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Content Quality Assurance on Media Platforms with User-Generated Content

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Abstract

This paper develops a duopoly model of user-generated content (UGC) platforms that compete for consumers and content producers in two-sided markets with network externalities. Each platform can choose the level of investment into a content quality assurance (CQA) system and the level of advertising. Our model shows that network effects are crucial in determining the platforms' optimal strategy and the behavior (single vs. multi-homing) of their users. Specifically, we find that consumers are multi-homing and producers are single-homing when the network effects obtained by producers are weak, while the opposite is true if these network effects are strong. Moreover, our model shows that the user behavior and the network effects determine whether a platform has incentives to place ads and/or invest into CQA. In general, weak network effects induce a platform to invest into a CQA system except when consumers and producers are multi-homing. The results in our model suggests the need for platform companies to assess the magnitude of network effects on their platform to predict the behavior of their users, which in turn will determine the optimal CQA and advertising strategy.

Keywords: UGC platform; two-sided market; multi-homing; network externalities; platform investment

JEL Classification: C72, D85, L14

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1 Introduction

User-generated content (UGC) platforms are an important class of media platforms that mainly host content produced by content producers (Daugherty et al. 2008; Saura et al. 2021). On UGC platforms, content producers upload their own produced content, which is then viewed by consumers on the platform. Along with the progress of communication technology, UGC platforms such as YouTube, Twitch, and TikTok have grown rapidly in recent years. For example, YouTube has grown from 0.8 billion users in 2012 to 2.6 billion users in 2021 and it is now the second-most popular social media platform behind Facebook. YouTube has over 122 million active daily users worldwide that watch more than 1 billion hours of videos on YouTube per day (GlobalMediaInsight 2022), making UGC platforms an important channel for people to obtain information and consume entertainment.

UGC platforms have typical characteristics of two-sided markets (Luca 2015). For example, YouTube, Twitch, and TikTok enable content producers to interact with consumers and cross-network effects characterize the economics of such UGC platforms: each additional participant on one side of the platform influences the attractiveness of the platform for the participants on the other side, and vice versa. The more content a producer generates on a platform, the more attractive this platform becomes to consumers, and the more consumers are on a platform, the more attractive this platform is for content producers.

A major source of revenue for UGC platforms is advertising. For example, in Q1 2022, YouTube's worldwide advertising revenues amounted to US$6.9 billion (Statista 2022). Advertising revenue depends on the number of active users who visit the platform and watch the content on the platform. Given that consumers prefer to watch high-quality content and that advertising companies are sensitive to inappropriate content, a major concern for UGC platforms is how to ensure that the content produced by content producers is of high quality and is appropriate. In response to this problem, some platforms are starting to establish content quality assurance (CQA) systems. For example, in December 2017 the CEO of YouTube announced that the platform would employ more than 10,000 people to review content and training algorithms on their platform as a response to several companies removing ads from YouTube after child abuse videos appeared online. These content reviewers intervene with the help of machine-learning algorithms to remove videos that are sensitive, vulgar, inappropriate, or spread misinformation (CNET 2022). In general, such CQA systems can contribute to removing content that does not meet the required levels of quality and ethical standards by reducing the number of low-quality content producers on the platform. The aim is to increase consumer stickiness and platform revenues. However, implementing and maintaining CQA systems is expensive due labor, module development, and maintenance costs.

Previous research in the digital content industry has studied how to provide incentives for content producers to encourage high-quality content creation through ad revenue sharing (Jain and Quian 2021), intrinsic and status motivation for content producers (Toubia and Stephen 2013) and price setting strategies by platforms (Guda and Subramanian 2019). However, to the best of our knowledge there is no theoretical research that studies the investment of UGC platforms in CQA systems to ensure high-quality content on a platform. Our paper tries to fill this gap.

Given the major role that UGC platforms play in the digital content industry and their reliance on high-quality content, it is important to understand the conditions under which UGC platforms should implement a CQA system. Thus, our paper tries to answer the following research questions that have not yet been addressed in the literature:

1. What are the general conditions under which a platform will invest into a CQA system?

2. What is the optimal strategy for a platform regarding the investment level into a CQA system on the one hand and the advertising levels on the other?

3. How do cross-network effects influence the optimal strategy and the market shares of consumers and content producers?

4. How do different user behaviors (single- versus multi-homing) influence the equilibrium?

To answer these and related research questions, we develop a simple duopoly Hotelling model with cross-network effects. In our model, two UGC platforms compete for consumers on one market side and content producers on the other. Network effects operate from one market side to the other and vice versa. Each platform has two choice variables: the level of investment into a CQA system and the level of advertising on the platform. We consider four different user behaviors:[1] single-homing on both market sides, multi-homing only on the consumer side, multi-homing only on the content producer side, and multi-homing on both sides.[2]

Our analysis shows that cross-network effects crucially determine (i) the platform's optimal strategy and (ii) the user behaviors. In particular, we find that consumers are multi-homing and producers are single-homing when the network effects that operate from the consumer's to the producer's side are weak, while the opposite is true if these network effects are strong, i.e., consumers are single-homing and producers are multi-homing.

[1]Consumers and content producers on both sides of the UGC platform are considered as platform "users".

[2]Users either join one platform, called "single-homing", or users join both platforms, called "multi-homing" (Ihlstrom et al. 2016). For example, consumers may access both YouTube and Twitch to watch videos, and content producers may upload their self-made content on both platforms at the same time.

Moreover, our model shows that user behavior (single- vs. multi-homing) and network effects determine whether a platform has incentives to place ads and/or invest into a CQA system. In general, weak network effects induce a platform to invest into a CQA system except in the scenario where consumers and producers are multi-homing. The results from our model suggest the need for platform companies to assess the magnitude of network effects on their platform in order to predict the behavior of their users (single versus multi-homing), which in turn will determine the optimal CQA and advertising strategy.

The main contributions of our paper are of theoretical and practical nature. Theoretically, we contribute to the existing literature on: (i) operational strategies on media platforms, (ii) the impact of user participation decisions in platform competition, and (iii) platform performance investments. Practically, our findings provide guidance for managers of platform companies on how to develop bilateral strategies, adjust the proportion of users with different participation options, and to determine the conditions under which it makes sense to investment into a CQA systems in order to reduce operating costs and optimize profits, thus maintaining sustainable market development.

The remainder of the paper is structured as follows. Section 2 reviews the related literature. Section 3 presents the model with its notation and main assumptions. Section 4 provides the results for different user behaviors and compares the different scenarios. Section 5 uses numerical analyses to verify and extend the results. Finally, Section 6 points out possible extensions and concludes the paper.

2 Literature Review

Our work is primarily related to three areas in the existing literature: (i) media platform operational strategies, (ii) the impact of user participation decisions in platform competition, and (iii) platform performance investments.

2.1 Media platform operational strategy

As a form of media platform development, there are many similarities between research related to UGC platforms and that related to media platforms, where platforms can charge both advertisers and consumers directly (Prasad et al. 2003; Rochet and Tirole 2003; Anderson and Coate 2005; Armstrong 2006; Amaldoss et al. 2021).

For media platforms, Shi et al. (2019) studied the impact of network externalities on platform content pricing strategies and found that when the marginal network effects of high- and low-quality products are asymmetric, platforms will lower the prices of their low-quality content. Barros et al. (2005) studied the content pricing strategies of media platforms and found that platforms charge consumers for content subscriptions regardless of whether they are in a monopoly or a competitive market.

Some other scholars consider advertisers into the bilateral market structure. For example, Esteban et al. (2012) constructed an informative advertising and price competition model, and found that when the platform is free to consumers, advertisers will place more ads to the platform and the platform's price per ad placement will increase. Kind et al. (2009) found that the smaller the variation in video quality offered by media platforms, the more advertisers will be placed. Reisinger et al. (2012) showed that heterogeneity in consumer preferences for platforms affects the level of advertising placement by advertisers. UGC platforms often benefit from consumers through ad placement, and this profit model is common in platforms such as YouTube and Tik Tok. Our research builds on existing studies and focuses on the ad placement decisions in UGC platforms.

2.2 Impact of user participation decisions on platform competition

The single-homing and multi-homing behavior of bilateral users is another focus of this research. Where single-homing refers to users belonging to a single platform only, multi-homing generally refers to partial multi-homing, meaning that some participating users join more than two platforms at the same time. Rochet and Tirole (2006) argue that users' motivation for multi-homing stems from their desire for better network externalities in a non-connected platform environment. Armstrong and Wright (2007) state that a competitive bottleneck occurs when sellers perceive platforms as homogeneous and buyers as heterogeneous, leading to multi-homing for the former and single-homing for the latter, and platforms will attract buyers by offering subsidies. Tan and Zhou (2021) study the presence of cross-network effects and multi-homing of users in bilateral markets, where inter-platform competition, pricing, and platform revenue increase subsequently, but consumer surplus decreases.

Anderson et al. (2019) used the classical product differentiation loop model to describe the advertising investment problem in media markets under multi-homing of users and showed that media platforms can only charge value-added prices to advertisers but not more to consumers in the scenario of multi-homing of users, and that multi-homing breaks the competitive equilibrium within the platform. Chellappa and Mukherjee (2021), in their study of platform competition in the video game console market, merged same-side and cross-side network effects and compared equilibrium results when developers chose single-homing and multi-homing, respectively, in a predefined industry context, assuming single-homing on the player side. Most studies in the bilateral field still focus on platform competition in a bilateral setting, which is the basis and theoretical foundation of our research. Based on these studies, we likewise consider the impact of cross-network effects that exist between bilateral users and introduce them into the field of UGC platform research.

2.3 Platform performance investment

CQA investment in UGC platforms is an investment strategy that tries to optimize the operating environment of the platform, which essentially belongs to utility investment for users on one side of the platform. Among such studies, investment in value-added services, innovation incentives, and performance investment of the platform are the focus of scholars' attention.

Dou et al. (2016) studied additional value-added service investment and pricing strategies for one side of a bilateral platform and found that the relative strength of the cross-side network effect measured the relative "importance" of the two sides, with the platform subsidizing the price of the more "important" side in real time to attract more users to the other side. Zhang et al. (2021) considered the impact of cross-side network effects and value-added services on the utility of manufacturers and suppliers joining the platform, and found that as supplier cross-side network effects increase, the platform can increase the level and price of value-added services for manufacturers and suppliers.

Jung et al. (2019) investigated the conditions for innovation incentives by platforms under the influence of network effects in the presence of bilateral platforms with multi-homing of consumers and service providers, and showed that subsidies to consumers were more effective in increasing the level of quality and technological innovation of platforms. Bakos and Halaburda (2020) studied multi-homing on both sides using the platform's subsidy policy and tasked that when both sides use multi-homing, the common strategic proposal to subsidize one side in order to maximize the total profit may be limited. In the existing studies, the platform's service investments all bring positive utility to users on one side, while CQA investments not only bring positive utility to users on one side, but also generate negative utility to users on the other side, which makes the platform's investment strategy more complicated. The study discussed here is complementary to such studies.

3 Model Setup

Based on the Hotelling model, we construct a duopoly model of platform competition. We consider two UGC platforms (denoted by subscript $i \in \{A, B\}$) that compete for two types of users: consumers (denoted by subscript c) and content producers (denoted by subscript p). Consumers and content producers, who are of mass one, are uniformly distributed along the unit interval. The two competing platforms are situated at the extremes of the interval with platform A located at 0 and platform B located at 1. We consider the Hotelling model with linear transport costs per unit of length, which are denoted by $t_c > 0$ and $t_p > 0$ for consumers and producers, respectively. Hence, the two platforms are horizontally differentiated from the perspective of the users and the parameter t can be interpreted as the differentiation parameter. A lower value of t means that the platforms are perceived as closer substitutes by the users. Each platform has two strategic variables at its disposal: the level of advertising and the level of CQA.

Consumers can enjoy the platforms' content for free, where $V > 0$ represents the consumers' intrinsic value from consuming content on the platform (Economides and Tag 2012, Dietl et al. 2013) but they have to watch the ads embedded in the content of the platform. We denote the amount of advertising placed on platform i by a with $i \in \{A, B\}$. We assume that consumers dislike ads and watching ads will thus induce a negative utility.[3] The parameter $\beta > 0$ describes the extent to which consumers dislike advertising because each advertisement produces a perceived nuisance cost of β by the consumers. Moreover, we assume that advertising generates revenue for the platform and the parameter $r > 0$ captures how much revenue a platform can generate per ad a. We assume that the advertising market is competitive, and that the advertising price is exogenously given. The parameter r can be interpreted as a measure for the effectiveness of advertising. For tractability, we assume a linear specification of advertising revenue (Dietl et al. 2022).

The level of CQA on platform i is denoted by δ^i with $i \in \{A, B\}$. We assume that implementing and maintaining a CQA system is costly, with the cost given by the convex cost function $c(\delta^i)^2/2$ with $c > 0$. These costs can be interpreted as labor, module development, and maintenance costs for the CQA system. We assume that the level of CQA induces a disutility δ^i for the content producers but a utility $\gamma\delta^i$ for the consumers. On the one hand, a CQA system raises the quality standard on the platform, which can be interpreted as additional costs for the content producers. On the other hand, consumers benefit through an improved quality of the content on the platform. The parameter $\gamma > 0$ describes the extent to which consumers value high-quality content on a platform.

Furthermore, we assume that network effects operate from one market side to the other on the platform. Specifically, the more consumers are on the platform, the more attention content producers receive for posting content; likewise, the more content producers are present on the platform, the more content is on the platform from which consumers can choose from. Therefore, we assume that positive cross-network effects operate between consumers and producers, which means that consumers' access to the platform brings additional utility to producers and producers' access to the platform brings additional utility to consumers. We denote the cross-network effects that operate from the consumer market to the producer market by $n_p > 0$ and the effects that operate from the producer

[3] A potential negative externality derived from ads could be that consumers want to watch videos not advertisements. For further discussion of this aspect, see Becker and Murphy (1993), Depken and Wilson (2004), and Reisinger et al. (2009).

market to the consumer market by $n_c > 0$. We also refer to n_p as the network effects obtained by producers and to n_c as the network effects obtained by consumers (Grossmann et al. 2021).

Finally, by denoting the number of consumers on platform i by Q_c^i and the number of content producers on platform i by Q_p^i, we can derive the profit function of platform i as follows:

$$\pi^i = Q_c^i a^i r - \frac{c}{2}\left(\delta^i\right)^2, \tag{1}$$

with $i \in \{A, B\}$.

Table 1 provides a summary of the notation used in our model.

Table 1: Notation for parameters and decision variables

Parameters			
n_c	Cross-side network effects obtained by consumers (from producers)	n_p	Cross-side network effects obtained by producers (from consumers)
t_c	Cost of consumer preference (transport costs)	t_p	Cost of producer preference (transport costs)
Q_c^i	Number of consumers on platform i	Q_p^i	Number of producers on platform i
β	Consumer's disutility of advertising	r	Unit advertising revenue of the platform
V	Reservation utility for consumers	γ	Consumer's utility derived from high quality content
c	Marginal cost of CQA investment	π^i	Profit function of platform i
Decision variables			
a^i	Advertising level on platform i	δ^i	CQA investment on platform i

4 Equilibrium Analysis

In this section, we derive the equilibrium outcomes. Given that users can choose to access one platform ("single-homing") or two platforms ("multi-homing"), we distinguish the following four scenarios:[4]

1. Consumers and content producers are both single-homing (S-S scenario).
2. Consumers are multi-homing and producers are single-homing (M-S scenario).
3. Consumers are single-homing and producers are multi-homing (S-M scenario).
4. Consumers and content producers are both multi-homing (M-M scenario).

For each of the four scenarios, we determine the optimal platform strategy by assuming that both platforms simultaneously choose the level of advertising and the level of CQA

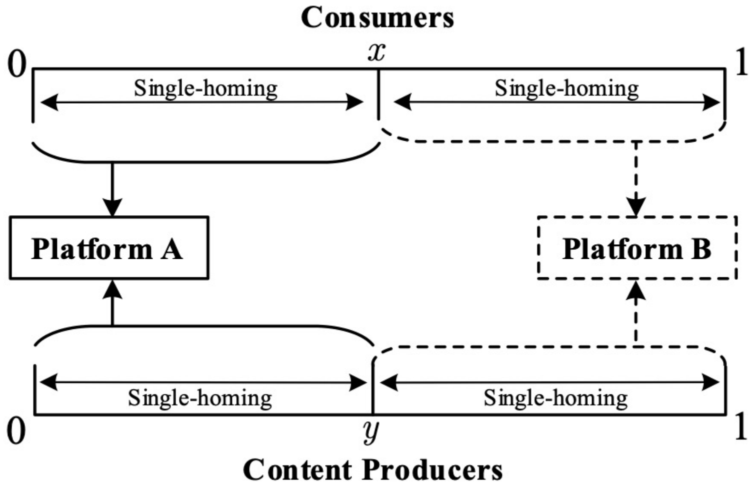
[4] We use abbreviations to refer to the different scenarios where the first letter represents the consumers and the second letter the content producers.

investment with the objective of maximizing their own profits. We then compare the four scenarios to determine the conditions under which consumers and content producers choose single-homing and multi-homing, respectively.

4.1 Single-homing on both sides

We start our analysis by considering the scenario in which consumers and content producers are both single-homing (S-S scenario). Figure 1 illustrates this scenario.

Figure 1: User structure of the platforms in the S-S scenario.



As shown in Figure 1, both users only access one platform. For consumers and content producers, there is a unique point on the Hotelling line denoted by x and y, respectively, for which the users are indifferent between choosing platform A and B. All users located on the left of the indifference points x and y decide to join platform A, and all users located on the right of x and y will join platform B.

The utility obtained by the consumer on platform $i \in \{A, B\}$ is thus given by

$$u_c^A = V - \beta a^A + n_c Q_c^A + \gamma\delta^A - t_c x, \quad (2)$$

$$u_c^B = V - \beta a^B + n_c Q_p^B + \gamma\delta^B - t_c (1 - x), \quad (3)$$

where V denotes the consumer's intrinsic value from the content on platform i and βa^i measures the level on consumers' disutility from ads. The term $n_c Q_p^i$ reflects the increase in consumer utility through network effects derived from the presence of content producers on the other market side. The more content producers are present on the platform, the higher the increase in utility. As mentioned above, the level of CQA on the platform increases consumer utility by $\gamma\delta^i$, and $t_c x$ and $t_c (1 - x)$ denote the cost of consumer preference.

The utility that content producers derive from platform $i \in \{A, B\}$ is

$$u_p^A = n_p Q_c^A - \delta^A - t_p y, \tag{4}$$

$$u_p^B = n_p Q_c^B - \delta^B - t_p (1-y), \tag{5}$$

where $n_p Q_c^i$ characterizes the increase in utility of the content producers through cross-network effects derived from the presence of consumers on the other market side. As above, the more consumers are present on the platform, the higher the increase in utility. The disutility induced by the level of CQA is given by δ^i and the preference costs of the content producer are $t_p y$ and $t_p (1-y)$.

We can obtain the indifference points of consumers and producers from the conditions of $u_c^A = u_c^B$ and $u_p^A = u_p^B$, respectively. Therefore, from equations (2)-(5), the number of consumers and content producers on platform i can be derived as

$$Q_c^i = \frac{t_p\left(\beta(a^j - a^i) + \gamma(\delta^i - \delta^j) + t_c\right) - n_c\left(\delta^i - \delta^j + n_p\right)}{2(t_c t_p - n_c n_p)}, \tag{6}$$

$$Q_p^i = \frac{t_c\left(t_p + \delta^j - \delta^i\right) - n_p(\beta(a^i - a^j) + n_c + \gamma(\delta^j - \delta^i)}{2(t_c t_p - n_c n_p)}, \tag{7}$$

with $i, j \in \{A, B\}$ and $i \neq j$.

To ensure nonnegative demand functions, we assume throughout the subsequent analysis that the cross-network externality parameters are small compared to the differentiation parameters, i.e., $t_c t_p - n_c n_p > 0$ (Armstrong 2006; Armstrong and Wright 2007; Jung et al. 2019).

By substituting the demand functions (6)-(7) into the profit function (1) and solving the maximization problem, we derive the equilibrium in the following proposition.

Proposition 1

(i) The equilibrium exists and is unique if the consumers' disutility from advertising is sufficiently large with $\beta > \beta_1'$.

(ii) In equilibrium, the level of advertising on platform i is given by

$$a^{i,SS} = \frac{t_c t_p - n_c n_p}{\beta t_p}$$

and the level of CQA investment on platform i is

$$\delta^{i,SS} = \frac{r\left(\gamma t_p - n_c\right)}{2c\beta t_p}.$$

(iii) In equilibrium, the number of consumers and producers on platform i is

$$Q_c^{i,SS} = \frac{1}{2} \text{ and } Q_p^{i,SS} = \frac{1}{2}.$$

Proof. See Appendix. ■

Part (i) of Proposition 1 shows the condition for the existence and uniqueness of an equilibrium in the S-S scenario: the consumers' disutility from advertising must be sufficiently large with $\beta > \beta_1'$.

Part (ii) presents the equilibrium level of advertising and CQA investment. We derive that the platform will always place ads, i.e., $a^{i,SS} > 0$ since $t_c t_p - n_c n_p > 0$. However, to ensure that the platform invests in CQA, i.e., $\delta^{i,SS} > 0$, the cross-network effect n_c obtained by consumers must be sufficiently weak with $n_c < \gamma t_p$. Weaker cross-network effects n_c from producers to consumers diminishes utility for the consumers and thus reduces their demand. To counterbalance this effect, the platform has incentives to make CQA investments in this case.

Part (iii) shows that consumers and producers on platforms i share the market equally since the S-S scenario is fully symmetric.

Next, we examine how cross-network externalities (n_c and n_p) and the sensitivity coefficient γ regarding the CQA investment impact the equilibrium solution of the platform.

Corollary 1
(i) As the cross-network effects n_c obtained by consumers increase, both the CQA investment and the level of advertising decrease, i.e.,

$$\frac{\partial \delta^{i,SS}}{\partial n_c} < 0 \text{ and } \frac{\partial a^{i,SS}}{\partial n_c} < 0.$$

(ii) As the cross-network effects n_p obtained by producers increase, the CQA investment is not affected, but the level of advertising decreases, i.e.,

$$\frac{\partial \delta^{i,SS}}{\partial n_p} = 0 \text{ and } \frac{\partial a^{i,SS}}{\partial n_p} < 0.$$

(iii) As consumers' sensitivity γ to CQA investment increases, the CQA investment increases, but the level of advertising is not affected, i.e.,

$$\frac{\partial \delta^{i,SS}}{\partial \gamma} > 0 \text{ and } \frac{\partial a^{i,SS}}{\partial \gamma} = 0.$$

Proof. See Appendix. ■

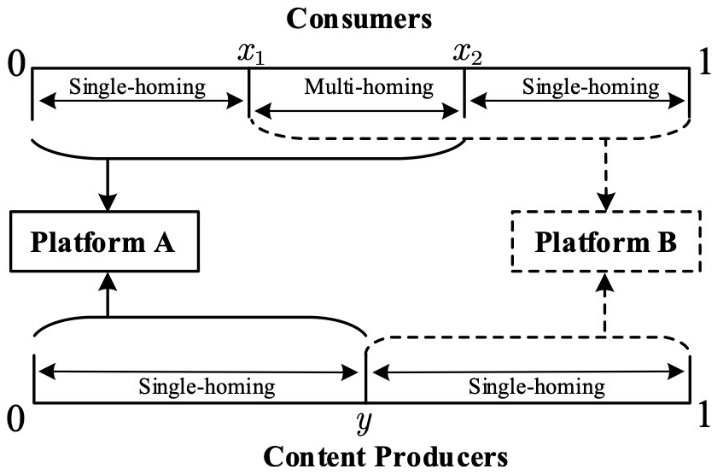
Parts (i) and (ii) of Corollary 1 reflect the fact that as the cross-network effect of producers on consumers increases, platforms reduce the level of CQA investment. The increase in network effects obtained by consumers increases consumer utility and thus diminishes incentives for platforms to attract consumers through CQA investments, which induces the platforms to reduce the level of CQA investment. As the cross-network effects obtained by either consumers or producers increase, the platform reduces the level of advertising since there is no incentive for the platform to increase CQA investment due to the increase in network effects obtained by consumers or producers, and in order to remain attractive to consumers, the platform needs to reduce the level of advertising.

Part (iii) of Corollary 1 reflects that the increase in the sensitivity to CQA investment by consumers increases the incentives for platforms to increase CQA investment, as this enhances the utility of CQA investment to consumers and increases the attractiveness of platforms to consumers.

4.2 Consumers multi-homing and producers single-homing

Figure 2 illustrates the user structure of the platforms when multi-homing occurs only on the consumer side (M-S scenario).

Figure 2: User structure of the platforms in the M-S scenario.



In this scenario, there exists a proportion of consumers who join both platforms to enjoy their content. Due to the presence of multi-homing consumers, total consumer demand exceeds 1, i.e., $Q_c^A + Q_c^B > 1$. As shown in Figure 2, there are two indifference points on the consumer's Hotelling line: the marginal consumer, who is indifferent between joining only platform A (single-homing) and joining both platforms (multi-homing), is located at x_1. Similarly, the marginal consumer, who is indifferent between joining only platform B (single-homing) and joining both platforms (multi-homing) is located at x_2.

The utility of a single-homing consumer joining platform i is the same as in the S-S scenario given by equations (2) and (3). The utility of a multi-homing consumer can be expressed as

$$u_c^{A,B} = V - \beta\left(a^A + a^B\right) + n_c\left(Q_p^A + Q_p^B\right) + \gamma\left(\delta^A + \delta^B\right) - t_c, \tag{8}$$

The two indifference points for consumers $u_c^A = u_c^{A,B}$ and $u_c^{A,B} = u_c^B$ can be obtained from x_1 and x_2. From Figure 2, we can observe that all consumers located on the left of x_2 join platform A and all consumers located on the right of x_1 join platform B.

The demand functions of consumers on platforms A and B are thus given by

$$\begin{aligned} Q_c^{A,B} &= x_2 - x_1 = \frac{1}{t_c}\left(\gamma\left(\delta^A + \delta^B\right) - \beta\left(a^A + a^B\right) - t_c + \left(Q_p^A + Q_p^B\right) n_c\right), \quad (9) \\ Q_c^A &= x_2 = \frac{1}{t_c}\left(n_c Q_p^A - \beta a^A + \gamma \delta^A\right), \quad (10) \\ Q_c^B &= 1 - x_1 = \frac{1}{t_c}\left(n_c Q_p^B - \beta a^B + \gamma \delta^B\right). \quad (11) \end{aligned}$$

As in the S-S scenario, the utility of a single-homing producer joining platform i is the same as in equations (4) and (5). Thus, the indifference point for producers joining platform A or B can be expressed in the M-S scenario as

$$y = \frac{1}{2t_p}\left(Q_c^A n_p - Q_c^B n_p - \delta^A + \delta^B + t_p\right).$$

All producers located on the left of y will join platform A, and all producers located on the right of y will join platform B, so that the producers' demand functions are given by

$$\begin{aligned} Q_p^A &= y = \frac{1}{2t_p}\left(Q_c^A n_p - Q_c^B n_p - \delta^A + \delta^B + t_p\right), \quad (12) \\ Q_p^B &= 1 - y = 1 - \frac{1}{2t_p}\left(Q_c^A n_p - Q_c^B n_p - \delta^A + \delta^B + t_p\right). \quad (13) \end{aligned}$$

Combining (9)-(13), we can derive the number of consumers and content producers on platforms A and B. By substituting these demand functions into the profit function (1) and solving the corresponding maximization problem, we derive the following proposition.

Proposition 2

(i) The equilibrium exists and is unique if the consumers' disutility from advertising is sufficiently large with $\beta > \beta_2'$.

(ii) In equilibrium, the level of advertising on platform i is given by

$$a^{i,MS} = \frac{ct_c n_c\left(t_c t_p - n_c n_p\right)}{c\beta t_c\left(4t_c t_p - 3n_c n_p\right) - r\gamma\left(t_c\left(2\gamma t_p - n_c\right) - \gamma n_c n_p\right)}$$

and the CQA investment on platform i is

$$\delta^{i,MS} = \frac{rn_c\left(\gamma\left(2t_c t_p - n_c n_p\right) - t_c n_c\right)}{2c\beta t_c\left(4t_c t_p - 3n_c n_p\right) - 2r\gamma\left(t_c\left(2\gamma t_p - n_c\right) - \gamma n_c n_p\right)}.$$

(iii) In equilibrium, the number of consumers on platform i is

$$Q_c^{i,MS} = \frac{c\beta n_c\left(2t_ct_p - n_cn_p\right)}{2c\beta t_c\left(4t_ct_p - 3n_cn_p\right) - 2r\gamma\left(t_c\left(2\gamma t_p - n_c\right) - \gamma n_cn_p\right)}$$

and the number of producers on platform i is

$$Q_p^{i,MS} = \frac{1}{2}.$$

Proof. See Appendix. ■

Similar to the S-S scenario, Part (i) of Proposition 2 shows that the disutility that consumers obtain from advertising must be sufficiently large with $\beta > \beta_2'$ to ensure the existance and uniqueness on an equilibrium.

From Part (ii), we can derive that the platforms will always advertise, i.e., $a^{i,MS} > 0$ because $t_ct_p - n_cn_p > 0$. Moreover, the platforms will invest in CQA if the network effects obtained by consumers and producers are sufficiently weak, i.e.,

$$\delta^{i,MS} > 0 \Leftrightarrow n_c < \frac{2\gamma t_p}{3} \text{ and } n_p < \frac{2t_c}{\gamma}.$$

In addition, Proposition 2 shows that, unlike in the S-S scenario, the equilibrium strategy of the platform in the M-S scenario is affected by both the cross-network effects of bilateral users and the sensitivity coefficient of CQA investments, which is formally derived in the following corollary.

Corollary 2

(i) The cross-network effects n_c obtained by consumers have an ambiguous effect on both the CQA investment and the level of advertising , i.e.,

$$\begin{aligned} \frac{\partial \delta^{i,MS}}{\partial n_c} &> 0 \Leftrightarrow r < r'_{MS,1} \textit{ and } \gamma > \gamma'_{MS,1}, \\ \frac{\partial a^{i,MS}}{\partial n_c} &> 0 \Leftrightarrow r > r'_{MS,2} \textit{ and } \gamma < \gamma'_{MS,2}. \end{aligned}$$

(ii) The cross-network effects n_p obtained by producers have an ambiguous effect on both the CQA investment and the level of advertising, i.e.,

$$\begin{aligned} \frac{\partial \delta^{i,MS}}{\partial n_p} &> 0 \Leftrightarrow \gamma > \gamma'_{MS,3}, \\ \frac{\partial a^{i,MS}}{\partial n_p} &> 0 \Leftrightarrow r > r'_{MS,4} \textit{ and } \gamma > \gamma'_{MS,4}. \end{aligned}$$

(iii) As consumers' sensitivity γ to CQA investment increases, both the CQA investment

and the level of advertising increase, i.e.,

$$\frac{\partial \delta^{i,MS}}{\partial \gamma} > 0 \text{ and } \frac{\partial a^{i,MS}}{\partial \gamma} > 0.$$

Proof. See Appendix. ■

Parts (i) and (ii) of Corollary 2 reflect the different nature of the M-S and S-S scenarios. In the M-S scenario, the CQA investment of the platform is affected by both types of cross-network effects n_c and n_p. Specifically, as the cross-network effects n_c obtained by consumers increase, the level of CQA investment on platforms increases when the platform's unit ad price r is below a certain threshold $r'_{MS,1}$ and the consumer's CQA investment sensitivity coefficient γ is above a certain threshold $\gamma'_{MS,1}$. This means that platforms will increase their CQA investment level with the increase of n_c when the profitability of the platform's advertising is low and the CQA investment made by the platform can bring more efficient use to consumers. As the cross-network effects n_p obtained by producers increase, the CQA investment of the platform will increase when the CQA investment sensitivity coefficient γ of consumers is above a certain threshold $\gamma'_{MS,3}$.

In the M-S scenario, the platform's advertising level is also affected by both types of network effects n_c and n_p, but the effect is non-monotonic in this case. Specifically, when one of the platform's unit ad price and consumer sensitivity to CQA investment is above a certain threshold and the other is below a certain threshold ($r > r'_{MS,2}$ and $\gamma < \gamma'_{MS,2}$ or $r < r'_{MS,2}$ and $\gamma > \gamma'_{MS,2}$), the level of advertising increases as the network effects n_c obtained by consumers increases. When both r and γ are above a certain threshold ($r > r'_{MS,4}$ and $\gamma > \gamma'_{MS,4}$), the level of advertising increases when the network effects n_p obtained by the producers increases.

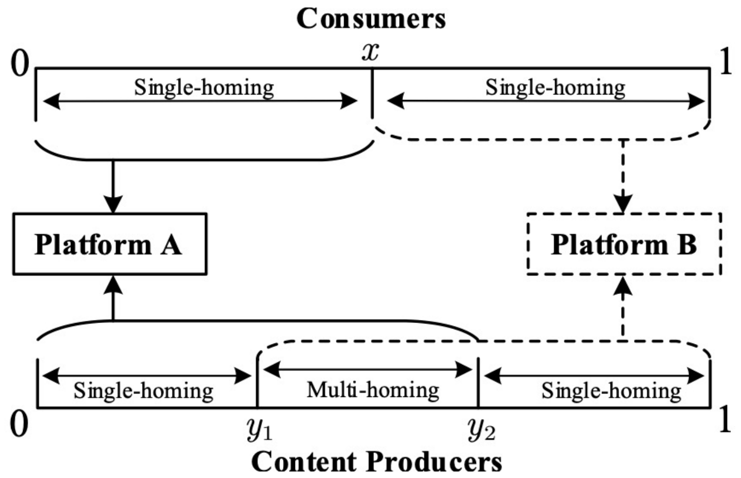
Part (iii) shows that in the scenario where consumers are multi-homing, platforms will have an additional incentive to increase CQA investments to attract more consumers if consumers' preferences for high-quality content increases. As a result, the overall number of consumers accessing the platform increases and, at the same time, platforms will engage in more advertising to generate more revenue.

4.3 Consumers single-homing and producers multi-homing

Figure 3 shows the user structure of the platforms when multi-homing occurs only on the producer side (S-M scenario).

As shown in Figure 3, consumers only join one platform, and the utility gained by joining either platform A or B is the same as for consumers in the S-S scenario given by equations (2) and (3). The location of the consumer, who is indifferent between joining

Figure 3: User structure of the platforms in the S-M scenario.



platform A or B can be expressed in the S-M scenario as

$$x = \frac{1}{2t_c}\left(t_c + \left(Q_p^A - Q_p^B\right) n_c + \gamma\left(\delta^A - \delta^B\right) - \beta\left(a^A + a^B\right)\right).$$

All consumers located on the left of x will join platform A, and all consumers located on the right of x will join platform B.

In the S-M scenario, there exists a proportion of producers who join both platforms to provide content. As shown in Figure 3, the marginal producer, who is indifferent between joining only platform A (single-homing) and joining both platforms (multi-homing) is located at y_1. Similarly, the marginal producer, who is indifferent between joining only platform B (single-homing) and joining both platforms (multi-homing) is located at y_2.

The utility of single-homing producers joining platform i is the same as in the S-S scenario given by equations (4) and (5). The utility of multi-homing producers can be expressed as

$$u_p^{A,B} = n_p\left(Q_c^A + Q_c^B\right) - \left(\delta^A + \delta^B\right) - t_p. \tag{14}$$

The two indifferent points y_1 and y_2 of the producers can be derived from $u_p^A = u_p^{A,B}$ and $u_p^{A,B} = u_p^B$.

From Figure 3, we can observe that all producers located on the left of y_2 join platform A and all consumers located on the right of $y_1 = 1 - y_1$ join platform B. The demand function of producers on platforms A and B can thus be derived as

$$Q_p^{A,B} = y_2 - y_1 = \frac{1}{t_p}\left(\left(Q_c^A + Q_c^B\right) n_p - \delta^A - \delta^B - t_p\right), \tag{15}$$

$$Q_p^A = y_2 = \frac{1}{t_p}\left(Q_c^A n_p - \delta^A\right), \tag{16}$$

$$Q_p^B = 1 - y_1 = \frac{1}{t_p}\left(Q_c^B n_p - \delta^B\right). \tag{17}$$

To ensure the existence of multi-homing producers, i.e., $Q_p^{A,B} > 0$, we assume that $n_p > t_p$.

We can derive the number of consumers joining platform A and B as

$$
\begin{aligned}
Q_c^A &= x = \frac{1}{2t_c}\left(t_c + \left(Q_p^A - Q_p^B\right) n_c + \gamma\left(\delta^A - \delta^B\right) - \beta\left(a^A + a^B\right)\right), && (18) \\
Q_c^B &= 1 - x = 1 - \frac{1}{2t_c}\left(t_c + \left(Q_p^A - Q_p^B\right) n_c + \gamma\left(\delta^A - \delta^B\right) - \beta\left(a^A + a^B\right)\right). && (19)
\end{aligned}
$$

Combining (15)-(19), we can obtain the number of consumers and content producers of platform A and B. By substituting these demand functions into the profit function (1) and solving the corresponding maximization problem, we derive Proposition 3.

Proposition 3

(i) The equilibrium exists and is unique if the consumers' disutility from advertising is sufficiently large with $\beta > \beta_1'$.

(ii) In equilibrium, the level of advertising on platform i is given by

$$a^{i,SM} = \frac{t_c t_p - n_c n_p}{\beta t_p}$$

and the CQA investment on platform i is

$$\delta^{i,SM} = \frac{r\left(\gamma t_p - n_c\right)}{2c\beta t_p}.$$

(iii) In equilibrium, the number of consumers on platform i is

$$Q_c^{i,SM} = \frac{1}{2}$$

and the number of producers on platform i is

$$Q_p^{i,SM} = \frac{r n_c + t_p\left(c\beta n_p - r\gamma\right)}{2c\beta t_p^2}.$$

Proof. See Appendix. ■

The condition that ensures existence of an equilibrium is the same as in the S-S scenario. Moreover, as in the S-S scenario, the platform will always place ads, i.e., $a^{i,SM} > 0$ since $t_c t_p - n_c n_p > 0$. In addition, the platform invests in CQA, i.e., $\delta^{i,SM} > 0$ if the cross-network effects n_c obtained by consumers are sufficiently weak with $n_c < \gamma t_p$.

In the S-M scenario, the duopoly platforms have their own single-homing producers and share the multi-homing producers in the market, while dividing the consumers equally. In this scenario, the platform's equilibrium advertising and CQA investment levels are the same as in the S-S scenario, but the platform has a larger number of producers, which leads to Corollary 3.

Corollary 3

(i) As the cross-network effects n_c obtained by consumers increase, both the CQA investment and the level of advertising decrease, i.e.,

$$\frac{\partial \delta^{i,SM}}{\partial n_c} < 0 \ and \ \frac{\partial a^{i,SM}}{\partial n_c} < 0.$$

(ii) As the cross-network effects n_p obtained by producers increase, the CQA investment is unaffected, but the level of advertising decreases, i.e.,

$$\frac{\partial \delta^{i,SM}}{\partial n_p} = 0 \ and \ \frac{\partial a^{i,SM}}{\partial n_p} < 0.$$

(iii) As consumers' sensitivity γ to CQA investment increases, the CQA investment increases, but the level of advertising is unaffacted, i.e.,

$$\frac{\partial \delta^{i,SM}}{\partial \gamma} > 0 \ and \ \frac{\partial a^{i,SM}}{\partial \gamma} = 0.$$

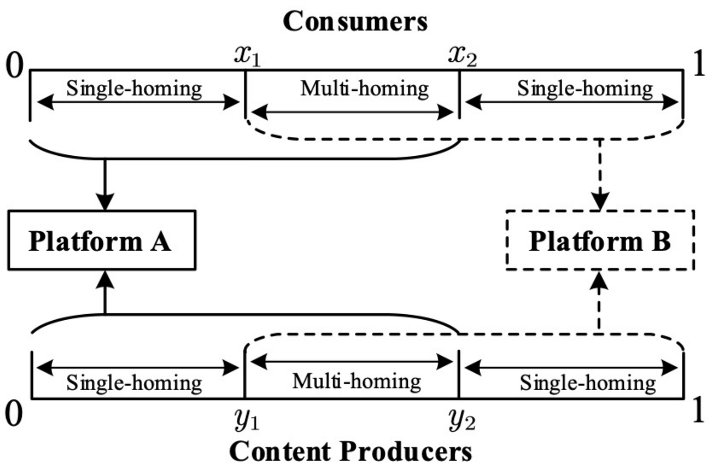
Proof. See Appendix. ■

Corollary 3 shows that the cross-network effects and consumers' sensitivity coefficients of CQA investment have the same effect on the level of platform advertising and CQA investment in the S-M scenario as in the S-S scenario. As consumers' sensitivity to CQA investment γ increases, platforms will increase CQA investment, which will increase costs for producers and cause a decline in the number of producers.

4.4 Multi-homing on both sides

Figure 4 shows the user structure of the platforms when multi-homing occurs on both market sides (M-M scenario).

Figure 4: User structure of the platforms in the M-M scenario.



As shown in Figure 4, consumers and content producers join both platforms. The utility functions of consumers and producers who join both platforms are the same as in equations (8) and (14) from which we can derive the demand functions of consumers and producers on platforms A and B. By substituting these demand functions into the profit function (1) and solving the corresponding maximization problem, we derive Proposition 4.

Proposition 4
(i) The equilibrium exists and is unique if the consumers' disutility from advertising is sufficiently large with $\beta > \beta_3'$.
(ii) In equilibrium, the level of advertising on platform i is given by

$$a^{i,MM} = \frac{cn_c(n_p - t_p)(t_c t_p - n_c n_p)}{t_p(r\gamma(\gamma t_p + n_c) - 2c\beta(t_c t_p - n_c n_p))}$$

and the level of CQA investment on platform i is

$$\delta^{i,MM} = \frac{r\gamma n_c(n_p - t_p)}{r\gamma(\gamma t_p + n_c) - 2c\beta(t_c t_p - n_c n_p)}.$$

(iii) In equilibrium, the number of consumers on platform i is

$$Q_c^{i,MM} = \frac{c\beta n_c(n_p - t_p)}{r\gamma(\gamma t_p + n_c) - 2c\beta(t_c t_p - n_c n_p)}$$

and the number of producers on platform i is

$$Q_p^{i,MM} = \frac{r\gamma t_p(n_c + \gamma n_p) - c\beta n_p(2t_c t_p - n_c(t_p + n_p))}{t_p(r\gamma(\gamma t_p + n_c) - 2c\beta(t_c t_p - n_c n_p))}.$$

Proof. See Appendix. ■

Part (i) shows that consumers' disutility from advertising must satisfy $\beta > \beta_3'$ to ensure the existence of an equilibrium solution.

From Part (ii), we can derive that the platform invests in CQA, i.e.,

$$\delta^{i,MM} > 0 \Leftrightarrow n_c > \frac{(2c\beta t_c - r\gamma^2)\, t_p}{r\gamma + 2c\beta t_p} \text{ and } n_p > t_p.$$

As a consequence, the platform will make CQA investments in the M-M scenario only when the cross-network effects n_c and n_p are both sufficiently large. Moreover, the conditions $n_p > t_p$ and $t_c t_p - n_c n_p > 0$ ensure that the platform will always place ads, i.e., $a^{i,MM} > 0$.

In the M-M scenario, there are multi-homing users on both sides of the platform. The equilibrium strategy of the platform is affected by both types of cross-network effects as well as the sensitivity coefficient of CQA investment. We summarize these results in Corollary 4.

Corollary 4
(i) As the cross-network effects n_c obtained by consumers increase, both the CQA investment and the level of advertising level decrease, i.e.,

$$\frac{\partial \delta^{i,MM}}{\partial n_c} < 0 \text{ and } \frac{\partial a^{i,MM}}{\partial n_c} < 0.$$

(ii) The cross-network effects n_p obtained by producers have an ambiguous effect on both the CQA investment and the level of advertising, i.e.,

$$\begin{aligned}\frac{\partial \delta^{i,MM}}{\partial n_p} &> 0 \Leftrightarrow r > r'_{MM,1},\\ \frac{\partial a^{i,MM}}{\partial n_p} &> 0 \Leftrightarrow r > r'_{MM,2} \text{ and } n_c < n'_{MM,1}.\end{aligned}$$

(iii) As consumers' sensitivity γ to CQA investment increases, both the CQA investment and the level of advertising decrease, i.e.,

$$\frac{\partial \delta^{i,MM}}{\partial \gamma} < 0 \text{ and } \frac{\partial a^{i,MM}}{\partial \gamma} < 0.$$

Proof. See Appendix. ■

Part (i) reflects that as the cross-network effects n_c obtained by consumers increase when multi-homing exists for both users, the level of CQA investment and advertising on the platform decrease accordingly, which is the same result as in Corollaries 1 and 3.

Part (ii) reflects that as the cross-network effects n_p obtained by producers increase, the CQA investment on the platform increases when the platform's unit advertising revenue r is above the threshold $r'_{MM,1}$. The conditions that need to be satisfied for the platform's advertising level to increase with n_p, in addition to r being above or below the threshold $r'_{MM,2}$, require n_c to be below or above the threshold $n'_{MM,1}$.

Part (iii) shows that CQA investments as well as the level of advertising on the platform decrease when the consumers' sensitivity to CQA investment increases.

4.5 Comparison

In this section, we compare the four scenarios and determine the conditions under which users have preferences for single-homing and multi-homing, respectively. We derive the following proposition.

Proposition 5

(i) Consumers are multi-homing and producers are single-homing (M-S scenario) if the network effects obtained by producers are sufficiently weak, i.e.,

$$n_p < \frac{t_c \left(2t_p \left(c\beta \left(2t_c - n_c\right) - r\gamma^2\right) + r\gamma n_c\right)}{n_c \left(c\beta \left(3t_c - n_c\right) - r\gamma^2\right)}.$$

(ii) Consumers are single-homing and producers are multi-homing (S-M scenario) if the network effects obtained by consumers are sufficiently strong, i.e.,

$$n_c > \frac{t_p \left(r\gamma + c\beta \left(t_p - n_p\right)\right)}{r}.$$

(iii) Consumers and producers are multi-homing (M-M scenario) if the network effects obtained by consumers are sufficiently weak and the network effects obtained by producers are sufficiently strong, i.e.,

$$n_c < \frac{\left(2c\beta t_c - r\gamma^2\right) t_p}{r\gamma + 2c\beta t_p} \text{ and } n_p > \frac{r\gamma}{c\beta} + t_p.$$

(iv) In all other scenarios, consumers and producers are single-homing (S-S scenario).

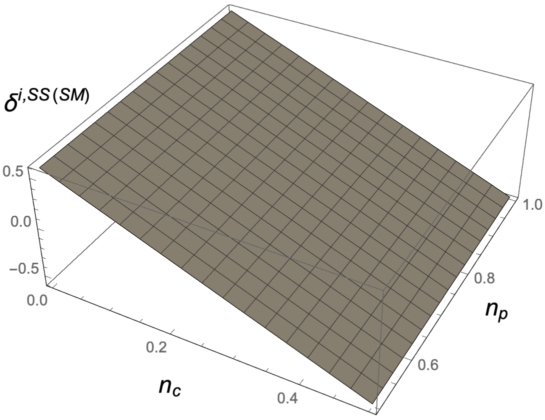
Proof. See Appendix. ■

Proposition 5 characterizes the conditions under which consumers and producers choose to join platform A, platform B, or both platforms. We find that the user decision is dependent on the strength of the cross-network effects. Part (i) shows that in the case of sufficiently weak cross-network effects n_p obtained by producers, platforms can reduce the level of advertising to attract more consumers to the platform to maintain the number of producers on the platform and thus consumers have incentives to join both platforms. When, on the other hand, the cross-network effects n_c obtained by consumers are strong (Part ii), the platforms provide less CQA investment, which reduces the negative utility of producers and thus increases incentives for producers to choose multi-homing. Part (iii) illustrates the case of multi-homing on both market sides: When the cross-networking effects n_c obtained by consumers are weak, platforms realize more CQA investments, which makes them more attractive to consumers and less attractive to producers. At the same time, when the cross-network effects n_p obtained by producers are strong, the larger number of consumers implies that producers can obtain greater cross-network utility, which increases the attractiveness of the platform for the producers. The simultaneous occurrence of these two conditions results in multi-homing behavior for both sides of users.

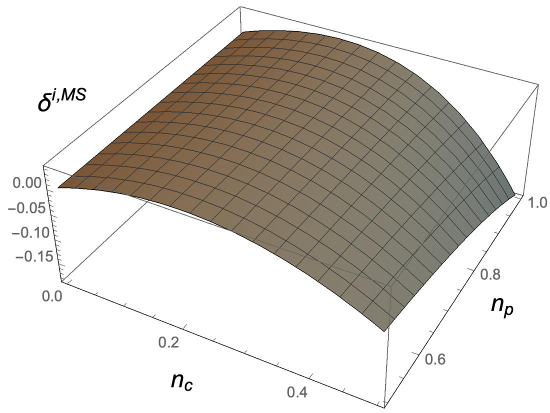
5 Numerical Analysis

In this section, we conduct several numerical analyses that enable us to illustrate our results graphically. In Figure 5, we examine the impact of the cross-network effects on the platforms' CQA investment levels in the four scenarios. The parameters are set to $t_c = 1$, $t_p = 0.5$, $r = 0.7$, $\beta = 0.5$, $c = 0.6$, and $\gamma = 0.5$.

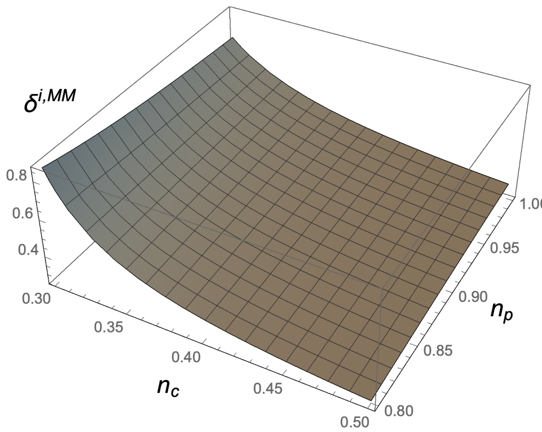
Figure 5: Impact of network effects on CQA investments.



(a) S-S and S-M scenarios



(b) M-S scenario



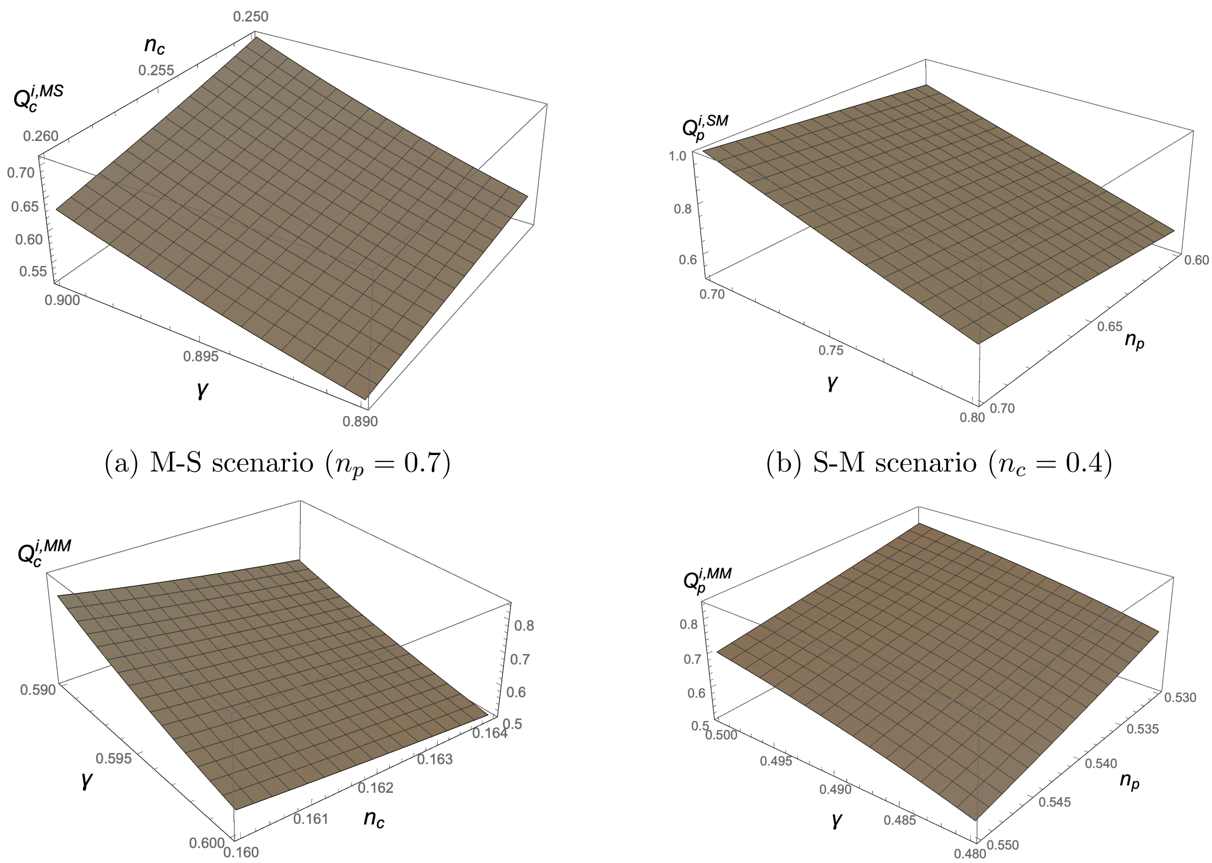
(c) M-M scenario

Figure 5(a) confirms that in the S-S and S-M scenarios, the platforms' CQA investments decrease monotonically with the cross-network effects n_c obtained by consumers, but they are not affected by the cross-network effect n_p obtained by producers. Figure 5(b) reflects the non-monotonic effect of n_c and n_p on the CQA investment of the platforms in the M-S scenario. Specifically, the figure shows that the CQA investments of the platforms first increase and then decrease as n_c increases. Figure 5(c) shows that in the M-M scenario, the CQA investments of the platforms are monotonically decreasing with n_c. The effect of n_p on the CQA investments of the platforms is non-monotonic. These results are consistent with Corollaries 1-4.

Figure 6 extends our results by examining the impact of the sensitivity coefficient γ

and the cross-network effects obtained by the respective users on the users' demand. In particular, the impact on consumer demand is illustrated in panels (a) and (c), while producer demand is displayed in panels (b) and (d). The parameters are set to $t_c = 1$, $t_p = 0.5$, $r = 0.6$, $\beta = 0.2$, and $c = 1$

Figure 6: Impact of network effects and sensitivity coefficient of CQA on user demand.



(a) M-S scenario ($n_p = 0.7$)

(b) S-M scenario ($n_c = 0.4$)

(c) M-M scenario ($n_p = 0.8$)

(d) M-M scenario ($n_c = 0.3$)

Figure 6 shows that in the M-S scenario the platforms attract more consumers if the sensitivity coefficient γ increases and the network effects n_c obtained by consumers decreases (Figure 6a), whereas in the S-M scenario the platforms attract less producers if the sensitivity parameter γ increases and the network effects n_p obtained by producers decreases (Figure 6b). In the M-M scenario, a higher sensitivity coefficient γ decreases demand on the consumer side (Figure 6c), but increases demand on the producer side (Figure 6d). The opposite is true for stronger network effects.

6 Conclusion

Platforms enable two or more market sides to interact with each other. An important class of such platforms are UGC platforms that mainly host content produced by content producers. Since participants on one side of the platform derive a substantial amount of their utility from the platform participants on the other market side(s), competition among UGC platforms is characterized by network externalities. To enhance our understanding of such platform competitions, we have developed a model to analyze the competition between two UGC platforms.

In our model, each platform can choose the level of investment into a CQA system and the level of advertising. CQA investment in UGC platforms is an important tool to help improving the quality of user-generated content. However, cross-network effects add complexity to the situation because the operational strategies of the platforms and the bilateral user engagement decisions are no longer independent: investing into CQA systems might be beneficial for attracting consumers, but it is an additional burden on content producers.

Our results indicate that network effects crucially determine the platforms' optimal strategy regarding their CQA investment and level of advertising as well as the user behavior (single- vs. multi-homing). Specifically, we find that consumers are multi-homing and producers are single-homing when the network effects obtained by producers are weak, while consumers are single-homing and producers are multi-homing when the network effects obtained by consumers are strong. In the case of weak network effects obtained by consumers and strong network effects obtained by producers, multi-homing on both market sides occurs. In addition, we derive that the user behavior and both types of network effects determine whether a platform has incentives to place ads and/or invest into a CQA system. A platform will realize CQA investments if the network effects obtained by consumers are weak for all scenarios except the scenario in which consumers and producers join both platforms.

Because the model in this paper is a stylized one, we have made some simplifying assumptions. For example, in our current setup the return on advertising (or advertising price) is exogenously given and advertisers are not restricted in how much advertising space they can buy at this price. However, in reality, advertisers are constrained by the amount of advertising they can contract and thus interesting interactions with the consumers and producers might arise. Another simplifying assumption is that the two UGC platforms are fully symmetric. An interesting avenue for further research would be to allow for heterogeneity in the consumer's intrinsic value from the content of a platform. In addition, further research could introduce vertical differentiation of service cost and quality between platforms to explore the issue of platform CQA investment strategies in a more realistic setting.

Summing up, our model may serve as a basic framework to further analyze UGC platform competition in two-sided markets. There is a broad range of further applications and model extensions. The issues surrounding UGC platform competition remain a fertile and important line of inquiry for economics, business, and management.

A Appendix: Proofs

A.1 Proof of Proposition 1

In the following, we derive the proof of Proposition 1 in the S-S scenario.

Part (i): The maximization problem of platform i is given by

$$\max_{(a^i,\delta^i)} \left[\pi^{i,SS} = Q_c^i a^i r - \frac{c(\delta^i)^2}{2}\right].$$

By substituting the demand function Q_c^i given by equation (6) into the profit function, we derive the first-order partial derivatives of π^i with respect to a^i and δ^i as follows:

$$\begin{aligned}
\frac{\partial \pi^i}{\partial a^i} &= -\frac{r\beta a^i t_p}{2t_c t_p - 2n_c n_p} + \frac{r\left(\beta t_p(a^j - a^i) + t_c t_p - n_c n_p + \delta^i(\gamma t_p - n_c) + \delta^j\left(n_c - \gamma t_p\right)\right)}{2t_c t_p - 2n_c n_p}, \\
\frac{\partial \pi^i}{\partial \delta^i} &= \frac{r a^i\left(\gamma t_p - n_c\right)}{2t_c t_p - 2n_c n_p} - c\delta^i.
\end{aligned}$$

From the second-order derivatives of π^i with respect to a^i and δ^i, we derive the Hessian matrix as

$$H_{SS} = \begin{vmatrix} -\frac{r\beta t_p}{t_c t_p - n_c n_p} & \frac{r(\gamma t_p - n_c)}{2(t_c t_p - n_c n_p)} \\ \frac{r(\gamma t_p - n_c)}{2(t_c t_p - n_c n_p)} & -c \end{vmatrix}.$$

To ensure the existence and uniqueness of an equilibrium, the Hessian matrix H_{SS} must be a negative definite matrix. Thus, all the leading principal minors of even order must be positive and all leading principal minors of odd order must be negative, which translates into the following conditions:

$$-\frac{r\beta t_p}{t_c t_p - n_c n_p} < 0 \text{ and } \frac{r\left(4c\beta t_p\left(t_c t_p - n_c n_p\right) - r(\gamma t_p - n_c)^2\right)}{\left(2t_c t_p - 2n_c n_p\right)^2} > 0.$$

We derive that these conditions are satisfied if

$$t_c t_p - n_c n_p > 0 \text{ and } \beta > \beta_1' \equiv \frac{r(\gamma t_p - n_c)^2}{4ct_p\left(t_c t_p - n_c n_p\right)}.$$

Part (ii): To derive the optimal level of advertising $a^{i,SS}$ and the optimal level of CQA investment $\delta^{i,SS}$, we solve the above system of first-order conditions for a^i and δ^i. We derive

$$\left(a^{i,SS}, \delta^{i,SS}\right) = \left(\frac{t_c t_p - n_c n_p}{\beta t_p}, \frac{r\left(\gamma t_p - n_c\right)}{2c\beta t_p}\right).$$

Part (iii): By substituting the equilibrium solution $\left(a^{i,SS}, \delta^{i,SS}\right)$ into the demand functions (6) and (7), we obtain

$$\left(Q_c^{i,SS}, Q_p^{i,SS}\right) = \left(\frac{1}{2}, \frac{1}{2}\right).$$

A.2 Proof of Corollary 1

To proof the comparative statics results of Corollary 1, based on the equilibrium solution of Proposition 1, we derive

$$\begin{aligned}
\frac{\partial \delta^{i,SS}}{\partial n_c} &= -\frac{r}{2c\beta t_p} < 0 \text{ and } \frac{\partial a^{i,SS}}{\partial n_c} = -\frac{n_p}{\beta t_p} < 0, \\
\frac{\partial \delta^{i,SS}}{\partial n_p} &= 0 \text{ and } \frac{\partial a^{i,SS}}{\partial n_p} = -\frac{n_c}{\beta t_p} < 0, \\
\frac{\partial \delta^{i,SS}}{\partial \gamma} &= \frac{r}{2c\beta} > 0 \text{ and } \frac{\partial a^{i,SS*}}{\partial \gamma} = 0.
\end{aligned}$$

A.3 Proof of Proposition 2

Given that the derivation of the equilibrium solution for Proposition 2 (M-S scenario) is similar to Proposition 1 (S-S), we will not repeat the calculations here.

From the second-order derivatives of $\pi^{i,MS}$ with respect to a^i and δ^i, we derive the Hessian matrix as

$$H_{MS} = \begin{vmatrix} -\frac{r\beta(2t_ct_p - n_cn_p)}{t_c(t_ct_p - n_cn_p)} & \frac{r(t_c(2\gamma t_p - n_c) - \gamma n_cn_p)}{2t_c(t_ct_p - n_cn_p)} \\ \frac{r(t_c(2\gamma t_p - n_c) - \gamma n_cn_p)}{2t_c(t_ct_p - n_cn_p)} & -c \end{vmatrix}.$$

To ensure that H_{MS} is a negative definite matrix, the following conditions must be satisfied:

$$\begin{aligned}
-\frac{r\beta\left(2t_ct_p - n_cn_p\right)}{t_c\left(t_ct_p - n_cn_p\right)} &< 0, \\
\frac{r\left(4c\beta t_c\left(t_ct_p - n_cn_p\right)\left(2t_ct_p - n_cn_p\right) - r\left(t_c\left(2\gamma t_p - n_c\right) - \gamma n_cn_p\right)^2\right)}{4t_c^2\left(t_ct_p - n_cn_p\right)^2} &> 0.
\end{aligned}$$

We derive that these conditions are satisfied if

$$t_ct_p - n_cn_p > 0 \text{ and } \beta > \beta_2' \equiv \frac{r(2\gamma t_ct_p - t_cn_c - \gamma n_cn_p)^2}{4ct_c\left(t_ct_p - n_cn_p\right)\left(2t_ct_p - n_cn_p\right)}.$$

A.4 Proof of Corollary 2

Part (i) From the equilibrium solution of Proposition 2, we calculate

$$\begin{aligned}\frac{\partial \delta^{i,MS}}{\partial n_c} &= -\frac{cr\beta t_c^2 t_p n_c (2t_c - \gamma n_p)}{(2c\beta t_c (4t_c t_p - 3n_c n_p) - 2r\gamma (t_c (2\gamma t_p - n_c) - \gamma n_c n_p))^2} \\ &\quad + \frac{r (\gamma (2t_c t_p - n_c n_p) - t_c n_c)}{2c\beta t_c (4t_c t_p - 3n_c n_p) - 2r\gamma (t_c (2\gamma t_p - n_c) - \gamma n_c n_p)}\end{aligned}$$

and derive

$$\frac{\partial \delta^{i,MS}}{\partial n_c} > 0 \Leftrightarrow r < r'_{MS,1} \text{ and } \gamma > \gamma'_{MS,1},$$

with

$$\begin{aligned}r'_{MS,1} &= \frac{c\beta t_c \left(\gamma \left(8t_c t_p (t_c t_p - n_c n_p) + 3n_c^2 n_p^2\right) - t_c n_c (8t_c t_p - 3n_c n_p)\right)}{\gamma(t_c (2\gamma t_p - n_c) - \gamma n_c n_p)^2}, \\ \gamma'_{MS,1} &= \frac{t_c n_c (8t_c t_p - 3n_c n_p)}{8t_c t_p (t_c t_p - n_c n_p) + 3n_c^2 n_p^2}.\end{aligned}$$

Similarly, we calculate

$$\begin{aligned}\frac{\partial a^{i,MS}}{\partial n_c} &= \frac{ct_c (c\beta t_c (2t_c t_p - 3n_c n_p) (2t_c t_p - n_c n_p))}{(c\beta t_c (4t_c t_p - 3n_c n_p) - r\gamma (\gamma (2t_c t_p - n_c n_p) - t_c n_c))^2} \\ &\quad - \frac{ct_c \left(r\gamma \left(\gamma \left((2t_c t_p - n_c n_p)^2 - 2t_c^2 t_p^2\right) + t_c n_c^2 n_p\right)\right)}{(c\beta t_c (4t_c t_p - 3n_c n_p) - r\gamma (\gamma (2t_c t_p - n_c n_p) - t_c n_c))^2}\end{aligned}$$

and derive that

$$\frac{\partial a^{i,MS}}{\partial n_c} > 0 \Leftrightarrow \left(r > r'_{MS,2} \text{ and } \gamma < \gamma'_{MS,2}\right) \text{ or } \left(r < r'_{MS,2} \text{ and } \gamma > \gamma'_{MS,2}\right),$$

with

$$\begin{aligned}\gamma'_{MS,2} &= \frac{t_c n_c^2 n_p}{2t_c^2 t_p^2 - (2t_c t_p - n_c n_p)^2}, \\ r'_{MS,2} &= \frac{c\beta t_c (2t_c t_p - 3n_c n_p) (2t_c t_p - n_c n_p)}{\gamma \left(\gamma \left((2t_c t_p - n_c n_p)^2 - 2t_c^2 t_p^2\right) + t_c n_c^2 n_p\right)}.\end{aligned}$$

Part (ii) From the equilibrium solution of Proposition 2, we calculate

$$\frac{\partial \delta^{i,MS}}{\partial n_p} = \frac{cr\beta t_c^2 (2\gamma t_p - 3n_c) n_c^2}{2(c\beta t_c (4t_c t_p - 3n_c n_p) - r\gamma (t_c (2\gamma t_p - n_c) - \gamma n_c n_p))^2}$$

and derive that

$$\frac{\partial \delta^{i,MS}}{\partial n_p} > 0 \Leftrightarrow \gamma > \gamma'_{MS,3} = \frac{3n_c}{2t_p}.$$

Similarly, we compute

$$\frac{\partial a^{i,MS}}{\partial n_p} = \frac{c t_c^2 n_c^2 \left(\left(r\gamma^2 - c\beta t_c \right) t_p - r\gamma n_c \right)}{\left(c\beta t_c \left(4 t_c t_p - 3 n_c n_p \right) - r\gamma \left(t_c \left(2\gamma t_p - n_c \right) - \gamma n_c n_p \right) \right)^2}$$

and derive that

$$\frac{\partial a^{i,MS}}{\partial n_p} > 0 \Leftrightarrow r > r'_{MS,4} = \frac{c\beta t_c t_p}{\gamma \left(\gamma t_p - n_c \right)} \text{ and } \gamma > \gamma'_{MS,4} = \frac{n_c}{t_p}.$$

Part (iii): From the equilibrium solution of Proposition 2, we obtain

$$\frac{\partial \delta^{i,MS}}{\partial \gamma} = \frac{r n_c \left(\gamma \left(2 t_c t_p - n_c n_p \right) - t_c n_c \right) \left(2 r\gamma \left(2 t_c t_p - n_c n_p \right) + 2 r \left(t_c \left(2\gamma t_p - n_c \right) + \gamma n_c n_p \right) \right)}{\left(2 c\beta t_c \left(4 t_c t_p - 3 n_c n_p \right) - 2 r\gamma \left(t_c \left(2\gamma t_p - n_c \right) - \gamma n_c n_p \right) \right)^2} + \frac{r n_c \left(2 t_c t_p - n_c n_p \right)}{2 c\beta t_c \left(4 t_c t_p - 3 n_c n_p \right) - 2 r\gamma \left(t_c \left(2\gamma t_p - n_c \right) - \gamma n_c n_p \right)}$$

and can show that

$$\frac{\partial \delta^{i,MS}}{\partial \gamma} > 0.$$

Moreover, we compute

$$\frac{\partial a^{i,MS}}{\partial \gamma} = \frac{c t_c n_c \left(t_c t_p - n_c n_p \right) \left(r\gamma \left(2 t_c t_p - n_c n_p \right) + r \left(t_c \left(2\gamma t_p - n_c \right) + \gamma n_c n_p \right) \right)}{\left(c\beta t_c \left(4 t_c t_p - 3 n_c n_p \right) - r\gamma \left(t_c \left(2\gamma t_p - n_c \right) - \gamma n_c n_p \right) \right)^2} > 0.$$

A.5 Proof of Proposition 3

From the second-order derivatives of $\pi^{i,SM}$ with respect to a^i and δ^i, we derive the Hessian matrix as

$$H_{SM} = \begin{vmatrix} -\frac{r\beta t_p}{t_c t_p - n_c n_p} & \frac{r(\gamma t_p - n_c)}{2(t_c t_p - n_c n_p)} & \frac{r(\gamma t_p - n_c)}{2(t_c t_p - n_c n_p)} \\ \\ \frac{r(\gamma t_p - n_c)}{2(t_c t_p - n_c n_p)} & -c & \end{vmatrix}$$

and we see that $H_{SM} = H_{SS}$. Thus, similar to the S-S scenario, the Hessian matrix H_{SM} in the S-M scenario is negative definite if $\beta > \beta'_1$.

A.6 Proof of Corollary 3

Part (i): From the equilibrium solution of Proposition 3, we derive

$$\frac{\partial \delta^{i,SM}}{\partial n_c} = -\frac{r}{2c\beta t_p} < 0 \text{ and } \frac{\partial a^{i,SM}}{\partial n_c} = -\frac{n_p}{\beta t_p} < 0.$$

Part (ii): We compute

$$\frac{\partial \delta^{i,SM}}{\partial n_p} = 0 \text{ and } \frac{\partial a^{i,SM}}{\partial n_p} = -\frac{n_c}{\beta t_p} < 0.$$

Part (iii): We calculate that

$$\frac{\partial \delta^{i,SM}}{\partial \gamma} = \frac{r}{2c\beta} > 0 \text{ and } \frac{\partial a^{i-SM}}{\partial \gamma} = 0.$$

A.7 Proof of Proposition 4

From the second-order derivatives of $\pi^{i,MM}$ with respect to a^i and δ^i, we derive the Hessian matrix as

$$H_{MM} = \begin{vmatrix} -\frac{2r\beta t_p}{t_c t_p - n_c n_p} & \frac{r\gamma t_p}{t_c t_p - n_c n_p} \\ \frac{r\gamma t_p}{t_c t_p - n_c n_p} & -c \end{vmatrix}.$$

Similarly, H_{MM} is a negative definite matrix if the following conditions are satisfied:

$$-\frac{2r\beta t_p}{t_c t_p - n_c n_p} < 0 \text{ and } \frac{rt_p\left(2c\beta\left(t_c t_p - n_c n_p\right) - r\gamma^2 t_p\right)}{\left(t_c t_p - n_c n_p\right)^2} > 0.$$

We derive that these conditions are satisfied if

$$t_c t_p - n_c n_p > 0 \text{ and } \beta > \beta_3' = \frac{r\gamma^2 t_p}{2c\left(t_c t_p - n_c n_p\right)}.$$

A.8 Proof of Corollary 4

Part (i): From the equilibrium solution of Proposition 4, we derive that

$$\frac{\partial \delta^{i,MM}}{\partial n_c} = -\frac{r\gamma\left(2c\beta t_c - r\gamma^2\right) t_p\left(n_p - t_p\right)}{\left(r\gamma\left(\gamma t_p + n_c\right) - 2c\beta\left(t_c t_p - n_c n_p\right)\right)^2} < 0$$

and

$$\begin{aligned} \frac{\partial a^{i,MM}}{\partial n_c} = & -\frac{c\left(2c\beta t_c - r\gamma^2\right)\left(n_p - t_p\right)\left(t_c t_p - n_c n_p\right)}{\left(r\gamma\left(\gamma t_p + n_c\right) - 2c\beta\left(t_c t_p - n_c n_p\right)\right)^2} \\ & -\frac{cn_c\left(n_p - t_p\right) n_p}{t_p\left(r\gamma\left(\gamma t_p + n_c\right) - 2c\beta\left(t_c t_p - n_c n_p\right)\right)} \quad < \quad 0. \end{aligned}$$

From the condition in Proposition 4 that ensures a negative definite matrix, we derive that $2c\beta\left(t_c t_p - n_c n_p\right) - r\gamma^2 t_p > 0$ and compute

$$2c\beta t_c t_p - r\gamma^2 t_p > 2c\beta\left(t_c t_p - n_c n_p\right) - r\gamma^2 t_p > 0.$$

Part (ii): Similarly, we calculate

$$\frac{\partial \delta^{i,MM}}{\partial n_p} = \frac{r\gamma n_c \left(r\gamma \left(\gamma t_p + n_c\right) - 2c\beta t_p \left(t_c - n_c\right)\right)}{\left(r\gamma \left(\gamma t_p + n_c\right) - 2c\beta \left(t_c t_p - n_c n_p\right)\right)^2}$$

and derive

$$\frac{\partial \delta^{i,MM}}{\partial n_p} > 0 \Leftrightarrow r > r'_{MM,1} = \frac{2c\beta \left(t_c - n_c\right) t_p}{\gamma^2 t_p + \gamma n_c}.$$

Moreover, we compute that

$$\frac{\partial a^{i,MM}}{\partial n_p} = \frac{c n_c \left(r\gamma \left(\gamma t_p + n_c\right)\left(t_p \left(t_c + n_c\right) - 2n_c n_p\right) - 2c\beta (t_c t_p - n_c n_p)^2\right)}{t_p((r\gamma^2 - 2c\beta t_c)\, t_p + n_c \left(r\gamma + 2c\beta n_p\right))^2}$$

and derive that

$$\frac{\partial a^{i,MM}}{\partial n_p} > 0 \Leftrightarrow r > r'_{MM,2} \text{ and } n_c < n'_{MM,1},$$

with

$$\begin{aligned} r'_{MM,2} &= \frac{2c\beta (t_c t_p - n_c n_p)^2}{\gamma \left(\gamma t_p + n_c\right)\left(t_p \left(t_c + n_c\right) - 2n_c n_p\right)}, \\ n'_{MM,1} &= \frac{t_c t_p}{2n_p - t_p}. \end{aligned}$$

Part (iii): We derive that

$$\begin{aligned} \frac{\partial \delta^{i,MM}}{\partial \gamma} &= -\frac{r n_c \left(n_p - t_p\right)\left(2c\beta \left(t_c t_p - n_c n_p\right) + r\gamma^2 t_p\right)}{\left(r\gamma \left(\gamma t_p + n_c\right) - 2c\beta \left(t_c t_p - n_c n_p\right)\right)^2} < 0, \\ \frac{\partial a^{i,MM}}{\partial \gamma} &= -\frac{c n_c \left(r\gamma t_p + r \left(\gamma t_p + n_c\right)\right)\left(n_p - t_p\right)\left(t_c t_p - n_c n_p\right)}{t_p (r\gamma \left(\gamma t_p + n_c\right) - 2c\beta \left(t_c t_p - n_c n_p\right))^2} < 0. \end{aligned}$$

A.9 Proof of Proposition 5

Part (i): To show that consumers are multi-homing and producers are single-homing (M-S scenario) when cross-network effects obtained by producers are sufficiently weak, we proceed as follows: From Proposition 2, we know that the number of consumers on platform i is given by

$$Q_c^{i,MS} = \frac{c\beta n_c \left(2t_c t_p - n_c n_p\right)}{2c\beta t_c \left(4t_c t_p - 3n_c n_p\right) - 2r\gamma \left(t_c \left(2\gamma t_p - n_c\right) - \gamma n_c n_p\right)}.$$

If $Q_c^{i,MS} > \frac{1}{2}$, then there are consumers who have chosen to use both platforms, i.e., there are multi-homing consumers. We derive that

$$Q_c^{i,MS} > \frac{1}{2} \Leftrightarrow n_p < \frac{t_c \left(2t_p \left(c\beta \left(2t_c - n_c\right) - r\gamma^2\right) + r\gamma n_c\right)}{n_c \left(c\beta \left(3t_c - n_c\right) - r\gamma^2\right)}.$$

Part (ii): For the producers, we can derive a similar condition to ensure that there producers, who have chosen to join both platforms. Specifically, we compute that

$$Q_p^{i,SM} = \frac{rn_c + t_p\left(c\beta n_p - r\gamma\right)}{2c\beta t_p^2} > \frac{1}{2} \Leftrightarrow n_c > \frac{t_p\left(r\gamma + c\beta\left(t_p - n_p\right)\right)}{r}.$$

Part (iii): Consumers and producers are multi-homing if

$$Q_c^{i,MM} = \frac{c\beta n_c\left(n_p - t_p\right)}{r\gamma\left(\gamma t_p + n_c\right) - 2c\beta\left(t_c t_p - n_c n_p\right)} > \frac{1}{2}$$

and

$$Q_p^{i,MM} = \frac{r\gamma t_p\left(n_c + \gamma n_p\right) - c\beta n_p\left(2t_c t_p - n_c\left(t_p + n_p\right)\right)}{t_p\left(r\gamma\left(\gamma t_p + n_c\right) - 2c\beta\left(t_c t_p - n_c n_p\right)\right)} > \frac{1}{2}.$$

We derive that

$$\left(Q_c^{i,MM} > \frac{1}{2} \text{ and } Q_p^{i,MM} > \frac{1}{2}\right) \Leftrightarrow n_c < \frac{\left(2c\beta t_c - r\gamma^2\right)t_p}{r\gamma + 2c\beta t_p} \text{ and } n_p > \frac{r\gamma}{c\beta} + t_p.$$

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