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Effects of Industry Concentration on Quality Choices for Network Connectivity

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Abstract

I examine the effects of market concentration on connectivity in network industries. Using Cournot interactions for a duopoly, each network chooses quantity, quality for communications within the provider's own network (internal quality), and quality for communications between the provider's network and other networks (external quality). I find that large networks choose higher internal quality than do small networks and large networks choose higher internal quality than external quality. I also find that providers prefer flexible technologies that allow them to simultaneously choose outputs and qualities. Small networks prefer higher external quality than internal quality except when they make credible quality commitments before choosing output and have higher marginal operating costs than large networks. Networks choose identical external quality unless they have exogenously determined customer bases.

1. Introduction

The liberalization of telecommunications markets has been marked by a number of mergers and alliances, some of which have been record setting. Examples of large mergers include the merger of Bell Atlantic with NYNEX in 1997, and then with GTE in 2000 to form Verizon; SBC's acquisition of Pacific Telesis in 1997, Southern New England Telephone in 1998, and Ameritech in 1999; WorldCom's purchase of MCI in 1998; Vodafone's acquisition of AirTouch in 1999 and Mannesmann in 2000; and the merger of AOL and Time Warner in 2001. The financial downturn in telecommunications in the early 2000s slowed the merger trend and resulted in some divestitures, but competition regulators, utility regulators, and continue to raise concerns that market dominance and mergers might hinder competition. Concerned with market dominance in the Internet, the European Union (EU) required MCI and WorldCom to divest a portion of their Internet business as a condition of approving WorldCom's purchase of MCI (Crémer et al., 2000, and Ungerer, 2000) and halted WorldCom's planned purchase of Sprint. As a precondition for approving the AOL Timer Warner merger, the US Federal Communications Commission (FCC) required AOL Time Warner to open its cable systems to competitor Internet Service Providers (ISPs) and to interconnect its Instant Messaging software with that of rivals before introducing advanced Instant Messaging-based services on its cable systems.[1]

Recent economic research has focused on incentives of larger network operators to discriminate against smaller rivals with respect to the quality of connectivity between

[1] The FCC did allow AOL Time Warner the opportunity to obtain relief from the Instant-Messaging requirement by showing clear and convincing evidence that the requirement no longer served the public interest.

networks. Crémer et al. (2000) find that larger Internet backbone networks have an incentive to lower the quality of their interconnection with smaller rivals. Foros and Hansen (2001) find conditions under which two rival Internet Service Providers over invest in compatibility to avoid competitive pressure when they compete a-la Hotelling. Cambini and Valletti (2003) find that operators have an incentive to under invest in quality when network quality has an impact on the number of calls. Ennis (2003) finds that when customers receive decreasing marginal utility from additional users on the network, then smaller networks derive more value from interconnection than do larger networks.

This paper extends this research by examining how market concentration and technology choices affect network quality. I examine a duopoly in which customers initially form expectations regarding network quality and size, then firms simultaneously choose either a flexible technology that makes it uneconomical to make quality commitments prior to choosing outputs, or a rigid technology that has the opposite effect. Previous models of network quality have assumed that firms make credible commitments for quality before choosing output. This sequence is probably appropriate for networks of fax machines and computer components, where hardware design determines compatibility with rivals' products. However, software determines interconnection quality in Instant Messaging and in some aspects of the Internet. Firms' network maintenance choices and circuit choices[2] also determine interconnection quality in the Internet. Firms can change these quality choices while providing output. As a result of

[2] Physical telecommunications networks interconnect through physical circuits. Variations in the quality of manufacturer equipment can cause circuits to vary in the quality of their transmission of telecommunications signals. A firm can discriminate against rivals by choosing to interconnect using circuits that provide below-average transmission quality.

this possibility, I assume that firms can choose technologies that determine whether the firm's make credible quality commitments before choosing outputs.

If firms choose the flexible technology, then they simultaneously choose output, network quality for internal communications (which I call internal quality), and interconnection quality for communications between networks (which I call external quality). Otherwise, firms choose qualities and then output. Lastly, customers choose their network providers.[3]

To examine how market concentration affects firms' incentives to provide quality, I consider two sources of asymmetry in network size. Following Crémer et al. (2000), I consider models where networks have exogenously determined existing customer bases of different sizes at the start of the game and that these existing customers' purchasing decisions do not change during the game. I also consider models where the firms have different marginal production costs. I find that differences in existing customer bases cause the large firm to prefer a lower external quality than the small firm when the two firms interconnect their networks. Networks optimally choose identical external qualities when differences in network size result from differences in marginal production costs. I also find that the small network prefers an internal quality that is lower than both the large network's preferred internal quality. Except when the small network makes a credible quality commitment before choosing output, the small network prefers an internal quality that is lower than its preferred external quality.

[3] I limit my analysis to situations where equilibria exist by considering only customer expectations of output and quality that are equal to actual output and quality in equilibrium. (Katz and Shapiro, 1985) I also limit my analysis to stable equilibria by considering equilibria where the demand curve intersects firms' marginal costs curves from above. (Rohlfs, 1974)

The analysis proceeds as follows. Section 2 describes the basic model. Section 3 presents situations where the firms can make credible quality commitments before choosing outputs. Section 4 presents the case in which quality and output are determined simultaneously. Section 5 is the conclusion. Proofs and details on simulations are in the Appendix.

2. The Model

2.1. Demand and Supply

I consider an extension of the model developed by Katz and Shapiro (1985) and Crémer et al. (2000) in which customers initially form expectations about network size and quality. Each firm then chooses either the flexible or rigid technology. Next the firms play a quality and quantity game and determine prices taking customer expectations as given. Lastly customers choose network providers based on prices and the value customers place on network services. The firms' technology choices in the second stage determine whether each firm chooses quality and output sequentially or simultaneously. I assume that each firm can choose one of two technologies: a flexible technology that makes it uneconomical to make quality commitments and a rigid technology that does the opposite. For simplicity, I assume that a firm incurs a fixed cost Γ for choosing the flexible technology. Condition 1 establishes conditions under which firm *i* would choose the rigid technology.

Condition 1. The fixed cost of choosing the flexible technology is greater than the difference between the profit the firm receives when it simultaneously chooses quality and output and the profit the firm receives when it chooses quality before choosing output. That is to say, $\Gamma^i > \pi_{sim}^{i\ *} - \pi_{seq}^{i\ *}$, where $\pi_{sim}^{i\ *}$ is *i*'s profit from simultaneously choosing its optimal quality and output and ${\pi_{seq}^{i}}^{*}$ is *i*'s profit when it chooses its optimal quality before choosing output.

Lemma 1. When Condition 1 holds for firm *i*, firm *i* optimally chooses the rigid technology.

A revealed preferences analysis is sufficient to confirm Lemma 1. Firm *i* is always able to make the same choices in a game where quality and output are chosen simultaneously as in a game where quality and output are chosen sequentially. Therefore, *i*'s profits are at least has great in a simultaneous move game as in a sequential move game. Consequently, firm *i* will choose the rigid technology only if it is less costly than the flexible technology by an amount that is greater in absolute value than the difference between firm *i*'s profits in a simultaneous move game and those in a sequential move game.

There are up to three markets for the network service and two firms, *L* and *S*. Markets are distinct because they are separated by geography and customers cannot migrate across markets to purchase the network service. There are Q_m customers in market *m*, *m* = 1, 2, 3. Network providers compete for customers in a single period. $q_m^i \geq 0$ will denote the number of customers that firm *i* serves in the market.

A customer of type $\tau \in [0, \bar{\tau}_m]$ in market *m* obtains a net surplus from buying from firm *i* at price p_m^i equal to $\tau + s_m^i - p_m^i$, where s_m^i denotes the value that the customer places on *i*'s network. I assume that τ is uniformly distributed. Customers desire to communicate with customers in all markets, so s_m^i is given by

$$s_m^i = v \sum_{j=L}^{S} \sum_{\mu=1}^{n} \theta^{i,j} q_\mu^j \, . \qquad (1)$$

I let $v \in (0, \bar{v})$ represent a parameter that reflects the constant marginal value that customers place on network communications of a given quality. This linearity assumption of value follows Crémer et al. (2000) and implies that, except for the firms' quality choices, each customer of type τ is indifferent with respect to which customers the τ-type customer communicates.

I assume that firms can choose to "interconnect" their networks.[4] In the setting of physical communications networks, this interconnection would be the lines and technical arrangements that allow customers to communicate. In the setting of virtual networks, such as computer software, this interconnection could be interpreted as features that allow customers to benefit from exchanging information with other customers. For example, a software provider may create features that allow its spreadsheet users to exchange data with customers that use a rival's spreadsheet.

Let $\theta^{i,i} \in [0, \bar{\theta}]$ represent *i*'s quality choice for communications between its customers and let $\theta^{i,j} \in [0, \bar{\theta}]$ represent firm *i*'s quality choice for external connectivity between its network and *j*'s network, for $j \neq i$. Quality includes such things as capacity for customers of physical networks to exchange messages, and features, such as with instant messaging. A choice of zero represents a refusal to interconnect. Network quality is perfectly observable to firms and customers alike.[5]

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[4] In some industries, regulators require firms to interconnect their networks. Regulated telecommunications is an example of a network industry where regulators require interconnection. The Internet is generally unregulated. Refusal to interconnect is rare in the Internet, but controversy over type of interconnection is common. See Kende (2000) for an excellent overview.

[5] Technically, the term q_μ^i in (1) should be $q_\mu^i - 1$ because customers do not obtain value from accessing themselves. I suppress the –1 and assume that q is sufficiently large that it does not affect the results. If the –1 were included, its effect would be to lower each firm's internal quality relative to external quality.

For simplicity, I assume that each firm chooses a single internal quality and that two firms have a single external quality for interconnecting with each other. I consider situations where only one quality choice can prevail for each network interconnection. For example, if one firm chose a capacity of 45 megabits per second and the other chose a capacity of 30 megabits per second, only 30 megabits per second of information could be passed between the networks. Following Crémer et al. (2000) and Ennis (2003), I assume that if firms prefer different external qualities that they engage in Nash bargaining to agree upon a single quality. (Nash, 1950; Lopomo and Ok, 2001)

Lemma 2. Given the assumptions of the model, each customer of type τ is indifferent between networks at equilibrium, i.e., $\tau + s_m^i - p_m^i = \tau + s_m^j - p_m^j$ for every *i*, *j* = *L*, *S* and $i \neq j$.

It follows from Lemma 2 that if firm *i* attracts customers, it has a quality-adjusted price

$$p_m^i - s_m^i \equiv \overline{p}_m. \tag{2}$$

I define the marginal customer to be the customer that, in equilibrium, is indifferent between buying and not buying network service. Such a customer exists because I assume that $\tau \in [0, \overline{\tau}_m]$, costs are strictly positive, and *v*, the constant marginal value of connectivity, is sufficiently large relative to firms' costs to ensure that $q_m^i > 0$ for every firm and sufficiently small to ensure that some customer $\tau \geq 0$ does not purchase. At equilibrium, the marginal customer will receive zero net surplus and so will have a value of $\tau = \overline{p}_m$. Because the distribution of customers is uniform, the quantity of customers that firms choose to serve in equilibrium is simply the total number of customers that lie between the upper bound of customer preferences and $\overline{p}_m$. Normalizing the density of customers to 1 in each market, the quantity of customers served in market *m* is

$$\sum_{i=L}^{S} q_m^i = \overline{\tau}_m - \overline{p}_m . \tag{3}$$

Combining (1), (2), and (3) gives the customers' inverse demand curve for firm *i* in market *m*

$$p_m^i = \overline{\tau}_m - \sum_{j=L}^{S} q_m^j + v \sum_{j=L}^{S} \theta^{i,j} \left(\beta^j + q_m^j \right) \tag{4}$$

where β^j is the number of customers that purchase from *j* in markets other than *m*.

I examine situations where *L* optimally chooses to provide a larger network than *S* optimally chooses. This might be the situation if the firms exogenously serve multiple markets and *L* has a larger customer base than does *S* in these markets, or if *L* has lower marginal production costs than *S* for every $q_m^L = q_m^S$. For simplicity, I model settings in which *L* and *S* serve multiple markets by assuming that the number of customers served in these markets is exogenous and that $\beta^L > \beta^S$. Also for simplicity, I assume the firms serve a single market *m* when the firms have asymmetric marginal production costs and are symmetric in all other parameters.

Costs for production are separable from costs for quality. I normalize fixed costs to zero (except for the cost of choosing the flexible technology) and assume a constant marginal cost $c^i > 0$ of production. For simplicity, there are no economies of scope across markets. $G(\boldsymbol{\theta}^i) \equiv e^{g\theta^{i,i}} + e^{g\theta^{i,j}}$ represents firm *i*'s cost function for quality, which is increasing in quality and convex. For simplicity, I assume that quality costs are independent of the number of customers. The assumption simplifies notation and does not affect results.

Each firm takes its rivals' quality and output choices as given when it chooses its own quality and output levels. Firm *i*'s profit maximization problem can be written as:

$$\begin{aligned} &\max_{q^i,\boldsymbol{\theta}^i} \pi^i = \sum_{m=1}^{3}\left(p_m^i - c^i\right)q_m^i - G^i\left(\boldsymbol{\theta}^i\right) \\ &\text{subject to} \qquad \theta^{i,j} \in \left[0,\overline{\theta}\right] \quad \text{for } j = \{L,S\} \\ &\qquad\qquad\qquad q^i \geq 0. \end{aligned} \tag{5}$$

2.2 <u>Welfare</u>

The surplus a customer receives from purchasing depends on the innate value the customer places on the network service, on the internal and external quality choices of the customer's network supplier, and the total number of customers who purchase the network services. In each market, a customer only purchases if he values the service at least as much as the marginal customer does. Recalling that utility and p_m^i are zero for customers that do not purchase from firm *i*, integrating over all customers who purchase and summing over all firms and all markets gives the net consumer surplus:

$$U^{net} \equiv \sum_{i=L}^{S}\left(\sum_{m=1}^{3}\int_0^{q_m}\left(u_m^i\left(\hat{q}_m,\mathbf{q},\boldsymbol{\theta}^i\right) - p_m^i\left(q_m,\mathbf{q},\boldsymbol{\theta}^i\right)\right)d\hat{q}_m - T^i\right),$$

and weighted social welfare:

$$Z \equiv \alpha U^{net} + (1-\alpha)\sum_{i=1}^{3}\left(\pi^i + T^i\right),$$

where α = [0, 1] is the weight given to net consumer surplus and T^i is a transfer payment from consumers to firm *i* that may be necessary to ensure non-negative profits, for example. If a social planner chooses **q** and θ to maximize weighted social welfare subject to a non-negative profit constraint for firms, she would: (*i*) equate the sum of the marginal consumer surplus and the positive network externality to the marginal production cost; and (*ii*) equate the marginal consumer surplus from quality and the marginal cost of quality.

3. Sequential Quality and Output Choices

In this section I consider situations where Condition 1 holds for both firms so that they make credible quality commitments before choosing output.[6] I first examine the situation where the large firm, *L*, has an existing customer base β^L and *S* has an existing customer base β^S, where $\beta^L > \beta^S$. I then consider the situation where the large firm has lower marginal production costs than the small firm.

3.1. Asymmetric Existing Customer Bases in the Sequential Move Setting

Crémer et al. (2000) show that the large firm prefers a lower external quality than does the smaller firm when $\beta^L > \beta^S$, so I simply state this result as Lemma 3.

Lemma 3. When Condition 1 holds for both firms and $\beta^L > \beta^S$, then firm *S* prefers a higher external quality than does firm *L*.

Proposition 1 provides this subsection's primary result.

Proposition 1. In the sequential choice setting with exogenous and asymmetric customer bases:

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[6] Future extensions will consider situations where one firm chooses the flexible technology and the other chooses the rigid technology.

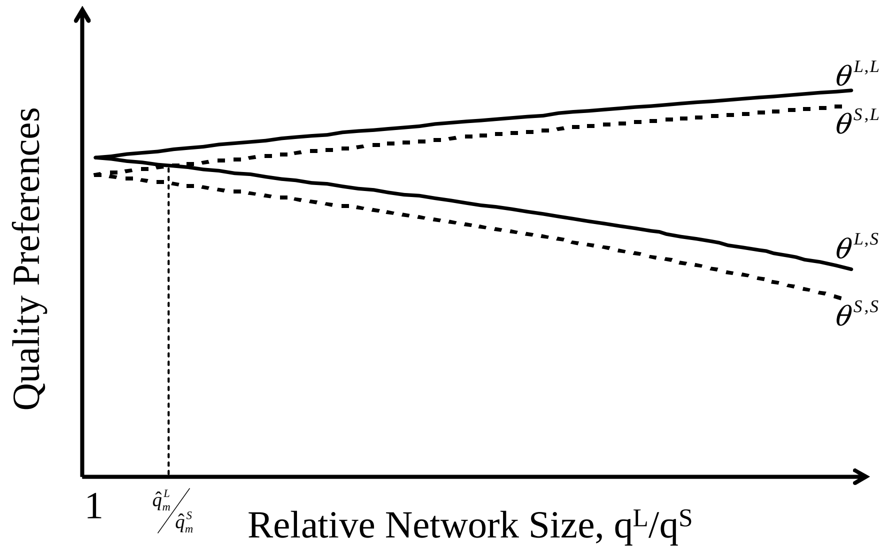
a. The large firm optimally chooses an internal quality that is greater than either firm's preferred external quality and that is greater than the small firm's optimal internal quality; and

b. The small firm optimally chooses an internal quality that is lower than either firm's preferred external quality.

That is to say, $\theta^{L,L^*} > \theta^{S,L^*} > \theta^{L,S^*} > \theta^{S,S^*}$.

My model does not solve analytically, so I demonstrate Proposition 1 using a simulation. Figure 1 shows the results of the simulation and the Appendix describes the calculations. The vertical axis in Figure 1 represents quality preferences and the horizontal axis represents relative network size, namely q_m^L / q_m^S. When the firms have symmetric outputs, i.e., $q_m^L = q_m^S$, the firms make symmetric quality choices. As q_m^L / q_m^S increases, firm *L* increases its internal quality and decreases its external quality preferences. Firm *S* decreases its internal quality and increases its external quality preferences. Firm *L*'s internal quality choice is always greater than its preferred external quality because higher external quality would lead its rival to increase its output, which would result in a lower market clearing price. Similarly, firm *L*'s internal quality choice is always greater than firm *S*'s preferred external quality. Firm *L*'s optimal internal quality is greater than firm S's optimal internal quality because the marginal benefit to a customer of increasing quality is increasing in the number of customers with whom this customer can communicate at the higher quality, i.e., a customer values communicating with *L*'s customers more than communicating with *S*'s customers.

Figure 1. Effects of Relative Network Size on Quality Preferences, Sequential Move



Lastly, firm *S*'s internal quality choice is greater than its preferred external quality when $q_m^{L^*} / q_m^{S^*} < \hat{q}_m^L / \hat{q}_m^S$ and lower than its preferred external quality when the reverse is true. This crossover results from asymmetries in network size affecting firms' internal and external quality preferences differently. An increase in q_m^L / q_m^S implies an increase in the value of interconnection for the small firm all other things being equal, which leads the small firm to prefer a higher external quality than when q_m^L / q_m^S is higher. However, an increase in q_m^L / q_m^S also implies a decrease in the value of internal quality for the small network's customers relative to the value of external quality. $\hat{q}_m^L / \hat{q}_m^S$ represents the point where these effects on *S*'s quality choices result in identical selections.

Proposition 1 adds to the results of previous research on network quality in the following manner. Crémer et al. (2000) and others have concluded that larger networks degrade interconnection quality with smaller networks. If it is appropriate to characterize this difference in external quality preferences as degradation in quality, then Proposition 1 shows that *S* degrades its internal quality relative to all other quality choices in the model.

3.2. <u>Asymmetric Marginal Production Costs in the Sequential Move Setting</u>

In this subsection I consider situations where Condition 1 holds and *L* has lower marginal production costs than *S*, i.e., $c^S > c^L$. Firms are identical in all other parameters. Proposition 2 provides this subsection's primary results.

Proposition 2. In the sequential choice setting with asymmetric marginal production costs:

a. The large firm optimally chooses an internal quality that is greater than either firm's preferred external quality and that is greater than the small firm's optimal internal quality;

b. The firms optimally choose identical external qualities that are lower than the small firm's optimal internal quality.

That is to say, $\theta^{L,L^*} > \theta^{S,S^*} > \theta^{L,S^*} = \theta^{S,S^*}$.

My model does not solve analytically, so I demonstrate Proposition 2 using a simulation. The Appendix provides the details and results of the simulation. When the firms have symmetric outputs, i.e., $q_m^L = q_m^S$, the firms make symmetric quality choices. As q_m^L / q_m^S increases, firm *L* increases its internal quality and *S* decreases its internal quality preferences in accordance with the greater (conversely, lower) value that customers place on connectivity with their respective networks.

In choosing external quality, each firm considers its expected network size, the expected size of the rival network, and *v*, the value a customer places on communicating with another customer. Each firm considers its own network size because this determines the number of customers that are willing to pay prices that reflect the value of the external quality. Each firm considers the other firm's network size because more customers on other networks increase the value of the interconnection. This symmetry in factors that determine quality leads the firms to choose symmetric external qualities. The large firm does not strategically degrade the quality of its interconnection with its rival.

Proposition 2 contributes to the literature on network connectivity by showing that the source of customers affects whether firms disagree on external quality. If some customers are exogenous, then firms have different external quality preferences because the large firm is unwilling to invest in quality for its exogenous customers to be able to communicate with the small firm's customers. However, the small firm is willing to invest in quality for its endogenous customers to be able to communicate with the large firm's customers. Thus the asymmetry in the number of exogenous customers drives an asymmetry in preferences for external quality.

4. Simultaneous Quality and Output Choices

In this section I consider situations where Condition 1 does not hold so that firms cannot make credible quality commitments before choosing output. I first consider the situation where the firms have existing customer bases such that $\beta^L > \beta^S$. I then consider the situation where *L* has lower marginal production costs than *S*, i.e., $c^S > c^L$.

4.1. Asymmetric Existing Customer Bases in the Simultaneous Move Setting

In this subsection I consider the situation where Condition 1 holds and $\beta^L > \beta^S$. Firms are identical in all other parameters. Proposition 3 provides this subsection's primary result.

Proposition 3. In the simultaneous choice setting with asymmetric customer bases:

a. The large firm optimally chooses an internal quality that is greater than either firm's preferred external quality and that is greater than the small firm's optimal internal quality; and

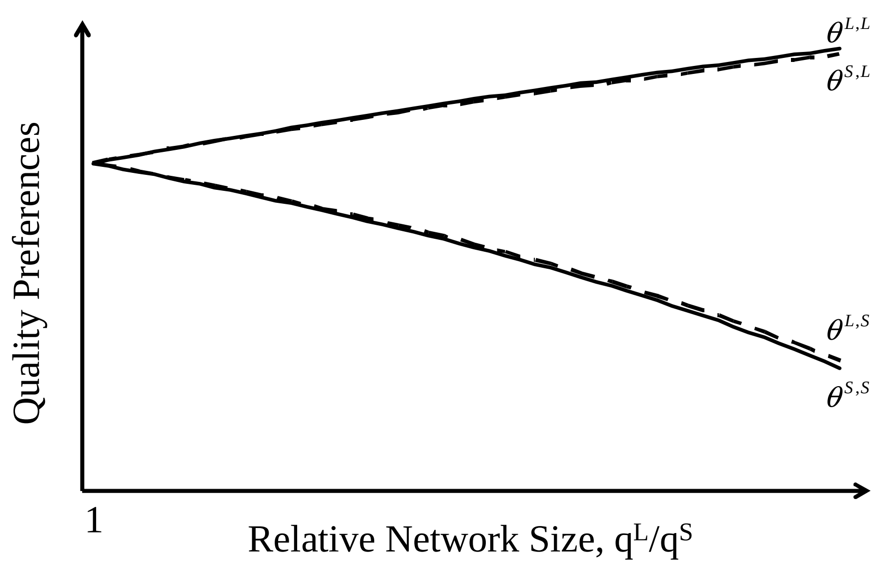
b. The small firm optimally chooses an internal quality that is lower than either firm's preferred external quality.

That is to say, $\theta^{L,L^*} > \theta^{S,L^*} > \theta^{L,S^*} > \theta^{S,S^*}$.

My model does not solve analytically, so I demonstrate Proposition 3 using a simulation. Figure 2 charts the results of the simulation and the Appendix describes the calculations. The vertical axis in Figure 2 represents quality preferences and the horizontal axis represents relative network size. When the firms have symmetric outputs, i.e., $q_m^L = q_m^S$, the firms make symmetric quality choices and their internal quality choices are equal to their external quality choices. An increase in q_m^L / q_m^S implies an increase in

L's optimal internal quality, a decrease in *L*'s preferred external quality, a decrease in *S*'s optimal internal quality, and an increase in *S*'s preferred external quality. Firm *L*'s internal quality choice is greater than its preferred external quality whenever $\beta^L > \beta^S$ because customers value access to $q_m^L + \beta^L$ customers more than they value access to the smaller number of customers, $q_m^S + \beta^S$. Similarly, firm *L*'s optimal internal quality is greater than firm *S*'s preferred internal and external qualities because *L*'s customers have more internal customer communication links than *S*'s customers have external or internal customer links, i.e., $q_m^L\left(q_m^L + \beta^L\right) > q_m^S\left(q_m^L + \beta^L\right) > q_m^S\left(q_m^S + \beta^S\right)$, which makes quality more profitable. It follows from the previous statement that *S* prefers a higher external quality than internal quality.

Figure 2. Effects of Relative Network Size on Quality Preferences, Simultaneous Move with Exogenous Customer Base



4.2. Asymmetric Marginal Production Costs in the Simultaneous Move Setting

In this subsection I consider situations where Condition 1 does not hold and *L* has lower marginal production costs than *S*, i.e., $c^S > c^L$. Firms are identical in all other parameters. Proposition 4 provides this subsection's primary results.

Proposition 4. In the simultaneous choice setting with asymmetric marginal production costs:

a. The large firm optimally chooses an internal quality that is greater than either firm's preferred external quality and that is greater than the small firm's optimal internal quality;

b. The small firm's optimal internal quality is lower than its preferred external quality; and

c. The two firms choose identical external qualities.

That is to say, $\theta^{L,L^*} > \theta^{S,L^*} = \theta^{L,S^*} > \theta^{S,S^*}$.

As I described for Proposition 2, in choosing external quality, each firm considers its network size, the size of the rival network, and *v*, the value a customer places on communicating with another customer, i.e., $\theta^{i,j^*} = K_\theta^{-1}\left(vq_m^{i\ *} \cdot q_m^{j\ *}\right)$. Because $\theta^{i,j^*} = K_\theta^{-1}\left(vq_m^{i\ *} \cdot q_m^{j\ *}\right)$ is the same for both firms, they choose symmetric external qualities. Furthermore, each firm determines internal quality based on *v* and its output choice squared, i.e., $\theta^{i,i^*} = K_\theta^{-1}\left(v\left(q_m^{i\ *}\right)^2\right)$. The output choice is squared because more customers on the firm's own network increase the value of the network, and each customer represents someone who will pay a price that reflects that value.

The large firm provides the highest quality because its optimal output is higher than its rival's optimal output. This higher output makes the large firm's network more valuable to customers than its rival's network. Furthermore, for connection to a network of a given size, the large firm's higher output makes quality more profitable for it than for its rival. The rival optimally chooses an internal quality that is lower than the quality of its interconnections with the large firm because connection with the large firm's network provides more value to the small firm's customers than does its own network.

5. Conclusion

In this paper, I examine incentives for quality in network connectivity. I find that when firms have exogenous customers, the large network prefers a lower external quality than does the small network. Otherwise, large and small networks agree on external quality. I also find in all situations that I model that the large network optimally chooses an internal quality that is higher than either firm's preferred external quality. The small network's optimal internal quality is lower than either firm's preferred external quality except when the firms choose the rigid technology and the firms have asymmetric marginal production costs.

My results extend the results of earlier research by identifying conditions under which a large network and small network would agree on external quality. This raises questions about past US and EU regulators' restrictions on mergers. According to my analysis, a large firm would provide its own customers with higher quality connectivity than it would provide its smaller rival, but the large firm's interconnection quality choice would be no different in a game with only endogenous output than the small network’s interconnection quality choice for connecting with the large firm. Furthermore, the interconnection quality the large firm would choose for connecting with the small firm would be higher than the quality the smaller firm would choose for its internal connectivity.

In this analysis I do not model situations in which one firm chooses flexible technology and the other chooses rigid technology. Nor do I explicitly model mergers. These extensions will be addressed in future research.

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Appendix

Proof of Proposition 4. From (5), the first order conditions for an internal solution include:

$$\frac{\partial \pi^L}{\partial \theta^{L,L}} = v\left({q_m^L}^2\right) - K_\theta\left(\theta^{L,L}\right) = 0\,, \tag{A1}$$

$$\frac{\partial \pi^L}{\partial \theta^{L,S}} = v\left(q_m^L \cdot q_m^S\right) - K_\theta\left(\theta^{L,S}\right) = 0\,, \tag{A2}$$

$$\frac{\partial \pi^S}{\partial \theta^{S,L}} = v\left(q_m^L \cdot q_m^S\right) - K_\theta\left(\theta^{S,L}\right) = 0\,, \tag{A3}$$

$$\frac{\partial \pi^S}{\partial \theta^{S,S}} = v\left({q_m^S}^2\right) - K_\theta\left(\theta^{S,S}\right) = 0\,, \tag{A4}$$

From (A2) and (A3), ${\theta^{S,L}}^* = {\theta^{L,S}}^*$ because the outputs are identical. From (A1) and (A2), ${\theta^{L,L}}^* > {\theta^{L,S}}^*$ because $q_m^L > q_m^S$. From (A3) and (A4), ${\theta^{S,L}}^* > {\theta^{S,S}}^*$ because $q_m^L > q_m^S$. This confirms Proposition 4.

Specifications for Simulations

Using (5), I approximate quality preferences using the *FindRoot* function in Mathematica. This function relies on versions of Newton's method for finding numerical solutions to systems of simultaneous equations that cannot be solved analytically. In sequential games, I use backwards induction to express optimal outputs in terms of parameters and quality choices. I then use *FindRoot* to find numerical solutions for quality preferences. In simultaneous move games, I solve for outputs and qualities together using *FindRoot*. Table A1 shows results for the simulation for Proposition 1 based on exogenous customer bases. For this simulation, I used parameter values $\bar{\tau}_m = 100$, v = 0.1, c = 0, and g = 6. Table A2 shows the results of the simulation for Proposition 2, for which I used the parameter values $\bar{\tau}_m = 100$, v = 0.1, and g = 7. Table A3 shows the results of the simulation for Proposition 3, for which I used the parameter values $\bar{\tau}_m = 100$, v = 0.1, c = 0, and g = 6. Simulations with other parameter values do not change results, so I only report simulations with the parameters specified above.

Table A1. Results of Simulation for Proposition 1.					
β^L	β^S	Quality Preferences			
		L,L	*L,S*	*S,L*	*S,S*
50	50	0.7393	0.7220	0.7220	0.7393
51	49	0.7410	0.7201	0.7238	0.7375
52	48	0.7428	0.7182	0.7257	0.7358
53	47	0.7445	0.7163	0.7275	0.7340
54	46	0.7461	0.7144	0.7293	0.7322
55	45	0.7478	0.7124	0.7311	0.7303
56	44	0.7495	0.7104	0.7328	0.7285
57	43	0.7511	0.7084	0.7345	0.7266
58	42	0.7528	0.7064	0.7363	0.7247
59	41	0.7544	0.7043	0.7380	0.7228
60	40	0.7560	0.7023	0.7396	0.7209
61	39	0.7576	0.7001	0.7413	0.7190
62	38	0.7591	0.6980	0.7430	0.7170
63	37	0.7607	0.6958	0.7446	0.7150
64	36	0.7623	0.6936	0.7462	0.7130
65	35	0.7638	0.6914	0.7478	0.7110
66	34	0.7653	0.6892	0.7494	0.7089
67	33	0.7668	0.6869	0.7510	0.7068
68	32	0.7683	0.6846	0.7525	0.7047
69	31	0.7698	0.6822	0.7541	0.7026
70	30	0.7713	0.6798	0.7556	0.7004
71	29	0.7728	0.6774	0.7571	0.6982
72	28	0.7742	0.6750	0.7586	0.6960
73	27	0.7757	0.6725	0.7601	0.6938
74	26	0.7771	0.6699	0.7616	0.6915
75	25	0.7785	0.6674	0.7631	0.6892
76	24	0.7800	0.6648	0.7645	0.6868
77	23	0.7814	0.6621	0.7660	0.6845
78	22	0.7828	0.6594	0.7674	0.6821
79	21	0.7841	0.6567	0.7688	0.6796
80	20	0.7855	0.6539	0.7702	0.6772
81	19	0.7869	0.6510	0.7716	0.6747
82	18	0.7882	0.6482	0.7730	0.6721
83	17	0.7896	0.6452	0.7743	0.6696
84	16	0.7909	0.6422	0.7757	0.6669
85	15	0.7923	0.6392	0.7771	0.6643
86	14	0.7936	0.6361	0.7784	0.6616
87	13	0.7949	0.6329	0.7797	0.6588
88	12	0.7962	0.6297	0.7810	0.6560
89	11	0.7975	0.6264	0.7823	0.6532
90	10	0.7988	0.6230	0.7836	0.6503
91	9	0.8001	0.6196	0.7849	0.6474
92	8	0.8014	0.6161	0.7862	0.6444
93	7	0.8027	0.6125	0.7875	0.6414
94	6	0.8039	0.6088	0.7887	0.6383
95	5	0.8052	0.6051	0.7900	0.6351
96	4	0.8064	0.6012	0.7912	0.6319
97	3	0.8077	0.5973	0.7925	0.6286
98	2	0.8089	0.5933	0.7937	0.6253
99	1	0.8101	0.5892	0.7949	0.6219

Table A2. Results of Simulation for Proposition 2.					
Marginal Costs		Quality Preferences			
c1	c2	*L,L*	*L,S*	*S,L*	*S,S*
0.150	0.150	0.481794	0.449724	0.449724	0.481794
0.148	0.152	0.481812	0.449724	0.449724	0.481776
0.146	0.154	0.481831	0.449724	0.449724	0.481757
0.144	0.156	0.481849	0.449724	0.449724	0.481739
0.142	0.158	0.481867	0.449724	0.449724	0.481721
0.140	0.160	0.481886	0.449724	0.449724	0.481702
0.138	0.162	0.481904	0.449724	0.449724	0.481684
0.136	0.164	0.481922	0.449724	0.449724	0.481666
0.134	0.166	0.481941	0.449724	0.449724	0.481647
0.132	0.168	0.481959	0.449724	0.449724	0.481629
0.130	0.170	0.481977	0.449724	0.449724	0.481610
0.128	0.172	0.481996	0.449724	0.449724	0.481592
0.126	0.174	0.482014	0.449724	0.449724	0.481574
0.124	0.176	0.482032	0.449724	0.449724	0.481555
0.122	0.178	0.482051	0.449724	0.449724	0.481537
0.120	0.180	0.482069	0.449723	0.449723	0.481519
0.118	0.182	0.482087	0.449723	0.449723	0.481500
0.116	0.184	0.482106	0.449723	0.449723	0.481482
0.114	0.186	0.482124	0.449723	0.449723	0.481463
0.112	0.188	0.482142	0.449723	0.449723	0.481445
0.110	0.190	0.482161	0.449723	0.449723	0.481427
0.108	0.192	0.482179	0.449723	0.449723	0.481408
0.106	0.194	0.482197	0.449723	0.449723	0.481390
0.104	0.196	0.482216	0.449723	0.449723	0.481372
0.102	0.198	0.482234	0.449723	0.449723	0.481353
0.100	0.200	0.482252	0.449723	0.449723	0.481335
0.098	0.202	0.482271	0.449723	0.449723	0.481316
0.096	0.204	0.482289	0.449723	0.449723	0.481298
0.094	0.206	0.482307	0.449723	0.449723	0.481280
0.092	0.208	0.482326	0.449723	0.449723	0.481261
0.090	0.210	0.482344	0.449723	0.449723	0.481243
0.088	0.212	0.482362	0.449723	0.449723	0.481225
0.086	0.214	0.482381	0.449723	0.449723	0.481206
0.084	0.216	0.482399	0.449723	0.449723	0.481188
0.082	0.218	0.482417	0.449723	0.449723	0.481169
0.080	0.220	0.482436	0.449723	0.449723	0.481151
0.078	0.222	0.482454	0.449723	0.449723	0.481133
0.076	0.224	0.482472	0.449723	0.449723	0.481114
0.074	0.226	0.482491	0.449723	0.449723	0.481096
0.072	0.228	0.482509	0.449723	0.449723	0.481077
0.070	0.230	0.482527	0.449723	0.449723	0.481059
0.068	0.232	0.482545	0.449723	0.449723	0.481041
0.066	0.234	0.482564	0.449723	0.449723	0.481022
0.064	0.236	0.482582	0.449723	0.449723	0.481004
0.062	0.238	0.482600	0.449722	0.449722	0.480985
0.060	0.240	0.482619	0.449722	0.449722	0.480967
0.058	0.242	0.482637	0.449722	0.449722	0.480949
0.056	0.244	0.482655	0.449722	0.449722	0.480930
0.054	0.246	0.482674	0.449722	0.449722	0.480912

Table A3. Results of Simulation for Proposition 3.

β^L	β^S	Quality Preferences			
		L,L	*L,S*	*S,L*	*S,S*
50	50	0.6709	0.6709	0.6709	0.6709
51	49	0.6728	0.6690	0.6728	0.6689
52	48	0.6747	0.6671	0.6746	0.6670
53	47	0.6766	0.6652	0.6764	0.6650
54	46	0.6785	0.6632	0.6782	0.6629
55	45	0.6804	0.6613	0.6800	0.6609
56	44	0.6822	0.6593	0.6818	0.6588
57	43	0.6840	0.6573	0.6835	0.6567
58	42	0.6858	0.6552	0.6852	0.6546
59	41	0.6876	0.6531	0.6869	0.6525
60	40	0.6894	0.6511	0.6886	0.6503
61	39	0.6911	0.6489	0.6903	0.6481
62	38	0.6929	0.6468	0.6919	0.6459
63	37	0.6946	0.6446	0.6936	0.6436
64	36	0.6963	0.6424	0.6952	0.6413
65	35	0.6980	0.6402	0.6968	0.6390
66	34	0.6996	0.6379	0.6984	0.6367
67	33	0.7013	0.6356	0.7000	0.6343
68	32	0.7029	0.6333	0.7015	0.6319
69	31	0.7045	0.6309	0.7031	0.6294
70	30	0.7062	0.6285	0.7046	0.6269
71	29	0.7078	0.6261	0.7061	0.6244
72	28	0.7093	0.6236	0.7076	0.6219
73	27	0.7109	0.6211	0.7091	0.6193
74	26	0.7125	0.6185	0.7106	0.6167
75	25	0.7140	0.6159	0.7121	0.6140
76	24	0.7156	0.6133	0.7135	0.6113
77	23	0.7171	0.6106	0.7150	0.6085
78	22	0.7186	0.6079	0.7164	0.6057
79	21	0.7201	0.6051	0.7178	0.6028
80	20	0.7216	0.6023	0.7192	0.5999
81	19	0.7231	0.5995	0.7206	0.5970
82	18	0.7245	0.5965	0.7220	0.5940
83	17	0.7260	0.5936	0.7234	0.5909
84	16	0.7274	0.5905	0.7247	0.5878
85	15	0.7289	0.5875	0.7261	0.5847
86	14	0.7303	0.5843	0.7274	0.5814
87	13	0.7317	0.5811	0.7287	0.5781
88	12	0.7331	0.5779	0.7300	0.5748
89	11	0.7345	0.5745	0.7313	0.5714
90	10	0.7359	0.5711	0.7326	0.5679
91	9	0.7373	0.5677	0.7339	0.5643
92	8	0.7387	0.5641	0.7352	0.5606
93	7	0.7400	0.5605	0.7365	0.5569
94	6	0.7414	0.5568	0.7377	0.5531
95	5	0.7427	0.5530	0.7390	0.5492
96	4	0.7441	0.5491	0.7402	0.5452
97	3	0.7454	0.5451	0.7414	0.5411
98	2	0.7467	0.5410	0.7426	0.5369
99	1	0.7480	0.5368	0.7438	0.5326