta < \theta_b$. By the characterization of θ_i, θ_j, and θ_b, it follows that $\mathbf{1}_u(\theta) = 0$. $\square$

We next provide the consumer market characterization for the proprietary strategy. The following technical lemma (Lemma EC.2) presents this characterization and is used in the proof of Lemma 1. Proofs of Lemmas EC.2 and 1 are similar to the proofs of their Open Source counterparts, Lemmas EC.3 and 2, which are more comprehensive and presented in detail in this supplement. We hence omit the proofs of the former two here for conciseness.

Lemma EC.2 *Let p, p_o, p_c, e_o and e_c be fixed. Suppose $Q_c > Q_o > Q_b$. The consumer market structure has the following characterization.*

(1) If $Q_b \geq c$, $0 \leq p \leq Q_b - c$ and either $\frac{p(Q_o-Q_b)+cQ_o}{Q_b} \leq p_o \leq \frac{p_c(Q_o-Q_b)+c(Q_c-Q_o)}{Q_c-Q_b}$ and $\frac{p(Q_c-Q_b)+cQ_c}{Q_b} \leq p_c \leq \frac{p(Q_o-Q_b)+cQ_o}{Q_b} + Q_c - Q_o$, or $p_c - (Q_c - Q_o) \leq p_o \leq \frac{p_c(Q_o-Q_b)+c(Q_c-Q_o)}{Q_c-Q_b}$ and $\frac{p(Q_o-Q_b)+cQ_o}{Q_b} + Q_c - Q_o \leq p_c \leq c + Q_c - Q_b$, then

$$0 \leq \theta_b = \frac{p+c}{Q_b} \leq \theta_o = \frac{p_o - c}{Q_o - Q_b} \leq \theta_c = \frac{p_c - p_o}{Q_c - Q_o} \leq 1; \tag{EC.4}$$

(2) If one of the following holds:

(a) $Q_b \geq c$, $0 \leq p \leq Q_b - c$, $p_c - (Q_c - Q_o) \leq p_o \leq \frac{p_cQ_o - p(Q_c-Q_o)}{Q_c}$, and $c \leq p_c \leq \frac{p(Q_c-Q_b)+cQ_c}{Q_b}$;

(b) $Q_c \geq c$, $Q_b - c \leq p \leq Q_c - c$, $p_c - (Q_c - Q_o) \leq p_o \leq \frac{p_cQ_o - p(Q_c-Q_o)}{Q_c}$, and $c \leq p_c \leq Q_c - p$;

(c) $Q_b \geq c$, $0 \leq p \leq Q_b - c$, $p_c - (Q_c - Q_o) \leq p_o \leq \frac{p(Q_o-Q_b)+cQ_o}{Q_b}$, and $\frac{p(Q_c-Q_b)+cQ_c}{Q_b} \leq p_c \leq \frac{p(Q_o-Q_b)+cQ_o}{Q_b} + Q_c - Q_o$,

then

$$0 \leq \theta_b = \theta_o = \frac{p+p_o}{Q_o} \leq \theta_c = \frac{p_c - p_o}{Q_c - Q_o} \leq 1; \tag{EC.5}$$

(3) If either $Q_b \geq c$*,* $0 \leq p \leq Q_b - c$*,* $p_o \geq \frac{p_c Q_o - p(Q_c - Q_o)}{Q_c}$*, and* $c \leq p_c \leq \frac{p(Q_c - Q_b) + cQ_c}{Q_b}$*,*
or $Q_c \geq c$*,* $Q_b - c \leq p \leq Q_c - c$*,* $p_o \geq \frac{p_c Q_o - p(Q_c - Q_o)}{Q_c}$*, and* $c \leq p_c \leq Q_c - p$*, then*

$$0 \leq \theta_b = \theta_o = \theta_c = \frac{p + p_c}{Q_c} \leq 1\,; \tag{EC.6}$$

(4) If $Q_b \geq c$*,* $0 \leq p \leq Q_b - c$*, and either* $\frac{p(Q_o - Q_b) + cQ_o}{Q_b} \leq p_o \leq c + Q_o - Q_b$ *and* $p_c \geq c + Q_c - Q_b$*,*
or $\frac{p(Q_o - Q_b) + cQ_o}{Q_b} \leq p_o \leq p_c - (Q_c - Q_o)$ *and* $\frac{p(Q_o - Q_b) + cQ_o}{Q_b} + Q_c - Q_o \leq p_c \leq c + Q_c - Q_b$*, then*

$$0 \leq \theta_b = \frac{p + c}{Q_b} \leq \theta_o = \frac{p_o - c}{Q_o - Q_b} \leq \theta_c = 1\,; \tag{EC.7}$$

(5) If one of the following holds:

(a) $Q_b \geq c$*,* $0 \leq p \leq Q_b - c$*,* $p_o \leq p_c - (Q_c - Q_o)$*, and* $c \leq p_c \leq \frac{p(Q_o - Q_b) + cQ_o}{Q_b} + Q_c - Q_o$*;*

(b) $Q_c \geq c$*,* $Q_b - c \leq p \leq Q_c - c$*,* $p_o \leq p_c - (Q_c - Q_o)$*, and* $c \leq p_c \leq Q_c - p$*;*

(c) $Q_b \geq c$*,* $0 \leq p \leq Q_b - c$*,* $p_o \leq \frac{p(Q_o - Q_b) + cQ_o}{Q_b}$*, and* $p_c \geq \frac{p(Q_o - Q_b) + cQ_o}{Q_b} + Q_c - Q_o$*;*

(d) $p \geq Q_c - c$*,* $p_o \leq Q_o - p$*, and* $p_c \geq c$*,*

(e) $Q_c \geq c$*,* $Q_b - c \leq p \leq Q_c - c$*,* $p_o \leq Q_o - p$*, and* $p_c \geq Q_c - p$*,*

then

$$0 \leq \theta_b = \theta_o = \frac{p + p_o}{Q_o} \leq \theta_c = 1\,; \tag{EC.8}$$

(6) If $Q_b \geq c$*,* $0 \leq p \leq Q_b - c$*,* $p_o \geq c + Q_o - Q_b$*, and* $p_c \geq c + Q_c - Q_b$*, then*

$$0 \leq \theta_b = \frac{p + c}{Q_b} \leq \theta_o = \theta_c = 1\,; \tag{EC.9}$$

(7) If $Q_b \geq c$*,* $0 \leq p \leq Q_b - c$*, and* $p_o \geq \frac{p_c(Q_o - Q_b) + c(Q_c - Q_o)}{Q_c - Q_b}$*, and*
$\frac{p(Q_c - Q_b) + cQ_c}{Q_b} \leq p_c \leq c + Q_c - Q_b$*, then*

$$0 \leq \theta_b = \frac{p + c}{Q_b} \leq \theta_o = \theta_c = \frac{p_c - c}{Q_c - Q_b} \leq 1\,; \tag{EC.10}$$

(8) If $p \geq Q_b - c$*,* $p_o \geq Q_o - p$*, and* $p_c \geq Q_c - p$*, then*

$$0 \leq \theta_b = \theta_o = \theta_c = 1\,; \tag{EC.11}$$

Lemma EC.3 *Let* p_o^O*,* p_c^O*,* e_o^O *and* e_c^O *be fixed and let* i *denote the higher quality provider among the Originator (o) and the Contributor (c) and* j *be the remaining one. That is, if* $Q_o > Q_c$ *then* $i = o$ *and* $j = c$ *and vice-versa.*

(i) The equilibrium consumer strategy profile is characterized by three threshold values $0 \le \theta_b \le \theta_j \le \theta_i \le 1$ *such that for customer* θ,

(1) if $\theta_i \le \theta \le 1$*, then she will use the product and contract service with* i*, i.e.,* $\mathbf{1}_i(\theta) = 1$*;*

(2) if $\theta_j \le \theta < \theta_i$*, then she will use the product and contract service with* j*, i.e.,* $\mathbf{1}_j(\theta) = 1$*;*

(3) if $\theta_b \le \theta < \theta_j$*, then she will use the product and contract service with a competitive integrator, i.e.,* $\mathbf{1}_b(\theta) = 1$*;*

(4) if $0 \le \theta < \theta_b$*, then she will not use the product, i.e.,* $\mathbf{1}_u(\theta) = 0$.

(ii) The consumer market structure has the following characterization of regions:[15]

(1) If $Q_b \ge c$, $cQ_j/Q_b \le p_j \le c + Q_j - Q_b$*, and* $\frac{p_j(Q_i-Q_b)-c(Q_i-Q_j)}{(Q_i-Q_b)-(Q_i-Q_j)} \le p_i \le p_j + Q_i - Q_j$*, then*

$$0 \le \theta_b = \frac{c}{Q_b} \le \theta_j = \frac{p_j - c}{Q_j - Q_b} \le \theta_i = \frac{p_i - p_j}{Q_i - Q_j} \le 1\,; \tag{EC.12}$$

(2) If $p_jQ_i/Q_j \le p_i \le p_j + Q_i - Q_j$ *and either* $Q_b \ge c$ *and* $p_j \le cQ_j/Q_b$*, or* $Q_b \le c$ *and* $p_j \le Q_j$ *are satisfied, then*

$$0 \le \theta_b = \theta_j = \frac{p_j}{Q_j} \le \theta_i = \frac{p_i - p_j}{Q_i - Q_j} \le 1\,; \tag{EC.13}$$

(3) If one of the following holds: $Q_b \ge c$, $p_j \le cQ_j/Q_b$*, and* $p_i \le p_jQ_i/Q_j$*;* $Q_b \le c$, $p_j \le Q_j$*, and* $p_i \le p_jQ_i/Q_j$*;* $Q_b \ge c$, $p_j \ge cQ_j/Q_b$*, and* $p_i \le cQ_i/Q_b$*; or* $Q_b \le c$, $p_j \ge Q_j$*, and* $p_i \le Q_i$*, then*

$$0 \le \theta_b = \theta_j = \theta_i = \frac{p_i}{Q_i} \le 1\,; \tag{EC.14}$$

(4) If $Q_b \ge c$, $cQ_j/Q_b \le p_j \le c + Q_j - Q_b$*, and* $p_i \ge p_j + Q_i - Q_j$*, then*

$$0 \le \theta_b = \frac{c}{Q_b} \le \theta_j = \frac{p_j - c}{Q_j - Q_b} \le \theta_i = 1\,; \tag{EC.15}$$

(5) If $Q_b \ge c$, $p_j \ge c + Q_j - Q_b$*, and* $p_i \ge c + Q_i - Q_b$*, then*

$$0 \le \theta_b = \frac{c}{Q_b} \le \theta_j = \theta_i = 1\,; \tag{EC.16}$$

(6) If $p_i \ge p_j + Q_i - Q_j$ *and either* $Q_b \ge c$ *and* $p_j \le cQ_j/Q_b$*, or* $Q_b \le c$ *and* $p_j \le Q_j$ *hold, then*

$$0 \le \theta_b = \theta_j = \frac{p_j}{Q_j} \le \theta_i = 1\,; \tag{EC.17}$$

(7) If $Q_b \ge c$ *and either* $cQ_j/Q_b \le p_j \le c + Q_j - Q_b$ *and* $cQ_i/Q_b \le p_i \le \frac{p_j(Q_i-Q_b)-c(Q_i-Q_j)}{(Q_i-Q_b)-(Q_i-Q_j)}$*, or* $p_j \ge c+$

[15] Given $e_o^O > 0$ or $e_c^O > 0$, $Q_j > Q_b$ is satisfied and $Q_i = Q_j$ cannot be satisfied in equilibrium.

$Q_j - Q_b$ and $cQ_i/Q_b \le p_i \le c + Q_i - Q_b$, then

$$0 \le \theta_b = \frac{c}{Q_b} \le \theta_j = \theta_i = \frac{p_i - c}{Q_i - Q_b} \le 1\,; \tag{EC.18}$$

(8) If $Q_b \le c$, $p_j \ge Q_j$, and $p_i \ge Q_i$, then

$$0 \le \theta_b = \theta_j = \theta_i = 1\,. \tag{EC.19}$$

Proof: For part (i), by (2), θ must satisfy

$$Q_i\theta - p_i \ge \max\left(Q_j\theta - p_j,\, Q_b\theta - c,\, 0\right) \tag{EC.20}$$

as a necessary condition for $\mathbf{1}_i(\theta) = 1$. Suppose that for some $\hat{\theta}_1 < 1$, we have $\mathbf{1}_i(\hat{\theta}_1) = 1$. By (EC.20), we obtain $Q_i\hat{\theta}_1 - p_i \ge \max(Q_j\hat{\theta}_1 - p_j,\, Q_b\hat{\theta}_1 - c,\, 0)$. Using this fact, (EC.20), and since, by definition, $Q_i \ge Q_j \ge Q_b$, it follows that $\mathbf{1}_i(\theta) = 1$ for all $\hat{\theta}_1 \le \theta \le 1$. Therefore, there exists $\theta_i \in \Theta$ such that for all $\theta \in \Theta$, $\mathbf{1}_i(\theta) = 1$ if and only if $\theta \ge \theta_i$. Similarly, by (2), a necessary condition for $\mathbf{1}_j(\theta) = 1$ is

$$Q_j\theta - p_j \ge \max\left(Q_i\theta - p_i,\, Q_b\theta - c,\, 0\right)\,. \tag{EC.21}$$

Suppose that for some $\hat{\theta}_2 < \theta_i$, we have $\mathbf{1}_j(\hat{\theta}_2) = 1$. By (EC.21), it follows that $Q_j\hat{\theta}_2 - p_j \ge \max(Q_i\hat{\theta}_2 - p_i,\, Q_b\hat{\theta}_2 - c,\, 0)$. Since $Q_j \ge Q_b$, by (EC.21), and by the characterization of θ_i, we obtain $\mathbf{1}_j(\theta) = 1$ for all $\hat{\theta}_2 \le \theta < \theta_i$. Therefore, there exists $\theta_j \in \Theta$ such that for all $\theta \in \Theta$, $\mathbf{1}_j(\theta) = 1$ if and only if $\theta_j \le \theta < \theta_i$. If there does not exist $\hat{\theta}_2 < \theta_i$ such that $\mathbf{1}_j(\hat{\theta}_2) = 1$, then, without loss of generality, we can set $\theta_j = \theta_i$. By (2), θ must satisfy

$$Q_b\theta - c \ge \max\left(Q_i\theta - p_i,\, Q_j\theta - p_j,\, 0\right) \tag{EC.22}$$

as a necessary condition for $\mathbf{1}_b(\theta) = 1$. Suppose that for some $\hat{\theta}_3 < \theta_j$, we have $\mathbf{1}_b(\hat{\theta}_3) = 1$. By (EC.22), we obtain $Q_b\hat{\theta}_3 - c \ge \max(Q_i\hat{\theta}_3 - p_i,\, Q_j\hat{\theta}_3 - p_j,\, 0)$. Using this fact, (EC.22), and the characterizations of θ_i and θ_j, it follows that $\mathbf{1}_b(\theta) = 1$ for all $\hat{\theta}_3 \le \theta < \theta_j$. Therefore, there exists $\theta_b \in \Theta$ such that for all $\theta \in \Theta$, $\mathbf{1}_b(\theta) = 1$ if and only if $\theta_b \le \theta < \theta_j$. Similarly, if there does not exist $\hat{\theta}_3 < \theta_j$ such that $\mathbf{1}_b(\hat{\theta}_3) = 1$, then, without loss of generality, we can set $\theta_b = \theta_j$. Finally, suppose $\theta < \theta_b$. By the characterization of θ_i, θ_j, and θ_b, it follows that $\mathbf{1}_u(\theta) = 0$.

For part (ii), by the definition of Θ, and (EC.20), $\mathbf{1}_i(\theta) = 1$ if and only if

$$\theta \ge t_A \triangleq \min\left(\max\left(\frac{p_i}{Q_i}, \frac{p_i - p_j}{Q_i - Q_j}, \frac{p_i - c}{Q_i - Q_b}\right), 1\right)\,. \tag{EC.23}$$

Similarly, $\mathbf{1}_j(\theta) = 1$ if and only if

$$t_B \triangleq \max\left(\frac{p_j}{Q_j}, \frac{p_j - c}{Q_j - Q_b}\right) \le \theta < t_C \triangleq \min\left(\frac{p_i - p_j}{Q_i - Q_j}, 1\right)\,. \tag{EC.24}$$

Finally, $\mathbf{1}_b(\theta) = 1$ if and only if

$$t_D \triangleq \frac{c}{Q_b} \leq \theta < t_E \triangleq \min\left(\frac{p_j - c}{Q_j - Q_b}, \frac{p_i - c}{Q_i - Q_b}, 1\right), \tag{EC.25}$$

and $\mathbf{1}_u(\theta) = 0$ if and only if

$$0 \leq \theta < t_F \triangleq \min\left(\frac{p_i}{Q_i}, \frac{p_j}{Q_j}, \frac{c}{Q_b}, 1\right). \tag{EC.26}$$

To see Region I, first define

$$\kappa_A \triangleq \frac{p_j(Q_i - Q_b) - c(Q_i - Q_j)}{(Q_i - Q_b) - (Q_i - Q_j)}. \tag{EC.27}$$

By (EC.23), $t_A = (p_i - p_j)/(Q_i - Q_j) \leq 1$ since $p_i \leq p_j + Q_i - Q_j$, $p_i \geq \kappa_A$ implies $(p_i - p_j)/(Q_i - Q_j) \geq (p_i - c)/(Q_i - Q_b)$, and $p_j \geq cQ_j/Q_b$ implies $\kappa_A \geq p_j Q_i/Q_j$ which, in turn, implies $(p_i - p_j)/(Q_i - Q_j) \geq p_i/Q_i$. It immediately follows that $t_C = t_A$. Further, $p_j \geq cQ_j/Q_b$ implies $t_B = (p_j - c)/(Q_j - Q_b)$, and $p_i \geq \kappa_A$ implies $t_B \leq t_C$. Because $p_j \leq c + Q_j - Q_b$ and $p_i \geq \kappa_A$, it follows that $t_E = t_B$, and further, $p_j \geq cQ_j/Q_b$ implies $t_D \leq t_E$. Finally, $t_F = t_D$ since $Q_b \geq c$, which finishes the characterization presented in (EC.12). The proofs of the remaining regions follow closely with that of Region I. $\square$

Proof of Lemma 2: First, define $\tau_A(\vec{Q})$, $\tau_B(\vec{Q})$, and $\tau_C(\vec{Q})$ are defined as follows:

$$\tau_A(\vec{Q}) \triangleq \frac{Q_b(Q_i - Q_j)}{4(Q_i - Q_b) - (Q_j - Q_b)}, \tag{EC.28}$$

$$\tau_B(\vec{Q}) \triangleq \frac{Q_b Q_j (Q_i - Q_j)}{Q_j(4Q_i - Q_j) - Q_b(2Q_i + Q_j)}, \tag{EC.29}$$

and

$$\tau_C(\vec{Q}) \triangleq \frac{Q_i Q_j}{2Q_i - Q_j}. \tag{EC.30}$$

Note that, it can be shown by algebraic manipulation that $0 \leq \tau_A(\vec{Q}) \leq \tau_B(\vec{Q}) \leq Q_j/2 \leq \tau_C(\vec{Q})$ as stated in the statement of the lemma. By Lemma EC.3, if the conditions of Region IV, V, VI, or VIII are satisfied, then, by (9) and (10), $\breve{\Pi}_i^O(p_i \mid p_j) = 0$. In each case, since $Q_i > c$, there exists $p > c$ such that $\breve{\Pi}_i^O(p \mid p_j) \geq 0$. Hence, none of these regions can occur in equilibrium. For Region VII, fix any set of parameters which satisfy the conditions, in which case, by Lemma EC.3, (9) and (10), $\breve{\Pi}_j^O(p_j \mid p_i) = 0$. However, since $Q_j > Q_b \geq c$, there exists $c < p < cQ_j/Q_b$ such that $\breve{\Pi}_j^O(p \mid p_i) \geq 0$. Thus, firm j would deviate, and this region cannot occur in equilibrium. Therefore, we can focus attention on Regions I, II, and III for candidate equilibria.

For Region I, by (EC.12), (9) and (10), we obtain

$$\breve{\Pi}_i^O(p_i \mid p_j) = (p_i - c)\left(1 - \frac{p_i - p_j}{Q_i - Q_j}\right) \tag{EC.31}$$

and

$$\breve{\Pi}_j^O(p_j \,|\, p_i) = (p_j - c)\left(\frac{p_i - p_j}{Q_i - Q_j} - \frac{p_j - c}{Q_j - Q_b}\right). \tag{EC.32}$$

Since $Q_i > Q_j > Q_b$, by (EC.31) and (EC.32), both residual profit functions are strictly concave, with unconstrained maximizers characterized by

$$p_i = \frac{p_j + c + Q_i - Q_j}{2} \tag{EC.33}$$

and

$$p_j = \frac{p_i(Q_j - Q_b) + c((Q_i - Q_j) + (Q_i - Q_b))}{2(Q_i - Q_b)}. \tag{EC.34}$$

Simultaneously solving (EC.33) and (EC.34) yields

$$p_i^O = c + \frac{2(Q_i - Q_b)(Q_i - Q_j)}{4(Q_i - Q_b) - (Q_j - Q_b)} \tag{EC.35}$$

and

$$p_j^O = c + \frac{(Q_j - Q_b)(Q_i - Q_j)}{4(Q_i - Q_b) - (Q_j - Q_b)}. \tag{EC.36}$$

By (EC.35), (EC.36), (EC.28), and the condition $c \le \tau_A(\vec{Q})$, it follows that $Q_b \ge c$, $cQ_j/Q_b \le p_j^O \le c + Q_j - Q_b$, and $(p_j^O(Q_i - Q_b) - c(Q_i - Q_j))/((Q_i - Q_b) - (Q_i - Q_j)) \le p_i^O \le p_j^O + Q_i - Q_j$ are satisfied. Therefore, p_i^O and p_j^O are the unique candidate equilibrium prices of Region I of Lemma EC.3 when $c \le \tau_A(\vec{Q})$. To ensure that neither firm prefers to deviate its price to another region, first fix firm j's price to p_j^O consider the pricing of firm i. If it sets $p_i \le cQ_i/Q_b$, then Region III applies and, by (EC.14), $\theta_i = p_i/Q_i$. If firm i sets $cQ_i/Q_b \le p_i \le (p_j^O(Q_i - Q_b) - c(Q_i - Q_j))/((Q_i - Q_b) - (Q_i - Q_j))$, then Region VII of Lemma EC.3 applies and, by (EC.18), $\theta_i = (p_i - c)/(Q_i - Q_b)$. If it sets $(p_j^O(Q_i - Q_b) - c(Q_i - Q_j))/((Q_i - Q_b) - (Q_i - Q_j)) \le p_i \le p_j^O + Q_i - Q_j$, then Region I applies and, by (EC.12), $\theta_i = (p_i - p_j)/(Q_i - Q_j)$. Finally, if $p_i \ge p_j^O + Q_i - Q_j$, then Region IV applies and, by (EC.15), $\theta_i = 1$. In summary, firm i's profit function is given by

$$\breve{\Pi}_i^O(p_i \,|\, p_j^O) = \begin{cases} (p_i - c)\left(1 - \frac{p_i}{Q_i}\right) & if \quad p_i \le \frac{cQ_i}{Q_b}\,; \\ (p_i - c)\left(1 - \frac{p_i - c}{Q_i - Q_b}\right) & if \quad \frac{cQ_i}{Q_b} \le p_i \le \frac{p_j^O(Q_i - Q_b) - c(Q_i - Q_j)}{Q_j - Q_b}\,; \\ (p_i - c)\left(1 - \frac{p_i - p_j^O}{Q_i - Q_j}\right) & if \quad \frac{p_j^O(Q_i - Q_b) - c(Q_i - Q_j)}{Q_j - Q_b} \le p_i \le p_j^O + Q_i - Q_j\,; \\ 0 & if \quad p_i \ge p_j^O + Q_i - Q_j\,. \end{cases} \tag{EC.37}$$

By (EC.37), $\breve{\Pi}_i^O(\cdot \,|\, p_j^O)$ is continuous. Further, it is increasing on $[0, cQ_i/Q_b]$ if and only if $p_i \le (Q_i + c)/2$, which is satisfied since $c \le \tau_A(\vec{Q})$ implies $cQ_i/Q_b \le (Q_i + c)/2$. Also, $\breve{\Pi}_i^O(\cdot \,|\, p_j^O)$ is increasing on $[cQ_i/Q_b, (p_j^O(Q_i - Q_b) - c(Q_i - Q_j))/((Q_i - Q_b) - (Q_i - Q_j))]$ if an only if $p_i \le c + (Q_i - Q_b)/2$ which is satisfied since $(p_j^O(Q_i - Q_b) - c(Q_i - Q_j))/((Q_i - Q_b) - (Q_i - Q_j)) \le c + (Q_i - Q_b)/2$. Therefore, p_i given in (EC.35) maximizes (EC.37).

Similarly, we fix firm i's price to p_i^O and examine firm j's price setting problem. Since $p_i^O - (Q_i - Q_j) \le cQ_j/Q_b$ when $c \le \tau_A(\vec{Q})$, by Region VI and (EC.17), if $p_j \le p_i^O - (Q_i - Q_j)$, then $\theta_j = p_j/Q_j$. Since $p_i^O \ge p_j Q_i/Q_b$ when $p_i^O - (Q_i - Q_j) \le p_j \le cQ_j/Q_b$, Region II applies and, by (EC.13), we obtain $\theta_j = p_j/Q_j$ and $\theta_i = (p_i^O - p_j)/(Q_i - Q_j)$. If $cQ_j/Q_b \le p_j \le c + Q_j - Q_b$, then all conditions of Region I are satisfied as shown above, in which case $\theta_j = (p_j - c)/(Q_j - Q_b)$ and $\theta_i = (p_i^O - p_j)/(Q_i - Q_j)$. Finally, if $p_j \ge c + Q_j - Q_b$, then $cQ_i/Q_b \le p_i^O \le c + Q_i - Q_b$, and hence, Region VII applies and, by (EC.18), $\theta_j = \theta_i$. In summary, firm j's profit function is given by

$$\breve{\Pi}_j^O(p_j \,|\, p_i^O) = \begin{cases} (p_j - c)\left(1 - \frac{p_j}{Q_j}\right) & if \quad p_j \le p_i^O - (Q_i - Q_j)\,; \\ (p_i - c)\left(\frac{p_i^O - p_j}{Q_i - Q_j} - \frac{p_j}{Q_j}\right) & if \quad p_i^O - (Q_i - Q_j) \le p_j \le \frac{cQ_j}{Q_b}\,; \\ (p_i - c)\left(\frac{p_i^O - p_j}{Q_i - Q_j} - \frac{p_j - c}{Q_j - Q_b}\right) & if \quad \frac{cQ_j}{Q_b} \le p_j \le c + Q_j - Q_b\,; \\ 0 & if \quad p_j \ge c + Q_j - Q_b\,. \end{cases} \tag{EC.38}$$

By (EC.38), $\breve{\Pi}_j^O(\cdot \,|\, p_i^O)$ is continuous. Further, it is increasing on $[0, p_i^O - (Q_i - Q_j)]$ if and only if $p_j \le (Q_j + c)/2$, which is satisfied since $c \le \tau_A(\vec{Q})$ implies $p_i^O - (Q_i - Q_j) \le (Q_j + c)/2$. Also, $\breve{\Pi}_j^O(\cdot \,|\, p_i^O)$ is increasing on $[p_i^O - (Q_i - Q_j), cQ_j/Q_b]$ if an only if $p_j \le (cQ_i + p_i^O Q_j)/(2Q_i)$ which is satisfied since $cQ_j/Q_b \le (cQ_i + p_i^O Q_j)/(2Q_i)$. Therefore, p_j given in (EC.36) maximizes (EC.38). This completes the proof of part (i).

Moreover, we can prove parts (ii) through (v) using the analysis similar to that applied for part (i). This analysis is omitted for brevity. $\square$

Proof of Proposition 1: Consider a strong contributor regime with small $\beta_c = 1/z$. We first investigate the behavior of e_c^O and e_o^O as $z \to \infty$. Define k, p $\in \mathbb{R}$ as

$$\lim_{z\to\infty} \frac{e_c^O}{z^p} = K_1\,, \text{ and } \lim_{z\to\infty} \frac{e_o^O}{z^k} = K_2\,, \tag{EC.39}$$

where K_1, K_2 $\in \mathbb{R}$ are constants, i.e., as $z \to \infty$, e_c^O is in the order of z^p, or in standard notation, $O(z^p)$, and e_o^O is in the order or z^k, or equivalently, $O(z^k)$. Since $Q_o = g_o e_o^O + g_c e_c^O + s_{oo}^O e_o^O + s_{oc}^O e_c^O$, it follows that Q_o is in the order of $z^{\max(k,p)}$. Similarly, $Q_c = g_o e_o^O + g_c e_c^O + s_{co}^O e_o^O + s_{cc}^O e_c^O$ is in the order of $z^{\max(k,p)}$, and $Q_b = g_o e_o^O + g_c e_c^O$ is in the order of $z^{\max(k,p)}$.

First, let $k > 0$. Suppose that $k \ge p$. In this case, $\max(k,p) = k$, hence Q_o is at most in the order of z^k. Moreover, the maximum possible price p_o^O for the service of the originator which can generate strictly positive demand is Q_o and the potential maximum demand is one. Consequently, $\breve{\Pi}_o^O$ is at most in the order of z^k. The originator's effort cost $C_o(e_o^O) = \beta_o (e_o^O)^2/2$ is in the order of z^{2k}. To guarantee non-negative profit for the originator, $k \ge 2k$ should be satisfied, but it cannot be for $k > 0$, leading to a contradiction. Therefore, if $k > 0$, then $p > k$.

Second, let $k \le 0$. Suppose that $p \le 0$. Then, Q_c is in the order of $z^{\max(k,p)}$ which is bounded by $O(1)$ because $\max(k,p) \le 0$. However, the selection of $p = 1/2$ implies that $\breve{\Pi}_c^O$ is in the order of $z^{1/2}$ whereas $C_c(e_c^O)$ is in the order of $z^{2p-1} = z^0$. Thus, the contributor would profitably deviate by choosing $p = 1/2$

which is a contradiction. Therefore, if $k \leq 0$, then $p > 0$.

Summarizing, $p > \max(0, k)$. Because $Q_c - Q_o$ is in the order of z^p, $Q_o - Q_b$ is in the order of z^p, and $Q_c - Q_b$ is in the order of z^p, by (EC.28), τ_A is in the order of z^p. Thus, Region I of Lemma 2 applies for sufficiently large z. The contributor's profit is given as

$$\Pi_c^O(e_c^O \,|\, e_o^O) = \frac{2(Q_c - Q_b)(Q_c - Q_o)}{4(Q_c - Q_b) - (Q_o - Q_b)} \cdot \left(1 - \frac{2(Q_c - Q_b) - (Q_o - Q_b)}{4(Q_c - Q_b) - (Q_o - Q_b)}\right) - C_c(e_c^O)\,. \tag{EC.40}$$

Substituting for Q_b, Q_o, and Q_c, and differentiating (EC.40) twice with respect to e_c^O, and then plugging in $e_c^O = O(z^p)$ and $e_o^O = O(z^k)$, we find that the second order condition is satisfied, i.e., $d^2\Pi_c^O/d(e_c^O)^2 < 0$ for all $e_c^O > 0$. Next, plugging e_c^O in the order z^p and e_o^O in the order z^k into the first order condition of e_c^O, and collecting the terms in powers of z, we obtain the following:

$$D_1 z^{p-1} + D_2 + Y_1(z) = 0\,, \tag{EC.41}$$

where D_1, D_2 $\in \mathbb{R}$, and $Y_1(z)$ is polynomial in z, with order lower than $\max(p-1, 0)$. Because as $z \to \infty$, (EC.41) should hold for all z, $p - 1 = 0$, i.e., $p = 1$ should be satisfied.

Next, for the originator's effort problem, the originator's profit is written as

$$\Pi_o^O(e_o^O) = \frac{(Q_o - Q_b)(Q_c - Q_o)(Q_c - Q_b)}{(4(Q_c - Q_b) - (Q_o - Q_b))^2} - C_o(e_o^O)\,, \tag{EC.42}$$

where $Q_o = g_o e_o^O + g_c e_c^O(e_o^O) + s_{oo}^O e_o^O + s_{oc}^O e_c^O(e_o^O)$, $Q_c = g_o e_o^O + g_c e_c^O(e_o^O) + s_{co}^O e_o^O + s_{cc}^O e_c^O(e_o^O)$, and $Q_b = g_o e_o^O + g_c e_c^O(e_o^O)$. Note that $e_c^O(e_o^O)$ is obtained from the first order condition of e_c^O above, and by the implicit function theorem, we also obtain

$$\frac{de_c^O(e_o^O)}{de_o^O} = -\frac{\frac{\partial^2}{\partial e_c^O \partial e_o^O}\breve{\Pi}_c^O(e_c^O|e_o^O)}{\frac{\partial^2}{\partial (e_c^O)^2}\breve{\Pi}_c^O(e_c^O|e_o^O) - \beta_c}\,. \tag{EC.43}$$

Using (EC.43), and taking a total derivative of (EC.42) with respect to e_o^O, and finally substituting the functional form of $e_c^O = E_1/z + O(1)$ and that e_o^O is in the order of z^k, we obtain

$$G_1 + G_2 z^k + Y_2(z) = 0\,, \tag{EC.44}$$

for constants $G_1, G_2 \in \mathbb{R}$ and a polynomial term $Y_2(z)$ whose order is less than a constant. Therefore, the highest order term of e_o^O is a constant term, i.e., $k = 0$. Finally, by taking another total derivative of $d\Pi_o^O(e_o^O)/de_o^O$ with respective to e_o^O, we confirm that the second order condition is satisfied in this case, i.e., $d^2\Pi_o^O/d(e_o^O)^2 \leq 0$.

Based on these two values, $p = 1$ and $k = 0$, substituting the resulting functional forms of e_c^O and e_o^O into two first order conditions and equating the lead coefficients of the highest order terms with respect to z to zero, similar to the methodology in August et al. (2014), we obtain the following optimal effort investment levels:

$$e_c^O = \frac{4(s_{cc}^O - s_{oc}^O)(s_{cc}^O)^2}{\lambda_1^2 \beta_c} + \frac{(e_o^O)^2(s_{oc}^O + 5s_{cc}^O)(s_{oc}^O s_{co}^O - s_{oo}^O s_{cc}^O)^2}{4(s_{oc}^O - s_{cc}^O)^2(s_{cc}^O)^4} \cdot \beta_c + O\left(\beta_c^2\right), \tag{EC.45}$$

where $\lambda_1 = 4s_{cc}^O - s_{oc}^O$, and

$$e_o^O = \frac{\lambda_2}{\beta_o \lambda_1^3} + O\left(\beta_c\right), \tag{EC.46}$$

where $\lambda_2 = (s_{oc}^O)^3 s_{co}^O + 2(s_{oc}^O)^2 s_{co}^O s_{cc}^O - 7s_{oo}^O s_{oc}^O (s_{cc}^O)^2 + 4s_{oo}^O (s_{cc}^O)^3$. Plugging the equilibrium effort levels in (EC.45) and (EC.46) into the quality expressions, we obtain that

$$Q_c - Q_o = \frac{4(s_{cc}^O - s_{oc}^O)^2(s_{cc}^O)^2}{\lambda_1^2 \beta_c} - \frac{\lambda_2(s_{oo}^O - s_{co}^O)}{\beta_o \lambda_1^3} + O\left(\beta_c\right), \tag{EC.47}$$

which is decreasing in s_{oc}^O. Furthermore, from (EC.42), (EC.45), and (EC.46), it then follows that

$$\Pi_o^O(e_o^O) = \frac{4s_{oc}^O (s_{cc}^O)^3 (s_{oc}^O - s_{cc}^O)^2}{\beta_c \lambda_1^4} + \frac{\lambda_2^2}{2\beta_o \lambda_1^6} + O\left(\beta_c\right). \tag{EC.48}$$

From $\Pi_o^O(e_o^O)$ given in (EC.48), the coefficient of the leading term with $1/\beta_c$ is $4s_{oc}^O(s_{cc}^O)^3(s_{cc}^O - s_{oc}^O)^2/(4s_{cc}^O - s_{oc}^O)^3$. Taking derivative with respect to s_{oc}^O, we obtain

$$\frac{\partial}{\partial s_{oc}^O}\left(\frac{4s_{oc}^O(s_{cc}^O)^3(s_{cc}^O - s_{oc}^O)^2}{(4s_{cc}^O - s_{oc}^O)^3}\right) = -\frac{4(s_{cc}^O)^3(s_{cc}^O - s_{oc}^O)((s_{oc}^O)^2 + s_{cc}^O(9s_{oc}^O - 4s_{cc}^O))}{(4s_{cc}^O - s_{oc}^O)^5}. \tag{EC.49}$$

Note that (EC.49) is negative if $4s_{cc}^O/9 < s_{oc}^O < s_{cc}^O$. Hence in this case, $\Pi_o^O(e_o^O)$ decreases in s_{oc}^O. In the same regime, it follows that

$$\lim_{\beta_c \to 0} \frac{\beta_c W^O}{A} = \kappa_1, \tag{EC.50}$$

for some constant $\kappa_1 > 0$, where

$$A = \frac{2(s_{cc}^O - s_{oc}^O)(s_{cc}^O)^2(g_c(4s_{cc}^O - s_{oc}^O)^2 + s_{cc}^O(8(s_{cc}^O)^2 + 3s_{oc}^O s_{cc}^O - 2(s_{oc}^O)^2))}{(4s_{cc}^O - s_{oc}^O)^4}. \tag{EC.51}$$

We then obtain

$$\frac{\partial A}{\partial s_{oc}^O} = -\frac{2(s_{cc}^O)^2(g_c(4s_{cc}^O - s_{oc}^O)^2(2s_{cc}^O + s_{oc}^O) - s_{cc}^O(12(s_{cc}^O)^3 - 55s_{oc}^O(s_{cc}^O)^2 + 14(s_{oc}^O)^2 s_{cc}^O + 2(s_{oc}^O)^3))}{(4s_{cc}^O - s_{oc}^O)^5}. \tag{EC.52}$$

Note that under the condition of $4s_{cc}^O/9 < s_{oc}^O < s_{cc}^O$, it follows that $12(s_{cc}^O)^3 - 55s_{oc}^O(s_{cc}^O)^2 + 14(s_{oc}^O)^2 s_{cc}^O + 2(s_{oc}^O)^3 < 0$. As a result, we obtain $\partial A/\partial s_{oc}^O < 0$, which implies that a less restrictive policy increases social welfare.

For part (ii) about consumer surplus, using the derived equilibrium effort levels in (EC.45) and (EC.46), and plugging the equilibrium prices given in (11) into consumer surplus expression in (15), we similarly obtain

$$\lim_{\beta_c \to 0} \frac{\beta_c CS^O}{B} = \kappa_2, \tag{EC.53}$$

for some constant $\kappa_2 > 0$, where

$$B = \frac{2(s_{cc}^O - s_{oc}^O)(s_{cc}^O)^2(g_c(4s_{cc}^O - s_{oc}^O)^2 + (s_{cc}^O)^2(5s_{oc}^O + 4s_{cc}^O))}{(4s_{cc}^O - s_{oc}^O)^4}\,. \tag{EC.54}$$

After taking a derivative of B with respect to s_{oc}^O, it follows that

$$\frac{\partial B}{\partial s_{oc}^O} = -\frac{2(s_{cc}^O)^2(g_c(4s_{cc}^O - s_{oc}^O)^2(2s_{cc}^O + s_{oc}^O) - (s_{cc}^O)^2(20(s_{cc}^O)^2 - 37s_{cc}^O s_{oc}^O - 10(s_{oc}^O)^2))}{(4s_{cc}^O - s_{oc}^O)^5}\,. \tag{EC.55}$$

Note that $20(s_{cc}^O)^2 - 37s_{cc}^O s_{oc}^O - 10(s_{oc}^O)^2 > 0$ if and only if $s_{oc}^O < \frac{40s_{cc}^O}{37+\sqrt{2169}}$. Hence, if $g_c < \underline{\gamma}$, where

$$\underline{\gamma} = \max\left(\frac{(s_{cc}^O)^2(20(s_{cc}^O)^2 - 37s_{cc}^O s_{oc}^O - 10(s_{oc}^O)^2)}{(4s_{cc}^O - s_{oc}^O)^2(2s_{cc}^O + s_{oc}^O)}\,, 0\right)\,, \tag{EC.56}$$

then $\partial B/\partial s_{oc}^O > 0$, which implies that a less restrictive license decreases consumer surplus. Otherwise, i.e., if $g_c \geq \underline{\gamma}$, a less restrictive license increases consumer surplus. ■

Proof of Proposition 2: First, for sufficiently small β_c and $s_{oc}^O > s_{cc}^O$, there exists a range of c, such that $Q_o > Q_c > Q_b$ and $\tau_B(\vec{Q}) < c \leq Q_c/2$ are satisfied. By Lemma 2, p_o^O and p_c^O satisfy (13). Hence, by part *(ii)* of Lemma EC.3, we obtain

$$\Pi_c^O(e_c \,|\, e_o) = \frac{Q_o(Q_o - Q_c)(Q_c - 2c)^2}{Q_c(Q_c - 4Q_o)^2} - C_c(e_c^O)\,. \tag{EC.57}$$

Let $\hat{e}_c$ denote the interior optimizer of (EC.57). Then, by (EC.57),

$$AQ_o(Q_o - Q_c)D^2 + (B(Q_c - 2c) + 2(g_c + s_{cc}^O)(Q_o - Q_c)Q_o)D - \beta_c\hat{e}_c = 0\,, \tag{EC.58}$$

where

$$A = (g_c + s_{cc}^O)(Q_c - 4Q_o)^2 + 2Q_c(Q_c - 4Q_o)(s_{cc}^O - 4s_{oc}^O - 3g_c)\,, \tag{EC.59}$$

$$B = (Q_o - Q_c)(g_c + s_{oc}^O) + Q_o(s_{oc}^O - s_{cc}^O)\,, \tag{EC.60}$$

and

$$D = \frac{Q_c - 2c}{Q_c(Q_c - 4Q_o)^2}\,. \tag{EC.61}$$

Now, suppose $c = K/\beta_c$ for some $K > 0$. It then follows, by (EC.58), that $\lim_{\beta_c \to 0} \hat{e}_c\beta_c/\gamma = \kappa$, for some $\kappa > 0$. Substituting for c, $\hat{e}_c$, Q_o, Q_c, A and B into (EC.58), we have

$$\begin{aligned}\gamma = \sup\big\{\hat{\gamma} > 0 \,|\, &4K^2(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O) - \hat{\gamma}^2(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O)^2 \\ &+ \hat{\gamma}^3(g_c + s_{cc}^O)(3g_c + 4s_{oc}^O - s_{cc}^O)^2 = 0\big\}\,.\end{aligned} \tag{EC.62}$$

Again, substituting into (EC.57), we obtain

$$\lim_{\beta_c \to 0} \Pi_c^O(\hat{e}_c \,|\, e_o^O) \cdot \left(\frac{\tau_1 + \tau_2}{\beta_c \tau_3}\right)^{-1} = \kappa_a\,, \tag{EC.63}$$

for some $\kappa_a > 0$, where

$$\tau_1 = 8K^2(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O) - 8K\gamma(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O), \tag{EC.64}$$

$$\tau_2 = 2\gamma^2(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O)^2 - \gamma^3(g_c + s_{cc}^O)(3g_c + 4s_{oc}^O - s_{cc}^O)^2, \tag{EC.65}$$

and

$$\tau_3 = 2\gamma(g_c + s_{cc}^O)(3g_c + 4s_{oc}^O - s_{cc}^O)^2\,. \tag{EC.66}$$

If $\tau = (\tau_1 + \tau_2)/\tau_3 > 0$ then $e_c^O = \hat{e}_c$, and hence, by (EC.29), we obtain

$$\lim_{\beta_c \to 0} \tau_B(\vec{Q}) \cdot \left(\frac{\gamma g_c(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O)}{(s_{cc}^O(4s_{oc}^O - s_{cc}^O) + g_c(2s_{oc}^O + s_{cc}^O))\beta_c}\right)^{-1} = \kappa_b\,, \tag{EC.67}$$

and

$$\lim_{\beta_c \to 0} Q_c \left(\frac{\gamma(g_c + s_{cc}^O)}{\beta_c}\right)^{-1} = \kappa_c\,, \tag{EC.68}$$

for some $\kappa_b > 0$ and $\kappa_c > 0$. By (EC.67), $c > \tau_B(\vec{Q})$ is satisfied whenever $\gamma < K(s_{cc}^O(4s_{oc}^O - s_{cc}^O) + g_c(2s_{oc}^O + s_{cc}^O))/(g_c(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O))$ which, by (EC.62), is satisfied when

$$K > \underline{K} = \max\left(\frac{s_{cc}^O(4s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O)\tau_6}{\tau_4\tau_5^3}\,, \quad \frac{2\tau_6}{3\tau_4^2\tau_5}\right), \tag{EC.69}$$

where $\tau_4 = 3g_c + 4s_{oc}^O - s_{cc}^O$, $\tau_5 = s_{cc}^O(4s_{oc}^O - s_{cc}^O) + g_c(2s_{oc}^O + s_{cc}^O)$ and $\tau_6 = g_c(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)^2(g_c + s_{cc}^O)^2$. By equations (EC.62)-(EC.66), the critical value of K such that $\tau = 0$ is given by

$$\hat{K} = \frac{4(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O)^2}{27(3g_c + 4s_{oc}^O - s_{cc}^O)^2}\,. \tag{EC.70}$$

Further, again by (EC.62)-(EC.66),

$$\frac{d\tau}{dK} = \frac{\partial\tau}{\partial K} + \frac{\partial\tau}{\partial\gamma} \cdot \frac{d\gamma}{dK} = \frac{4(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)(2K - \gamma(g_c + s_{cc}^O))}{\gamma(g_c + s_{cc}^O)(3g_c + 4s_{oc}^O - s_{cc}^O)^2} < 0 \tag{EC.71}$$

is satisfied for $\gamma > 2K/(g_c + s_{cc}^O)$ which holds when $K < \tilde{K}$ where

$$\tilde{K} = \frac{(g_c + s_{oc}^O)(s_{oc}^O - s_{cc}^O)(g_c + s_{cc}^O)^2}{\sqrt{27}(3g_c + 4s_{oc}^O - s_{cc}^O)^2}\,. \tag{EC.72}$$

Since $\underline{K} < \hat{K}$ is satisfied when $7g_c s_{cc}^O + 4s_{oc}^O s_{cc}^O > 4g_c s_{oc}^O + (s_{cc}^O)^2$ and $c \leq Q_c/2$ is satisfied when $\gamma > 2K/(g_c + s_{cc}^O)$, by (EC.70) and (EC.72), we obtain $\underline{K} < \hat{K} < \tilde{K}$ such that $\tau_B(\vec{Q}) < c \leq Q_c/2$ and $\tau < 0$ are satisfied for all $K\in(\hat{K},\tilde{K})$. By (EC.62) and $\tau=(\tau_1+\tau_2)/\tau_3$, we obtain

$$\frac{d\tau}{ds_{oc}^O}=\frac{\partial\tau}{\partial s_{oc}^O}+\frac{\partial\tau}{\partial\gamma}\cdot\frac{d\gamma}{ds_{oc}^O}=\frac{(3g_c+2s_{oc}^O+s_{cc}^O)(2K-\gamma(g_c+s_{cc}^O))^2}{\gamma(3g_c+4s_{oc}^O-s_{cc}^O)^3}>0\,, \tag{EC.73}$$

hence there exist parameter values $s_{oc}^O<\bar{s}_{oc}^O$ and an interval $S_K\subset(\hat{K},\tilde{K})$ such that if $K\in S_K$, then $\tau<0$ under s_{oc}^O and $\tau>0$ under $\bar{s}_{oc}^O$. Since $\tau<0$ implies $e_c^O=0$ which implies $\rho^*=P$, and since $c=K/\beta_c$, it then follows that $|Q_o-Q_c|$, Π_o^O, CS^O and W^O under $\bar{s}_{oc}^O$ are larger than $|Q_o-Q_c|$, Π_o^P, CS^P and W^P under s_{oc}^O. ■

B. The Analysis for the Case where the Contributor is not Profit Seeking

In this section, we examine a case where the contributor has an altruistic motivation as opposed to a profit-seeking motivation associated with the services market. The sequence in the timeline remains similar to the primary model employed in the paper. First, the originator chooses a source code strategy: proprietary or open-source. Second, the originator determines her effort investment e_o to increase the quality of her software offering. Third, the altruistic contributor's effort e_c is modeled as a random shock, uniformly distributed over the support $[\underline{e}_c,\bar{e}_c]$, and realized in this period. Fourth, after all development efforts have been observed, the originator sets price(s). If the originator employed a proprietary strategy, then it sets both its software price p^P and the price for its services p_o^P. However, if the originator employed an open-source strategy, then it sets only the price for its services p_o^O. Having only an altruistic motivation, the contributor does not compete in the market for services. Fifth and finally, consumers decide whether to use/purchase (OSS/proprietary) the software and, if so, whether to contract with the originator or the competitive integrator for services. To be consistent with analyses provided in the main body, we focus on the strong contributor regime. Specifically, we assume that $\underline{e}_c>\max\left(\frac{2c}{g_c},\frac{g_o(g_o+2s_{oo}^O)-8\beta_o c}{8\beta_o s_{oc}^O}\right)$ and $\beta_o<(g_o+s_{oo}^P)^2/(6\sqrt{3}c)$.

Under an OSS strategy and the sufficient condition, $\underline{e}_c>2c/g_c$, the originator's profit is given by

$$\Pi_o^O=\begin{cases}(p_o^O-c)\left(1-\frac{p_o^O-c}{Q_o^O-Q_b^O}\right)-\frac{\beta_o(e_o^O)^2}{2} & \text{if}\quad p_o^O\geq\frac{Q_o^Oc}{Q_b^O}\,;\\ (p_o^O-c)\left(1-\frac{p_o^O}{Q_o^O}\right)-\frac{\beta_o(e_o^O)^2}{2} & \text{if}\quad p_o^O<\frac{Q_o^Oc}{Q_b^O}\,.\end{cases} \tag{EC.74}$$

Maximizing (EC.74) with respect to p_o^O, we obtain $p_o^O=c+(Q_o^O-Q_b^O)/2$, where $Q_o^O=g_oe_o^O+g_ce_c+s_{oo}^Oe_o^O+s_{oc}^Oe_c$ and $Q_b^O=g_oe_o^O+g_ce_c$. This price, p_o^O, corresponds to the interior optimal price for the first case in (EC.74), i.e., $p_o^O\geq Q_o^Oc/Q_b^O$. In this case, the originator's expected profits are given by

$$\Pi_o^O=\frac{s_{oo}^Oe_o^O+s_{oc}^OE[e_c]}{4}-\frac{\beta_o(e_o^O)^2}{2}\,. \tag{EC.75}$$

Maximizing (EC.75) over e_o^O, the optimal effort of the originator is given by $e_o^{O,*} = s_{oo}^O/(4\beta_o)$, and its optimal expected profit can be written as

$$\Pi_o^{O,*} = \frac{(s_{oo}^O)^2}{32\beta_o} + \frac{E[e_c]}{4} s_{oc}^O\,, \tag{EC.76}$$

noting that $\Pi_o^{O,*}$ in (EC.76) is continuously increasing in s_{oc}^O. Expected social welfare can be simplified to

$$W^O = E\left[\frac{g_o(s_{oo}^O)^2(2g_o + s_{oo}^O) + 32\beta_o^2(g_c e_c - c)^2 + 4\beta_c s_{oo}^O(g_c(g_o + s_{oo}^O)e_c - 4cg_o)}{16\beta_o(4\beta_o g_c e_c + g_o s_{oo}^O)}\right] + \frac{3E[e_c]}{8} s_{oc}^O\,. \tag{EC.77}$$

Similar to the originator's expected profit, W^O is also continuously increasing in s_{oc}^O. Expected consumer surplus is written as

$$CS^O = E\left[\frac{g_o(s_{oo}^O)^2(4g_o + s_{oo}^O) + 64\beta_o^2(g_c e_c - c)^2 + 4\beta_c s_{oo}^O(g_c(8g_o + s_{oo}^O)e_c - 8cg_o)}{32\beta_o(4\beta_o g_c e_c + g_o s_{oo}^O)}\right] + \frac{E[e_c]}{8} s_{oc}^O\,, \tag{EC.78}$$

which is also linearly increasing in s_{oc}^O.

Next, under a proprietary strategy and the sufficient condition provided above, the originator's pricing problem can be expressed

$$\max_{p^P,\, p_o^P} \quad \Pi_o^P(p^P, p_o^P \,|\, e_o^P, e_c) = p^P \int_\Theta \mathbf{1}_u(\theta)d\theta + \left(p_o^P - c\right) \int_\Theta \mathbf{1}_o(\theta)d\theta - \tfrac{1}{2}\beta_o(e_o^P)^2\,, \tag{EC.79}$$

where $\mathbf{1}$ is the indicator function, and $\int_\Theta \mathbf{1}_u(\theta)d\theta$ and $\int_\Theta \mathbf{1}_o(\theta)d\theta$ correspond to the total demand for the software and the total demand for the originator's services, respectively. Even with the presence of the competitive integrator, one can establish that the originator obtains monopoly profits. Specifically, as long as $Q_o > c$, the originator can set $p_o^P = c$ and $p^P = (Q_o - c)/2$, pushing the competitive integrator out of the market and achieving monopoly profits, which can be written as

$$\Pi_o^P = \frac{(Q_o - c)^2}{4Q_o} - \frac{1}{2}\beta_o(e_o^P)^2\,, \tag{EC.80}$$

where $Q_o = (g_o + s_{oo}^P)e_o^P$. Note that if $Q_o \le c$, $\Pi_o^P = -\frac{1}{2}\beta_o(e_o^P)^2 \le 0$. The first order condition for the maximization of the originator's profit in (EC.80) with respect to e_o^P can be simplified to

$$-(g_o + s_{oo}^P)(e_o^P)^2(4\beta_o e_o^P - (g_o + s_{oo}^P)) - c^2 = 0\,. \tag{EC.81}$$

Under the sufficient condition of $\beta_o < (g_o + s_{oo}^P)^2/(6\sqrt{3}c)$, the first order condition (EC.81) has two positive solutions, among which the larger one is the unique local maximizer. Consequently, for the proprietary case, $e_o^{P,*}$ is either 0 or the larger positive solution of (EC.81). In other words, if the larger positive solution of (EC.81) leads to positive profit in (EC.80), it becomes the optimal effort level of the originator. Otherwise, the originator does not invest in quality improvement. Under the sufficient condition, $\underline{e}_c > \frac{g_o(g_o+2s_{oo}^O)-8\beta_o c}{8\beta_o s_{oc}^O}$, the upper bound of (EC.80), $\frac{Q_o - c}{4} - \frac{1}{2}\beta_o(e_o^P)^2$, is less than (EC.76). As a result, in the strong contributor regime, it is optimal for the originator to choose an open source strategy for this case of an altruistic contributor.