QUALITY AND QUANTITY EFFECTS IN

PLATFORM MARKETS WITH OPEN GOVERNANCE

Claudio Panico[1] , and Carmelo Cennamo[2]

Bocconi University

Via Roentgen, 1, 20136 Milano, Italy

Abstract. The value of modern platforms depends critically on the quantity and quality of the complementary products offered to the end users by independent developers. In this paper, we consider the problem of a platform provider that manages the ecosystem of developers by means of an open governance. The provider sets the price for the end users that access the platform, and the royalties for the developers that transact with them in the platform market; yet, the developers have full autonomy when making investment and pricing decisions for their complementary products. Our framework enriches the existing formal analyses by addressing the developers' incentives and their strategic role for value co-creation. By focusing not just on quantity and variety but also on quality of complementary products, we clarify the importance of indirect network effects and highlight the trade-offs of platform ecosystem governance strategies.

Keywords: platform markets; open governance; indirect network effects; quality and quantity.

[1] Corresponding author. Tel: (39) 02-58363693. E-mail: claudio.panico@unibocconi.it.

[2] Tel: (39) 02-58363459. E-mail: carmelo.cennamo@unibocconi.it.

1. INTRODUCTION

Platform technologies and their ecosystems of external developers have gained central role in today's information economy. Hardware platforms like video game consoles, mobile systems, personal computers, software platforms like SAP, or else digital platforms, are just a few examples. Besides offering core products or services and investing in their features and performance, platform providers need to attract developers and end users (Armstrong 2006; Parker and Van Alstyne 2005; Rochet and Tirole 2003) but also nurture an innovative ecosystem (Cusumano 2010). Platforms that offers superior quality or better consumption experiences can be successful even when starting with a smaller user base (Shankar and Bayus 2003; Zhu and Iansiti 2012). For example, Apple's mobile iOS platform accounts for less than 15% of the mobile market, yet the quality and value generated from app sales makes the Apple iOS platform more valuable and profitable than Android OS, that accounts for almost 80% of the mobile market. Encouraging independent developers to exert innovative efforts, and thus having better complementary products, can also stimulate the users to join the platform and to transact more with the developers, leading ultimately to greater platform value. Google News, the content aggregator, is valuable to users only to the extent that the content generated by developers is relevant to them, as even Google's chair acknowledges. On Groupon, the digital platform that matches local merchants with local buyers, the limited usage of the platform by most buyers has been largely attributed to the poor quality of the deals. The videogame industry, in the early 1980s, crashed following low investments and the influx of low quality games; to the opposite, in the 1990s Sony's Playstation dominated the console market thanks also to the large number of high quality games.

Because the value of modern platforms depends critically on the quantity and quality of complementary products, it is crucial to understand the incentives to innovate of independent developers and the role of the platform strategy. In this paper, we set up a formal model that sheds light on the co-creation of platform value when both the developers and the platform provider "shape the rules of trade and reward sharing on the platform" (Alstyne, Parker, Choudary 2016). We focus on platforms markets with an open governance, whereby the developers maintain full autonomy to make investment and pricing choices about their complementary products. For the purpose of the discussion, we contextualize the model to the case of hardware platforms such as video game consoles. This is a good example because the gamers' need for high quality products seems to be stronger than in other platform markets, and our theoretical findings match well with the pricing strategy commonly observed in video games.

To illustrate, the developers supply complementary products (games), which can only be used by the end users (gamers) in combination with the core hardware (console). The independent developers decide autonomously how much to invest in the development of their games, as well as the price charged to the gamers. The ecosystem of developers is formed before the console is launched in the market; then, to join the platform the gamers purchase the console and pay the price to the provider, and also decide which game to buy. The platform provider also receives royalties from the developers that sell their games on the platform market. Gamers are more willing to purchase a console with a larger library of games and especially if more high-quality games are available (Binken and Stremersch 2009; Cennamo and Santaló 2013; Kim et al. 2014).

Platforms like this have been investigated from different perspectives. The information system literature emphasizes a modular design, whereby the platform guarantees interoperability via standardized interfaces while exercising minimal control over the developers; modularity allows to augment the core functionality and lets autonomous parties to specialize (Gawer 2014; Tiwana et al. 2010), creating more value for end users than integrated, firm-centric systems (Adomavicious et al. 2007; Boudreau 2010; Gawer 2014; Xu et al. 2010). This literature is not primary concerned with the role of platform strategies to encourage desiderable behaviors by independent developers. The economics literature instead emphasizes the virtuous cycle fueled by indirect network effects that link developers and users, stressing the importance of volume (and variety) of complementary products (Armstrong 2006; Clements and Ohashi 2005; Corts and Lederman 2009; Evans 2003; Parker and Van Alstyne 2005; Rochet and Tirole 2003; Shankar and Bayus 2003). By looking at the relationship between the platform provider and the two sides of the market primarily as a seller-buyer relationship, traditional models focus on fees for joining and transacting within the platform in relation to adoption decisions. Little work takes the perspective of developers beyond the decision to join a platform, to address the decisions about their complementary products (but see Huang et al. 2013; Claussen et al. 2015).

Following standard reasoning, by granting access to the developers, platform providers can open up a market for complementary innovations around the core product, attracting then more end users. Yet, as revealed by our examples above, just solving the problem of attracting the two sides to create a platform system might not be sufficient to create value. In addition to the much emphasized *quantity* aspect, many platforms need to nurture and innovative ecosystem to guarantee the *quality* of complementary products and stimulate high usage from the end users (Binken and Stremersch 2009; Claussen et al. 2015). Moreover, a strategy that targets only quantity could also hasten competition among developers, with ambiguous effects on quality (e.g., Boudreau 2012; Cennamo and Santaló 2013) and ultimately on platform value. Platforms in different contexts adopt alternative strategies to control quality.

Sometimes platform providers rely on certifications of quality; for example, SAP's integration and certification centers conduct extensive testing of the products of independent software vendors before endorsing the interoperability with the SAP platform. To the opposite, Google's Android remains open and lets developers innovate without approval, or else, like in the example of Google Play store or Apple's App store, platforms exclude only the low-quality applications. Thus, in many contexts it may be too costly or even impossible to control or to contract ex ante for innovative efforts and product quality. Thus, when maintaining an open platform governance, quality is chosen autonomously by developers that have their own, unique objectives when being active on a given platform market. To encourage then desiderable behaviors by autonomous developers, platform providers leverage both the platform architecture and interface (Anderson, Parker and Tan 2013) and the set of rules, or governance, to establish protocols, rights, but also the pricing terms that govern transactions (Tiwana et al. 2010; Alstyne, Parker, Choudary 2016).

For example, platform modularization calls for minimum control over modules, whereas with an integrated system the platform maintains a strict control over the ecosystem aspects. Research has focused on the benefits of a modular architecture with minimal control, i.e., open architecture and open governance for boosting variety of platform extensions and self-evolvability. But these aspects are still much under-theorized, and have been identified as an important area for information system research where we hold yet limited knowledge (Tiwana et al. 2010). Also, although a modular platform architecture may accelerate complementary innovation, it does not reduce interdependence with developers, who remain key for creating more value, nor guarantee the proper level of investment in the extensions (Baldwin and Clark 2006; Tiwana 2015). Overall, we still lack a proper understanding of the incentives of external developers within a platform market with an open governance; how their choices relate to the strategy chosen by the platform to attract the two sides of the market; and how this interaction affects the co-creation of platform value (e.g., Anderson et al. 2014; Boudreau 2010; Cennamo and Santaló, 2013; Ceccagnoli et al. 2012; Claussen et al. 2015; Huang et al. 2014; Wareham et al. 2014).

To shed light on these aspects, we build on existing formal analyses of platforms to offer a broader picture of developers' incentives beyond the decision to join the platform. Also, we account for the role of quantity *and* quality of complementary products to explain users' decision to join a platform. We then offer a formal model that clarifies the importance of the two indirect network effects for the functioning of a platform market (Clements and Ohashi 2005; Corts and Lederman 2009; Evans 2003; Kim et al. 2014; Shankar and Bayus 2003). In a platform market with an open governance, managing the platform ecosystem to induce the supply of *better* complementary products and stimulate greater usage is equally, if not more, important than solving the problem of having *more* complementary products and attract the two sides of the market.

To illustrate the main ingredients and findings, consider our leading example. Gamers are more willing to buy the console in the presence of a larger ecosystem of developers/games, which is the standard *quantity effect.* But gamers are also more willing to buy the console if games of greater quality are available, especially if they sell at lower prices; this is the *quality effect*. Starting with a demand for the hardware platform and for the complementary products that accounts for these two indirect network effects, our analysis emphasizes the strategic relationship between a platform provider and the independent developers. Developers choose the quality and prices of games in full autonomy, and their choices are driven by the competition for gamers. The platform provider sets the price of the console charged to the gamers as well as the royalties charged to the developers when they sell their games within the platform. The provider and the developers make (profit maximizing) choices that determine the demand for the console and for the available games, and ultimately the platform value. A key aspect of the analysis is the relative importance that gamers attribute to quantity and quality of games, and how these two effects drive the platform provider's and the developers' strategies. With this example in mind, we make the following steps for studying a platform market with an open governance.

First, we determine the developers' profit maximizing choices that correspond to a given pricing strategy chosen by the platform provider. This analysis allows to identifying two scenarios. In contexts in which end users consider the quality of products relatively more important than the quantity, a larger ecosystem of developers is associated with greater quality products that are sold to the end users at lower prices. Therefore, *quality and prices of complementary products are negatively correlated along the quantity dimension*. If instead the quantity of products is relatively more important, price and quality of products are greater in larger ecosystems; in this case, *quality and prices of complementary products are positively correlated along the quantity dimension*. Thus, when competing in the platform market, if users are mainly attracted by quality (quantity) of products available on the platform, the developers have greater (smaller) incentives to invest in quality, and they supply cheaper and greater (lower) quality products. These findings speak to the above mentioned ambiguous relationship between quantity and quality due to the hastened competition for users in larger ecosystem (e.g., Boudreau 2012; Cennamo and Santaló 2013).

Second, we investigate the (profit maximizing) platform strategy. To do so, we study the price of the core product (charged to the users) and of the royalties (charged to the developers) set in anticipation of the developers' investment and pricing decisions. Like previous studies, our model suggests that the end users are subsidized, i.e., they purchase the hardware at a price below the marginal cost of production; in addition, the model reveals that when the users value the quality of the complementary products more than quantity, the platform provider lowers the price of the hardware. This move is needed to increase the users' demand given that they are less attracted by the size of the ecosystem per se. Having stimulated the users' demand, and hence the number of potential transactions within the platform, the provider also increases the royalties charged to the developers to cover the losses. This pricing prescription is fully in line with what we observe in videogames, where the consoles tend to be priced below cost (see Eisenmann et al. 2016); thus, although the users strongly demand quality, they are subsidized, whereas the developers that supply games by making large investments in quality, are taxed with a royalty. Our model then suggests that as quality effects become relatively more important than quantity effects, the platform provider shifts the relative burden of price from the end users to the developers.

The model also reveals that, although the value jointly co-created by the platform provider and the independent developers increases with the size of the platform ecosystem, it is the platform provider that captures the lion's share of such value; and whereas the platform's profits increase, the developers' profits decrease due to greater competition in the platform market. On the other hand, the platform value decreases when the users value more the quality rather than the quantity of complementary products.

The remainder of the paper is organized as follows. Section 2 reviews the theoretical and empirical literature most closely related to our framework. In Section 3, we introduce the model of a platform market with open governance, explaining the role of the indirect network effects for the users' demand and how they affects the decisions of the platform provider and of the independent developers. In Section 4 we solve the model and obtain our main theoretical implications, explaining the economic intuition behind. In Section 5, we discuss the main limitations and comment on a few possible extensions, and Section 6 concludes.

LITERATURE REVIEW

Platform ecosystems coalesce when multiple players in distinct segments of an industry value chain respond to a core innovation (the platform) by developing complementary products (extensions, applications, content, etc.) that augment the platform's functionality to users (Adomavicious et al. 2007; Gawer 2014; Tiwana et al. 2010). Because of the interdependencies among the platform, its components and interfaces, and the extensions, scholars do not just consider the core technology of a platform per se, but its entire ecosystem, or "the network of innovation [that produces] complements that make a platform more valuable" (Ceccagnoli et al. 2012: 263). A modular design can boost innovation at the "periphery" of the platform and augments its core functionality by allowing independent parties to specialize on the innovation of complements, with the platform exercising minimal control while guaranteeing interoperability via standardized interfaces (Gawer 2014; Tiwana et al.

2010). By harnessing heterogeneous knowledge and capabilities that reside outside a single firm, helping to extend the functionality of the platform and generate better solutions, platform ecosystems can create more value for final users than integrated, firm-centric systems (Adomavicious et al. 2007; Boudreau 2010; Gawer 2014; Xu et al. 2010).

Indeed, when users decide whether or not to adopt a platform, they evaluate both the platform and its complements (Anderson et al. 2014; Xu et al. 2010). This aspect has been emphasized by the economics literature, that refers to platform ecosystems as peculiar ("two-sided") markets in which the platform matches final users with developers, and each member affiliates with the platform to transact with the other side (Armstrong 2006; Caillaud and Jullien 2003; Clements and Ohashi 2005; Rochet and Tirole 2006). Thus, in addition to the so-called direct network effects in communication markets (e.g., Economides 1996; Katz and Shapiro 1986), two-sided platform markets are influenced by indirect network effects (Armstrong 2006; Evans 2003; Rochet and Tirole 2003, 2006) that arise between the two sides of the market. These indirect effects are crucial determinants of a platform's strategy (Clements and Ohashi 2005; Corts and Lederman 2009; Evans 2003; Shankar and Bayus 2003). Formal models suggest optimal pricing strategies in relation to the chicken-and-egg problem of attracting members on the two sides (Caillaud and Jullien 2003), and defend the use of freemium strategies to increase the size of the network (Eisenmann et al. 2006; Parker and Van Alstyne 2005).

A typical approach in the economics literature is to start with a utility (or demand) function for the members on the two sides that accounts for (indirect) network effects, then derive the number of members (that play the simultaneous coordination game or arrive in a defined order) as a function of the (membership and usage) fees charged by the platform, and finally compute optimal fees (e.g., Armstrong 2006; Caillaud and Jullien 2003; Hagiu 2006; Rochet and Tirole 2003, 2006). This approach offers deep insights about the role of indirect network effects, and provides a fair description of two-sided markets such as payment systems (e.g., credit cards, Paypal), matching platforms (e.g., Match.com; InnoCentive), or pure marketplaces (e.g., eBay.com), where the number and the variety of the transactions that members can realize represent the main sources of platform value. But in platform markets such as videogame or smartphone systems, or in software and digital platforms, the quality of the complementary products is equally or even more important than the quantity.

In such cases, the information system literature highlights the importance of design of the platform architecture and the governance of the platform ecosystem (Tiwana et al. 2010; Wareham et al. 2014). The platform provider typically has no direct control over the ecosystem's output; nevertheless, it makes choices about the attributes and the performance of the core technology, the interface and programming tools that would affect the complementary innovation by developers (Anderson et al. 2014; Gawer 2014). Also, it can set the licensing policy to select who participate in the ecosystem and induce investment in greater quality. Because complements are critical assets developed (and owned) by external, independent developers, platform providers must design the architecture and the set of rules to enhance developers' participation and innovation (Anderson et al. 2014, 2016; Boudreau 2010; Cennamo and Santaló 2013; Gawer 2014; Tiwana 2015). To this end, they typically build system interfaces that structure their ecosystems as marketplaces (Boudreau and Lakhani 2009), setting standard selection policies for ecosystem participation while letting developers free to decide which complementary extensions to develop, their price and quality. As additional developers join the ecosystem, competitive pressure emerges, greater variation and experimentation would occur that should make the market self-regulating with developers differentiating their extensions and users selecting the most valuable one, and guarantee ecosystem growth and evolvability. However, these areas have been underresearched so far (Tiwana et al. 2010), with little work exploring platform provider-developers relationships or intra-platform competition among developers (but see Huang et al. 2014; Tiwana 2015). We know little about whether and how these effects apply, particularly in contexts where the quality of the complementary extensions is crucial for a platform to offer value to end users.

Recently the literature has started investigating the relationship between the platform provider's decisions about platform features and performance and the developers' nonprice decisions (e.g., Anderson, Parker, Tan 2014; Zhu and Iansiti 2012). For instance, how platform quality influences platform adoption and ecosystem growth (Xu et al., 2010; Zhu & Iansiti, 2012), and when enhanced levels of platform performance can actually hinder innovation efforts on the complements' side (Anderson et al. 2014; Claussen et al., 2015), undermining the overall quality of the platform system. A few empirical studies have also considered the trade-off between hardware attributes and availability of complementary products (Claussen et al. 2015; Gretz 2010; Nair et al. 2004). Other studies have examined more directly developers' decision to join the ecosystem and their level of contribution as function of the control/selection mechanisms and incentives set by the platform provider. Boudreau (2010) studies how different levels of access to the platform ecosystem granted to independent developers (i.e., the degree of openness of the platform market for complementary components) affect its rate of innovation; he found that, for handheld computing system over the period 1990-2004, licensing approaches granting greater participation into the ecosystem boosted the rate of complementarity components' innovation.

Tiwana (2015) examines 342 platform extensions in Mozilla's Firefox browser ecosystem, and shows that competition among these extensions over a platform's end users leads to refined versions to better meet users' needs; yet, input control by the platform provider, which is defined as the degree to which a platform provider adjudicates allowing revisions of an extension into the ecosystem (2015: 269), is needed to guarantee greater complementarity with the extension modularization, and enhance an extension's market performance. Wareham et al (2014) highlight the paradox of change that lies in the trade-off between allowing freer entry into the ecosystem and letting developers free to innovate to boost content variety and ecosystem evolvability, and exercising control over the ecosystem to avoid potential fragmentation. Other studies have also highlighted how the level of competition within the ecosystem and value capture concerns can limit the level of participation by developers and complement variety (Ceccagnoli et al., 2012; Gawer & Henderson, 2007; Huang et al. 2014).

However, relatively little analysis exists on content quality. Binken and Stremersch (2009) show that a technological platform is more valuable, and thus attractive to users, when there are high-quality complements (compatible applications). Platforms in which developers face intense competition can experience a decrease in the quality and rate of innovation of complements (Boudreau 2012). Similarly, Cennamo and Santaló (2013) provide evidence that enhancing competition among developers while also tying them in exclusivity deals to the platform, actually can undermine the quality of the complements, and thus platform market performance. However, it remains unclear when greater access to platform ecosystem and thus greater levels of within-platform competition affect positively or negatively platform value, and how value capture tensions between the platform provider and developers ultimately affect developers' incentives for greater quality investments.

Here, we investigate how a platform provider's pricing decisions regulating access (membership) and trade (usage) in a open governance regime affects developers' incentives, specifically, the average quality level of the complements they supply. Our paper complements this stream of research focusing on the developers' choices about quality of content. By emphasizing the role of both content quality and content variety, we can derive a formal model that highlights the links between the platform provider's and the developers' strategic choices affecting platform value. Our analysis helps clarify when and why an increased level of (within-platform) competition affects content quality, negatively or positively. This is an important aspect also for obtaining good empirical measures of the indirect network effects (Kim et al. 2014).

3. MODEL SET UP

In this section, we build a formal model of platform markets with an open governance, i.e., platforms with an ecosystem of developers that compete for the end users by making decisions in full autonomy. As we said, the model targets hardware platforms such as videogame, but it could also be extended to other settings. Here we are not concerned with the much studied problem of attracting *both* sides of the market (simultaneously or sequentially). Instead, we want to emphasize the problem of nurturing an innovative ecosystem and of increasing the volume of trade. So, as a first step, we consider as a given the number of developers already active on the platform market, before the end users arrive. In line with previous works on two-sided markets, the end users are more willing to join a platform with a larger ecosystem of developers, such that the demand for the core product increases with the number of developers/complementary products. Adding to the standard quantity effect, the users are also more willing to join the platform if complementary products of greater quality are available (especially if they sell at lower prices). Thus, the demand of the core product increases (decreases) with the average quality (price) of the complementary products.

Our formal model allows to study how the two indirect network effects due to quality and quantity shape the platform strategy (that aims to attract and sell the core product to more users, and to stimulate them to transact more) and the strategy of the independent developers (who compete to attract and sell their complementary products to the end users). The model is centered around the strategic interaction between the platform provider and the developers, examining how the platform strategy affects the strategy of the autonomous developers.

Main variables

The platform provider produces the core hardware at a constant marginal cost $C > 0$. In line with previous literature (e.g., Anderson et al. 2014), in our model the platform provider sets the price P that the users pay to purchase the hardware, and the royalty R that the developers pay when selling their products through the platform. Following Rochet and Tirole (2006), we refer to (P, R) as the platform's price structure.[3] The platform ecosystem is made of a large number m of developers, each offering one complementary product and all competing for the end users that join the platform. Developer $i = 1, \ldots, m$ supplies a product of quality $q_i \geq 0$ and sells it at a price $p_i \geq 0$, incurring a cost of development, that is assumed

[3] Rochet and Tirole (2006) distinguish between membership (ex ante) and usage (ex post) fees and note that in two-sided markets, the volume of transactions between members on the two sides depends on the structure not only just the overall level of fees charged by the platform.

to be quadratic and equal to $\frac{c}{2}(q_i)^2$, $c > 0$, but no marginal cost.[4] Let $p = (p_1, \ldots, p_m)$ and $q = (q_1, \ldots, q_m)$ be the vectors of prices and qualities of the complementary products. The platform is then fully described by $(P, R; p, q)$, and all these variables are endogenously determined by referring to the parties' profit maximizing decisions. With an open platform governance, the investment and the pricing decisions about the complementary products are fully under the developers' control, and are driven by the competition for the end users.

Demands and profits

On the users' side, we distinguish between demand for the core hardware and demand for the complementary products. The hardware demand is determined by the function $D(P, Q, p, q, m)$, where D is decreasing with the price of the hardware P and the technological attributes or functionalities of the platform Q; to account for the standard indirect network effects due to quantity, more users purchase the hardware if there are more developers, such that D increases with m; and finally, D is greater if the developers supply cheaper and better applications, such that D decreases with p_i and increases with q_i, $i = 1, \ldots, m$, which captures the quality effect. As for the demand for each application that corresponds to the total number of users that join the platform, developer i's market share is a fraction $s^i(p, q)$ of D, where s^i is increasing (decreasing) with q_i (p_i) and increasing (decreasing) with the price p_j (quality q_j) of rival developers, $j \neq i$. The functions D and s^i, $i = 1, ..., m$, are well-behaved and admit first, second, and cross-order derivatives.

The profits of the platform provider, Π, correspond to the sum of the revenues from selling the hardware to the users and of the royalties collected from the developers, less the

[4] A fixed cost of production and a zero marginal cost of replication is a typical cost structure for information goods.

cost of production, which we write as

$$\Pi = (P-C)D(P,p,q,m) + \sum\nolimits_{i=1}^{m} Rs^i(p,q)D(P,p,q,m) \tag{1}$$
$$= [P-C+R]\, D(P,p,q,m).$$

Developer i's profits, π^i, are instead given by the revenues from selling its product, net of the royalties paid and the cost of development, which we write as

$$\pi^i = (p_i - R)s^i(p,q)D(P,p,q,m) - \frac{c}{2}(q_i)^2. \tag{2}$$

The developers' choices of the price and quality, (p,q), is set in response to the price structure (P,R), and result from the competition for users in the platform market. The provider's problem then reduces to choosing the price structure taking the developers' incentives and the users' purchasing behavior into account. To reveal the intuitions behind the formal results of this analysis, we seek to provide closed-form solutions. To this scope, we use specified functional forms for the demand D and the shares s^i, $i = 1,...,m$, and also make symmetry assumptions in the model.

First, to capture the developers' competition for users, we refer to the users' attraction for product i as a function that decreases with the price p_i and increases with the quality q_i of the application, while imposing three properties. First, no user purchases a product i that is not attractive at all, such that the developer i sells no products if its attraction is zero. Second, to maintain symmetry in the model, we ensure that developers i and j that sell equally attractive products end up having the same market share. Third, we require that the equally attractive products i and j are affected in the same way by changes in the attraction of a third product k. As proved by Bell, Keeney, and Little (1975), these three properties imply that the market share of each developer is a linear normalization of attraction. This is an example of a share-attraction framework familiar to marketing and strategy scholars (e.g., Karnani 1985). Following a standard approach, we assume that the attraction of developer i's product is $q_i p_i^{-\delta}$, where $\delta > 1$ is the price elasticity, and that developer i's market share is

$$s^i(p, q) = \frac{q_i p_i^{-\delta}}{\sum_{j=1}^{m} q_j p_j^{-\delta}}. \tag{3}$$

Thus, a developer's market share corresponds to the attraction of his complementary product relatively to the overall attraction of the complementary products available on the platform.

Second, we account for the hardware demand using a specification with two distinct approaches, gleaned from different literature streams, that reduce to particular cases of our setting. As for the complementary products, define the hardware's attraction as $QP^{-\sigma}$, where $\sigma > 1$ is the price elasticity. To start, suppose that if the hardware is a stand-alone product, the baseline demand corresponds to $D = QP^{-\sigma}$. As is standard, in a two-sided market, demand reflects the indirect network effects; we assume that the users' willingness to join the platform increases linearly with the number of developers, such that $D = QP^{-\sigma}m$. This specification captures the quantity effect but does not account for users' actual benefits from using the complementary products, which is instead a key aspect of the platform markets we have in mind. Therefore, we augment the demand assuming that users are more willing to join the platform if the developers supply cheaper and better products, and the hardware demand D increases, at a decreasing rate, with the *average attraction* of the complementary products,

$$\left(\frac{\sum_{j=1}^{m} q_i p_i^{-\delta}}{m}\right)^{\theta}, \ \theta \in (0, 1). \tag{4}$$

Thus, the hardware demand corresponds to:

$$D(P, p, q; m) = QP^{-\sigma} m \left(\frac{\sum_{i=1}^{m} q_i p_i^{-\delta}}{m} \right)^{\theta} = QP^{-\sigma} m^{1-\theta} \left(\sum_{i=1}^{m} q_i p_i^{-\delta} \right)^{\theta}. \tag{5}$$

With this specification, quality becomes increasingly more important than quantity for the users as θ increases. Intuitively, when both effects are more prominent, there is a larger hardware demand, but here we are concerned with the relative importance of these two effects, as captured by θ. Note that our assumptions lead to the much used Cobb-Douglas specification, with the hardware demand being homogeneous of degree 1 with respect to the characteristics of the ecosystem, i.e., the number of developers and the attraction of their complementary products. Finally, in our specification the demand D is linear with respect to the hardware's attraction, $QP^{-\sigma}$, but concave with respect to the developers' products attraction. Alternative specifications might entail different weights for the components of the demand as to capture the relative importance of the hardware and the complementary products.

With the specification in Equations (3) and (5), the demand for application i becomes

$$s^i(p, q) D(P, p, q, m) = \left(QP^{-\sigma} \right) \left(m^{1-\theta} \right) \frac{q_i p_i^{-\delta}}{\left(\sum_{j=1}^{m} q_j p_j^{-\delta} \right)^{1-\theta}} \tag{6}$$

This is consistent with the standard specification used in share-attraction frameworks that accounts for the so-called *system* effect, whereby it is assumed that the total market size is an increasing (concave) function of total attraction. Our setting augments the standard formula with the term $m^{1-\theta}$ to account for the quantity effect in a two-sided platform.

Finally, the platform's and developer i's profits in Equations (1) and (2) can be rewritten as

$$\Pi = (P - C + R) \left[QP^{-\sigma} m^{1-\theta} \left(\sum_{i=1}^{m} q_i p_i^{-\delta} \right)^{\theta} \right] \tag{7}$$

and

$$\pi^i = (p_i - R)QP^{-\sigma}m^{1-\theta}\left(\frac{q_i p_i^{-\delta}}{\left(\sum_{j=1}^{m} q_j p_j^{-\delta}\right)^{1-\theta}}\right) - \frac{c}{2}(q_i)^2. \tag{8}$$

Equations (7) and (8) reveal the strategic interaction between the platform provider and its developers on the one hand, and among the developers active in the platform market on the other hand. Each party makes profit maximizing choices; the profits of each party depend on its choices, as well as on the choices of others. The equilibrium concepts that we use for solving the model are subgame-perfect equilibrium and Nash equilibrium. The platform provider chooses the pricing structure (P, R), and the developers then decide, independently and simultaneously, the price and quality of their complementary products, such that the vectors p and q are determined. End users make their purchasing decisions; they decide whether to buy the hardware or not, which defines the demand D, and which product to buy, which determines the market shares s^i, $i = 1, ..., m$.

4. SOLVING THE MODEL

We now compute the platform's and the developers' equilibrium decisions, and the resulting level of profits. We first consider as given the price structure (P, R) and determine the developers' equilibrium choices accordingly. Because we have maintained symmetry in the model, we can focus on the symmetric Nash equilibrium. Then we use backward reasoning to solve for the optimal price structure (P^*, R^*) and then find the resulting equilibrium values p^* and q^*. As we proceed with this analysis, we also illustrate the comparative statics and the different scenarios that can emerge.

The developers' choices

We start by determining the equilibrium price and quality of complementary products that correspond to a given price structure (P, R). For ease of exposition, the formal proofs and the complete formulas of the equilibrium values appear in the Appendix. Below we report propositions that reveal the main properties of the equilibrium values in relation to the key parameters of the model, m and θ.

When being active in the platform market, the independent developers participate in the competition game to attract users that have joined the platform, and we can prove the following:

Proposition 1. *With an open governance, the price of complementary products in a platform market decreases with the size of the ecosystem (m). Moreover, prices are lower when the end users value more the quality of the complementary products rather than the quantity.*

To explain the intuition behind Proposition 1, it is useful to derive the well-known Lerner pricing formula for the equilibrium price, $\hat{p}(R)$:

$$\frac{\hat{p}(R) - R}{\hat{p}(R)} = L = \frac{1}{\delta} \frac{m}{m - (1 - \theta)}. \tag{9}$$

Equation (9) reveals first the intuitive fact that there is greater competitive pressure when there are more developers competing for users within the platform, such that the equilibrium price decreases with m due to the competition effect. But as m increases, the equilibrium price does not converge to the "marginal cost" R, as happens in standard oligopolistic models. The negative competition effect instead is compensated for by the market expansion ensuing from the indirect network effects due to the greater quantity of complementary products. Thus, each developer maintains a local monopoly power in the platform market thanks to the positive demand effects, and though declining, the developers' price margin $p - R$ remains positive in equilibrium as it converges to the standard condition for the single product monopolist, with $L = \frac{1}{\delta}$. Note that Equation (9) coincides with this last standard pricing formula in the limit case when $\theta = 1$, that is, when the indirect network effects are purely driven by the quality effect. Thus, when $\theta = 1$, the greater competition for a given number of end users is exactly compensated for by an increase in the number of users, and therefore the market power of each developer active in the platform market remains unchanged.

Our second result pertains to the developers' incentives to invest and to the equilibrium level of quality of the complementary products. We can prove the following:

Proposition 2. *With an open governance, the quality of complementary products in a platform market increases with the size of the ecosystem (m) if the users value enough more the quality of products rather than the quantity, with $\theta > \frac{1}{\delta}$, and decreases otherwise.*

Unlike price, the impact of the number of developers m on the quality of complementary products is not straightforward. This ambiguity is not specific to our model. Standard analyses of vertical differentiation reveal that, for example, the level of quality in a perfectly competitive benchmark can be greater or lower than the monopolist's choice (see Tirole 1988). Our analysis reveals the main drivers of developers' choice of quality in platform contexts. Similar to what happens with prices though, when the number of developers increases, there is greater competition for users and also greater indirect network effects that raises the demand. The competition effect does not always dominate over the demand effect, and so the comparative statics about the equilibrium level of quality reveals different scenarios.

The first scenario corresponds to the case in which the users are highly sensitive to the prices of complementary products and/or they value much the product quality rather than their quantity, such that $\delta\theta > 1$. This is the case when the negative effects of competition dominate the benefits of market expansion resulting from indirect network effects. As prescribed by Proposition 1, developers charge lower prices as m increases, and the greater competitive pressure is such that they also increase the quality of their products to make them more attractive for users. Ultimately, in this scenario we observe a negative correlation between prices and quality when the platform ecosystem gets larger. (We will focus on this scenario when analyzing the platform's optimal pricing strategy.)

The second scenario corresponds to the case when users value much the quantity of products rather than the quality, and/or users are not too sensitive to the price of products, such that $\delta\theta < 1$. In this case, the competition effect is dominated by the market expansion due to indirect network effects, and because the users are mainly attracted by the quantity of developers/products, there are fewer incentives to invest in quality. Therefore a larger number of developers is associated with lower quality products, and now price and quality covary as the ecosystem gets larger.

The preceding discussion assumes that the price structure is given. As we said, the developers make their investment and pricing decisions responding to the observed price structure chosen by the platform provider. To fully reveal the functioning of the platform market, the last step is to endogenize P and R.

The platform provider's choices

Having determined the developers' equilibrium choice of the price and quality of complementary products that correspond to a given price structure, the next step is to close the model and consider the price of the core hardware and the royalty that are chosen in anticipation of the equilibrium outcome described in Propositions 1 and 2. This last step allows us to provide different insights into the platform's pricing strategy. The analysis refers to the case $\delta\theta > 1$ (i.e., strong quality effect), when the platform's profits are well defined and the first-order conditions characterize the optimal strategy.

The first result pertains to the optimal price of the core hardware:

Proposition 3. *With an open governance, the end users in the platform market are subsidized and the price that they pay for the core hardware is lower when they value more the quality of complementary products rather than the quantity, with* $P^* = \frac{\sigma}{\sigma+\delta\theta-1}C < C$.

As is standard, in a two-sided market the platform provider can expand the platform market and the number of transactions by reducing the price burden for one side (Parker and Van Alstyne, 2005; Rochet and Tirole 2006). This inducement also can happen without any competition among platforms. Yet, as we said, the driving force behind Proposition 3 is not the standard chicken-and-egg problem of attracting the two sides simultaneously. Here the number of developers m is given, so that one side of the market is already in place when the members on the other side arrive; then, the end users make their decision to join the platform based on the observed choices made by the platform provider and the developers. Therefore, the market expansion induced by subsidizing the core hardware aims at changing the incentives of the m developers as to modify their equilibrium choices. Thus, holding as fixed the quantity and quality effects, the expectation of a greater demand induces the developers to invest more in quality in equilibrium; and a reduction in the price of the core hardware ultimately allows the platform provider to leverage on the quality effect.

Note that, because the core hardware is sold at a loss, the burden of the price transfers from the end users to the developers, that have to pay royalties. To complete the analysis of the platform's pricing strategy, we must consider how the platform charges the developers, and the final effects on their equilibrium choices. This leads to our last proposition.

Proposition 4. *With an open governance, the developers in the platform market pay greater royalties when the users value more the quality of complementary products rather than the quantity, with* $R^* = \frac{\theta(2\delta\theta-1)}{2(\sigma+\delta\theta-1)}C > 0$.

The platform provider subsidizes the end users by selling the core hardware at a loss, but then it makes money by charging the developers a royalty $R^* > 0$; in order to recover the losses, the platform provider needs to charge greater royalties the larger the marginal cost C. The increase in the royalties induces changes in the developers' equilibrium behavior that dampen the market expansion effect due to the users' subsidization; thus, the developers respond to an increase in the royalties by increasing the price and investing less in the quality of their complementary products, such that the overall attraction of their products, and hence the hardware demand, is now reduced. We offer a more detailed analysis of the equilibrium outcomes next.

Understanding quantity, quality, and competition effects[5]

Having fully solved the model, we can now look at the details of the functioning of the platform market. Specifically, this section seeks to address how the relative importance of quantity and quality effects, and the effect of competition among developers, influence the platform's pricing strategy, (P^*, R^*), and the corresponding price and quality of applications,

[5] The assumption of homogeneity is the key reason for our result that the optimal price structure does not depend on the number of developers. We comment on this later on.

(p^*, q^*).

First, we can note how the price structure (P^*, R^*) reflects the relative importance of the quality effect θ. Consistently with the market expansion induced by the subsidization of the users, the platform provider decreases the price of the core hardware when the product quality is valued more than the quantity, such that the users are less attracted by the size of the ecosystem per se; then, the platform provider asks for greater royalties to recover the losses. This means that the relative burden of price shifts from the users to the developers, as it can be immediately noted by checking that the ratio $\frac{P^*}{R^*} = \frac{2\sigma}{\theta(2\delta\theta-1)}$ decreases with θ. The full resolution of the model further reveals that the quality effect is also a key driver of the equilibrium price and quality of complementary products, as illustrated graphically in Figure 1a below.[6] Particularly, as the platform provider increases P^* and R^* when θ increases, the developers react mainly increasing the prices in equilibrium, while they react less when modifying the product quality.

Figure 1 about here.

Second, we can also note that the size of the ecosystem does not play a major role in explaining the equilibrium price structure and the price and quality of complementary products. According to Propositions 3 and 4, the platform strategy does not depend on m, and whereas the developers's choices in response to a given price structure depend on m (Propositions 1 and 2), the full resolution of the model confirms that the quality effect θ is the main driver of the price and quality of complementary products, as illustrated graphically in Figure 1. As we comment above, this finding that the size of the ecosystem explains much

[6] In Figures 1 and 2 we have set $\delta = \sigma = 2$, $c = 1$, $C = 10$, $Q = 100$.

less of the variation in all the key variables stems from the properties of the demand function. Particularly, it is driven by the assumption that the demand $D(P, p, q; m)$ is homogeneous of degree 1 with respect to the size of the ecosystem and the overall attraction of the available products. Nevertheless, the size m plays a crucial role in determining the platform provider's equilibrium profits. Figure 2 illustrates graphically how the size m and the quality effect influence the platform provider's and the developers' equilibrium profits, Π^* and π^*.

Figure 2 about here.

Note first that an increase in the size of the ecosystem has opposite effects on Π^* and π^*. As already noted, a greater m induces both increased competition in the platform market, holding the number of users on the platform as fixed, and a market expansion, given that the products' price/quality combinations offered by a greater number of developers attract more users. The developers only bear the cost of increased competition, because they sell, at a lower price, applications of greater quality, and π^* is always decreasing with m, though at a decreasing rate. The greater average attractiveness of products makes the users more willing to purchase the core hardware, so the platform provider can appropriate the benefits of a larger base of users, and Π^* increases with m.

As for the role of the product quality, both π^* and Π^* decrease with θ, because the size of the ecosystem is relatively less attractive, and it is interesting to to highlight again the mechanism. According to Propositions 1 and 2, for a given price structure (P, R), a larger θ should correspond to a lower price and greater quality of products. Yet P^* and R^* change with θ; as the quality effect becomes more important, the platform reduces the price of the hardware, but then it also increases the royalties, as in Propositions 3 and 4. Thus, with greater θ the platform provider transfers the price burden from users to developers, and the developers react to the increased royalty mainly by increasing the price p^*, rather than reducing the quality q^*.

The last remark looks at the overall effect on profits, focusing on the value jointly created by the platform and its developers, $\Pi^* + m\pi^*$, and how it gets distributed. The combined effect of a larger ecosystem of developers is such that the overall value of the platform market increases, because it drives users' adoption. Moreover, when more users join the platform, the platform provider manages to appropriate an increasing share of the overall profits. Thus, in addition to the tension highlighted above, according to which the platform provider and the developers' profits move in opposite directions as m increases, we further clarify that the developers are at disadvantage relative to the platform provider, because the latter obtains a large and increasing share of overall profits.

DISCUSSION, LIMITATIONS AND EXTENSIONS

A key learning point of our model is that the effect of product quality, rather than the quantity per se, is the main driver of the platform strategy and of the choices of the independent developers. This is not a trivial point; most studies of platform markets emphasize solely the importance of the number of members on the two sides and the indirect network effects. This has also implications for the empirical strategy adopted to measure indirect network effects. Thus, previous works use count of complementary products (e.g., Clements and Ohashi 2005; Corts and Lederman 2009), but as shown by Kim et al. (2014), this measurement can result in biased estimations if it does not account also for variations in product quality. Our model sheds light on the role of indirect network effects, disentangling the role of quality and quantity effects.

Another finding with implications for empirical studies relates to whether the quality of complementary products is greater in platforms with a larger ecosystem of developers. Our model suggests that this could happen in contexts where product quality is relatively more important than quantity, like in videogames. Yet, developers may also suffer from increased competition that eventually reduce their incentives to provide high quality complements to the platform (e.g., Boudreau 2012; Cennamo and Santaló 2013) or prevent from contributing at all to the platform (Huang et al. 2013). Empirical studies have started to document these tensions, but more research is needed to uncover the underlying dynamics and effects of the strategic interaction between developers and the platform provider. We believe that the propositions advanced herein offer a good theoretical foundation for such future work.

Related, the end users may value more the quantity of complementary products at certain stages of platform evolution, while quality may be more important at other stages. Gaining a sizeable user base (and developers) might be more important in early stages, to show the value of the platform; at later stages, once the platform has a well-established and installed base of users and developers, what they do on the platform likely becomes more important and contributes more to platform value than does adding additional new members from both sides. Following this interpretation, our model suggests that pricing and other strategies devised by developers and by the platform provider need to change. In contexts where quality and usage effects are relatively stronger than quantity and membership effects, developers may decide to keep supplying high quality products to platforms with a larger ecosystem, i.e., with high levels of within-platform competition. To the extent that users value quality more than quantity, developers can attract users mainly on the basis of the quality of their products, which may explain why, in highly competitive platform markets such as those for videogames or smartphone applications, we still observe an influx of "hit" products. However, our model also predicts that the platform provider appropriates an increasing share of the total value created, such that developers thus may suffer value capture concerns that eventually reduce their incentives to provide high quality products. Empirical studies have started to document these tensions (e.g., Ceccagnoli et al. 2012), but more research is needed to uncover the underlying dynamics and effects of the strategic interaction between developers and the platform providers.

Our model could also be extended to investigate other levers that platform providers can use to affect indirectly the developers' incentives. For example, a platform could decide to invest in technological infrastructures or development kits that lower development costs (the variable c in our model) and facilitate the production of higher quality complementary products. When it entered the video game industry, Microsoft provided its development kit for free to early developers that committed to its Xbox console. Similarly, Apple provides a development kit to developers of apps, which allow them to build apps that can perfectly integrate within the iPhone operating system and run smoothly. Platform providers can also invest to increase the technical quality of the platform (the variable Q in our model), that can be a critical determinant of platform value and performance (Zhu and Iansiti 2012). (For a formal analysis of the effect of investments in platform technology vs. supporting tools for developers, see Anderson et al. 2014). These investments could also be valuated in relation to the pricing strategy of subsidizing one side of the market; though it might be theoretically effective, it also could require heavy cash allowances, specially when platform needs to subsidize a large installed base of users. Within the framework of our model, it would also be possible to allow for different effects of the attraction of the core hardware ($QP^{-\sigma}$) and of the complementary products ($qp^{-\delta}$). Exploring the different sources of quality and their relative impacts on platform value would greatly enrich our knowledge of platform value creation and extend the range of strategies available for platforms to create value.

As a first step to study the strategic interaction between the platform provider and the independent developers that are active in the platform market, our analysis refers to monopoly platforms and focuses on within-platform competition among homogeneous developers. Our formal model could be extended to account for other interesting aspects. First, a platform provider eventually might produce the needed complementary products in house, as demonstrated in reality on many platforms (e.g., Apple or Google in mobile operating systems, or Microsoft or Nintendo in videogame console systems). Such a strategy might create conflicting incentives for developers (Gawer and Henderson 2007), that would face an additional source of (asymmetric) competition (Zhu and Liu 2015). Thus, the developers' choices would also be influenced by the platform's choice of the price and quality of its own products (Gil and Warzynski 2009). To account for this additional source of strategic interaction between the platform and its developers, we might augment the share attraction framework presented herein by adding a number n of first-party complementary products to the number m offered by the independent developers. Again, developers could respond to the increased competition in the platform market by limiting their investments in quality or deciding not to join the platform. Second, the assumption of homogeneous developers allows us to keep the model tractable and to provide closed-form solutions that highlight the main economic intuitions. Yet, in practice high quality games or "superstars" contribute most to a console's adoption by gamers (Binken and Stremersch's 2009). Here we only highlight that our framework could also be considered as a kind of winner-take-all competition among developers, if we interpret the function s^i not as a market share but as the probability that developer i's product becomes the killer app that all the end users buy after having joined the platform. Future work might analyze the functioning of platform markets with heterogeneous developers, allowing for variation in product quality. Third, an important extension to our formal model would be to allow for competition in the market for platforms – for example, having two platforms. To create value, platforms must compete to attract the users and the developers. This leaves open the question of how platform strategies affect product quality when across platform competition is added to the within-platform competition. Although many models study this setting, to the best of our knowledge, none of them consider how platform competition affects the quality of complementary products provided to competing platforms, or the platform capacity to create value through usage effects. This case is technically more demanding but also highly interesting. This setting would also acknowledge the possibility that end users and developers are active on multiple platforms and might engage in multi-homing. We leave such extensions to future studies.

CONCLUSIONS

Most extant theorizing about platforms has focused on how to solve the problem of attracting end users and developers at early stages of platform evolution. Mainstream theory about two-sided platforms mainly assumes that the value of a platform increases with the members joining the platform on each side due to indirect network effects, and focuses on platform pricing strategies that attract the two sides. On the other hand, the works that emphasize a modular design with minimal control over the developers are not concerned with the role of platform strategies and the incentives of independent developers. Yet, the value of modern platforms depends critically on the quantity and quality of complementary products, and platforms that aim to nurture an innovative ecosystem must encourage the developers to exert innovative efforts. Our goal in this paper is to bring into the picture the incentives of autonomous developers that are active in the platform market, emphasizing the role of quality of the complementary products in addition to the much studied quantity and variety effects. By capturing this distinction, our model sheds a light on the role of indirect network effects in two-sided platform markets.

We consider the quality (and price) of complementary products as an important component of platform value, which the platform provider that chooses an open governance can only affect indirectly through a strategic interaction with the autonomous developers. One implication from our theory is that what platforms do to influence the developers' incentives and the transactions with the end users is equally important than (and can contribute to) solving the problem of attracting the two sides of the market. This aspect adds to the complexity of the well-explored coordination problem associated with matching the two sides of the market when managing a platform system. Our findings then describe the functioning of platform markets differently from a standard view, and reveal that the relationship between platform strategy, the size of the ecosystem, the developers' incentives, and the co-creation of platform value is more nuanced then previously thought. Gaining a better knowledge of these relationships is crucial to understand the functioning of platform markets and, ultimately, how to design platform strategies.

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Appendix

Proof of Proposition 1

Proof. By deriving Equation (8) with respect to p_i, neglecting the constant term $QP^{-\sigma}m^{1-\theta}$, the first-order condition can be written as

$$\frac{q_i p_i^{-\delta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{1-\theta}} + (p_i - R)\left[\frac{(-\delta)q_i p_i^{-\delta-1}\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{1-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-2\theta}} \right. \tag{A1}$$

$$\left. - \frac{q_i p_i^{-\delta}(1-\theta)(-\delta)q_i p_i^{-\delta-1}\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-2\theta}}\right]$$

$$= \frac{q_i p_i^{-\delta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{1-\theta}} - (p_i - R)\delta q_i p_i^{-\delta-1}\frac{\sum_{j=1}^m q_j p_j^{-\delta} - q_i p_i^{-\delta}(1-\theta)}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-\theta}} = 0.$$

Imposing the symmetry condition $q_i = q$, $p_i = p$, $i = 1, ...m$, Equation $(A1)$ becomes

$$\frac{qp^{-\delta}}{(mqp^{-\delta})^{1-\theta}} - \delta(p-R)qp^{-\delta-1}\frac{(mqp^{-\delta}) - qp^{-\delta}(1-\theta)}{(mqp^{-\delta})^{2-\theta}} = 0. \tag{A2}$$

After simplifying, the equilibrium price is

$$\hat{p}(R) = R\frac{\delta\,(m-(1-\theta))}{\delta\,(m-(1-\theta)) - m} = Rl(m). \tag{A3}$$

For the second-order condition, deriving Equation $(A1)$, we obtain

$$q_i\frac{-\delta p_i^{-\delta-1}\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{1-\theta} + p_i^{-\delta}(1-\theta)\delta q_i p_i^{-\delta-1}\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-2\theta}} \tag{A4}$$

$$-\left[\delta q_i p_i^{-\delta-1} + (p_i - R)\delta q_i\left(-\delta-1\right)p_i^{-\delta-2}\right]\cdot\frac{\sum_{j=1}^m q_j p_j^{-\delta} - q_i p_i^{-\delta}(1-\theta)}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-\theta}}$$

$$-(p_i - R)\delta q_i p_i^{-\delta-1}\left[\frac{\left[-\delta q_i p_i^{-\delta-1} + \delta q_i p_i^{-\delta-1}(1-\theta)\right]\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{4-2\theta}}\right.$$

$$\left.+\frac{\left[\sum_{j=1}^m q_j p_j^{-\delta} - q_i p_i^{-\delta}(1-\theta)\right](2-\theta)q_i\delta p_i^{-\delta-1}\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{1-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{4-2\theta}}\right] < 0,$$

which at the symmetric equilibrium reduces to

$$
\begin{aligned}
& q\frac{-\delta p^{-\delta-1}\left(mqp^{-\delta}\right)^{1-\theta}+p^{-\delta}(1-\theta)\delta qp^{-\delta-1}\left(mqp^{-\delta}\right)^{-\theta}}{\left(mqp^{-\delta}\right)^{2-2\theta}} && \text{(A5)}\\
& -\left[\delta qp^{-\delta-1}+(p-R)\delta q\left(-\delta-1\right)p^{-\delta-2}\right]\cdot\frac{mqp^{-\delta}-qp^{-\delta}(1-\theta)}{\left(mqp^{-\delta}\right)^{2-\theta}}\\
& -(p-R)\delta qp^{-\delta-1}\left[\frac{\left[-\delta qp^{-\delta-1}+\delta qp^{-\delta-1}(1-\theta)\right]\left(mqp^{-\delta}\right)^{2-\theta}}{\left(mqp^{-\delta}\right)^{4-2\theta}}\right.\\
& \left.+\frac{\left[mqp^{-\delta}-qp^{-\delta}(1-\theta)\right](2-\theta)q\delta p^{-\delta-1}\left(mqp^{-\delta}\right)^{1-\theta}}{\left(mqp^{-\delta}\right)^{4-2\theta}}\right]<0,
\end{aligned}
$$

and after simplifying,

$$
-\left[m-(1-\theta)\right]\left[2-\frac{\delta+1}{\delta}\frac{m}{m-(1-\theta)}\right]-\left[\frac{\left[m-(1-\theta)\right](2-\theta)-m\theta}{m-(1-\theta)}\right]<0, \qquad \text{(A6)}
$$

such that it is always satisfied. ■

Proof of Proposition 2

Proof. By deriving Equation (8) with respect to q_i, the first-order condition can be written as

$$
\begin{aligned}
& QP^{-\sigma}m^{1-\theta}(p_i-R)p_i^{-\delta}\left[\frac{\left(\sum_{j=1}^{m}q_jp_j^{-\delta}\right)^{1-\theta}}{\left(\sum_{j=1}^{m}q_jp_j^{-\delta}\right)^{2-2\theta}}\right. && \text{(A7)}\\
& \left.-\frac{(1-\theta)q_ip_i^{-\delta}\left(\sum_{j=1}^{m}q_jp_j^{-\delta}\right)^{-\theta}}{\left(\sum_{j=1}^{m}q_jp_j^{-\delta}\right)^{2-2\theta}}\right]-cq_i\\
= \; & QP^{-\sigma}m^{1-\theta}(p_i-R)p_i^{-\delta}\frac{\sum_{j=1}^{m}q_jp_j^{-\delta}-(1-\theta)q_ip_i^{-\delta}}{\left(\sum_{j=1}^{m}q_jp_j^{-\delta}\right)^{2-\theta}}-cq_i=0.
\end{aligned}
$$

Imposing the symmetry condition $q_i = q$, $p_i = p$, $i = 1, ...m$, Equation $(A6)$ becomes

$$
\begin{aligned}
& QP^{-\sigma}m^{1-\theta}(p-R)p^{-\delta}\frac{\left(mqp^{-\delta}\right)-(1-\theta)qp^{-\delta}}{\left(mqp^{-\delta}\right)^{2-\theta}}-cq && \text{(A8)}\\
& =QP^{-\sigma}(p-R)p^{-\delta}\frac{m-(1-\theta)}{m\left(qp^{-\delta}\right)^{1-\theta}}-cq=0.
\end{aligned}
$$

Substituting Equation ($A3$) into ($A8$) and solving for q, the equilibrium level of quality is

$$\hat{q}(P,R) = \left(\frac{Q}{\delta c} l(m)^{1-\delta\theta}\right)^{\frac{1}{\theta}} \cdot \left(P^{-\sigma} R^{1-\delta\theta}\right)^{\frac{1}{\theta}} \tag{A9}$$

For the second-order condition, deriving Equation ($A8$),

$$QP^{-\sigma} m^{1-\theta}(p_i - R)p_i^{-\delta} \left[\frac{\left[p_j^{-\delta} - (1-\theta)p_i^{-\delta}\right]\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{2-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{4-2\theta}} \right. \tag{A10}$$
$$\left. - \frac{\left[\sum_{j=1}^m q_j p_j^{-\delta} - (1-\theta) q_i p_i^{-\delta}\right](2-\theta)p_i^{-\delta}\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{1-\theta}}{\left(\sum_{j=1}^m q_j p_j^{-\delta}\right)^{4-2\theta}} \right] - c < 0,$$

which at the symmetric equilibrium becomes

$$QP^{-\sigma} m^{1-\theta}(p - R)p^{-\delta} \left[\frac{\left[p^{-\delta} - (1-\theta)p^{-\delta}\right]\left(mqp^{-\delta}\right)^{2-\theta}}{\left(mqp^{-\delta}\right)^{4-2\theta}} \right. \tag{A11}$$
$$\left. - \frac{\left[mqp^{-\delta} - (1-\theta)qp^{-\delta}\right](2-\theta)p^{-\delta}\left(mqp^{-\delta}\right)^{1-\theta}}{\left(mqp^{-\delta}\right)^{4-2\theta}} \right] - c$$
$$= \frac{QP^{-\sigma}(p-R)p^{-2\delta}}{m\left(qp^{-\delta}\right)^{2-\theta}} \left[\frac{(1-\theta)(2-\theta-m)}{m}\right] - c < 0,$$

which is always satisfied. ■

Proof of Proposition 3 and 4.

Proof. Substituting $\hat{p}(R)$ and $\hat{q}(P,R)$ into Equation (7), the platform provider's profits reduce to

$$\Pi = \left[(P - C + R)\, P^{-2\sigma} R^{1-2\delta\theta}\right] \cdot \left[Q^2 m(\delta c)^{-1} l(m)^{1-2\delta\theta}\right]. \tag{A12}$$

Neglecting the constant terms, the first-order condition for P and Q can be written as

$$P \quad : \quad P^{-2\sigma} - 2\sigma P^{-2\sigma-1}\left[P - C + R\right] = 0,$$
$$\longrightarrow \quad \frac{P - C + R}{P} = \frac{1}{2\sigma}$$

and

$$R \quad : \quad R^{1-2\delta\theta} + (1-2\delta\theta)R^{-2\delta\theta}\left[P - C + R\right] = 0. \tag{A13}$$

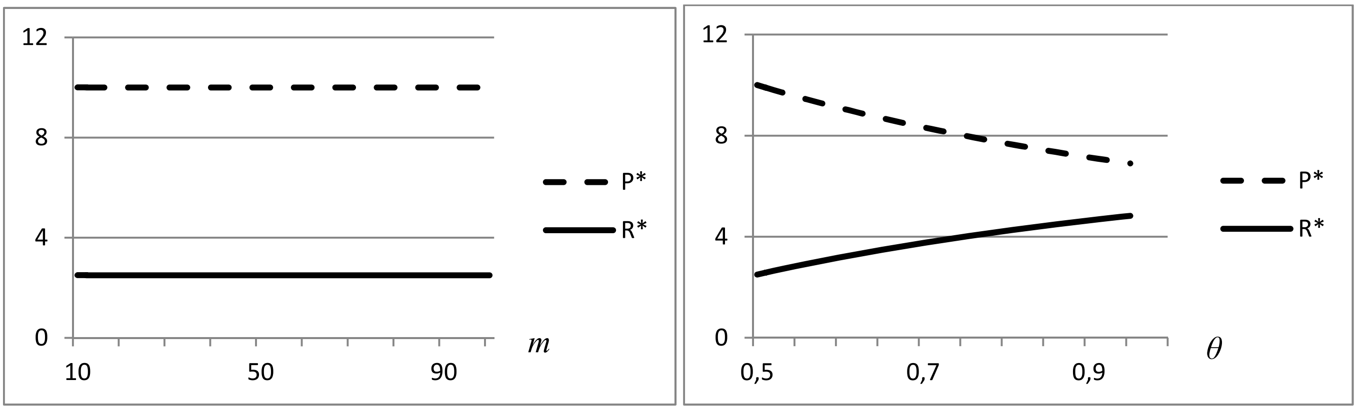
$$\longrightarrow \quad \frac{P - C + R}{R} = \frac{1}{2\delta\theta - 1} \tag{1}$$

Solving for P and R, we obtain

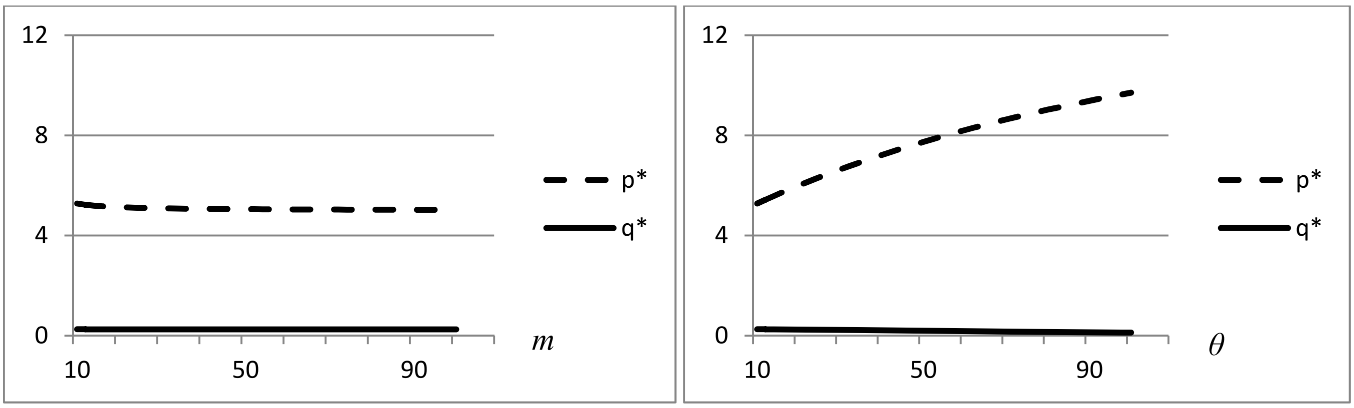
$$P^* = \frac{\sigma}{\sigma + \delta\theta - 1}C < C, \text{ and} \tag{A14}$$

$$R^* = \frac{1}{2}\frac{2\delta\theta - 1}{\sigma + \delta\theta - 1}C > 0. \tag{A15}$$

It can be easily checked that the second-order conditions are satisfied, provided that $\delta\theta > 1$. ■

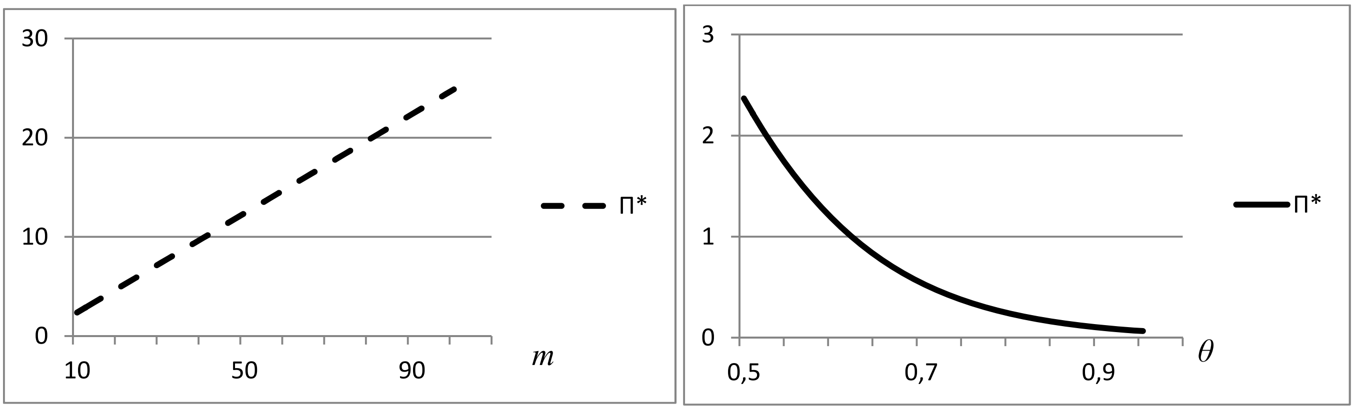


1a: The equilibrium price and royalties P^* and R^* as a function of *m* (left) and *θ* (right).

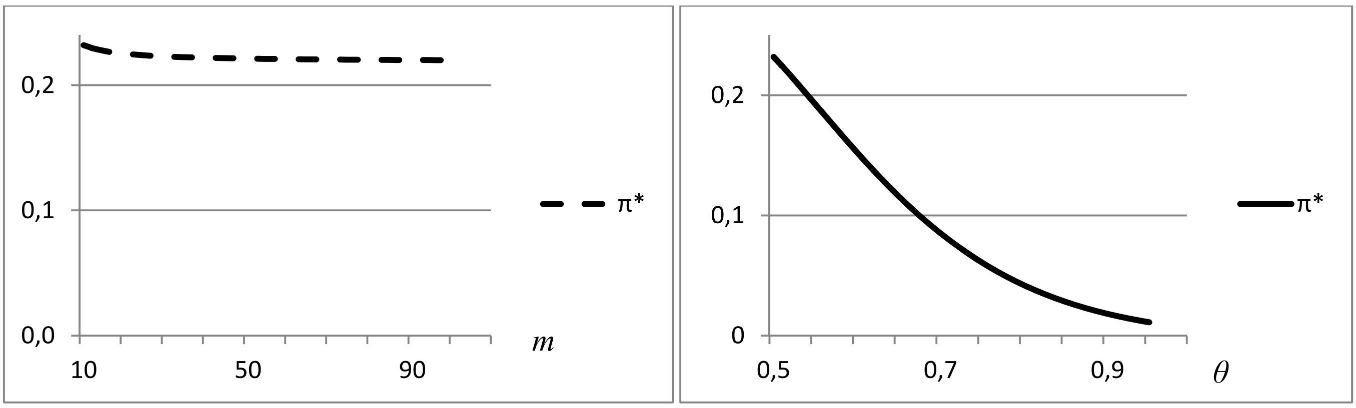


1b: The equilibrium price and quality p^* and q^* as a function of *m* (left) and *θ* (right).

Figure 1: The equilibrium values of the main variables.



2a: The equilibrium profits Π^* as a function of *m* (left) and θ (right).



2a: The equilibrium profits π^* as a function of *m* (left) and θ (right).

Figure 2: The equilibrium values of profits.