



Winning while losing: Competition dynamics in the presence of indirect network effects[☆]

Sarit Markovich^{a,*}, Johannes Moenius^{b,1}

^a Kellogg School of Management, Northwestern University, Evanston, IL 60208-2013, United States

^b School of Business, University of Redlands, Redlands, CA 92373-0999, United States

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ABSTRACT

What determines competition dynamics in markets with indirect network effects? We analyze this question in a dynamic hardware–software framework, where software firms compete in quality upgrades. We identify market structure as a major determinant of competition dynamics. Indirect network effects tie together the performance of firms on the same platform: a successful competitor raises the value of all firms on the same platform, where an unsuccessful firm may enjoy a windfall increase in its market value. In contrast to the tipping result in the literature, we find tendencies toward increasing competition across platforms for a wide range of market structures.

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1. Introduction

It is a commonly observed phenomenon that software firms regularly upgrade their products. For example, Microsoft upgraded its Office 95 suite in 1997, in 2000, in 2003, and again in 2007. At the same time, we have observed massive increases in R&D spending by software firms, both as a share of sales and in absolute numbers: for example, IBM's R&D expenditure share on software more than doubled from 1994 to 2003; similar increases took place at Oracle, Microsoft and many other software firms. During 2000, typical R&D spending as a share of revenue for software firms was around 10–20% (Wilson, 2001). Moreover, software has grown in economic importance relative to hardware. In 1969, turnover in the US software industry was less than \$0.5 billion, or 3.7% of the total computer business (Campbell-Kelly, 1995). In 2005, revenues of US software

publishers were close to \$120 billion – more than triple the size of US hardware shipments in the same year (U.S. Census Bureau, 2008).

Software is usually hardware specific: it needs compatible hardware to run on and if written for one type of hardware, cannot be used on a different type. Different types of hardware are called platforms. When software firms invest in the quality of their product, they do so not only to attract consumers already using the compatible hardware, but also to attract consumers that currently use a different type of hardware. Consumers' choice of hardware typically depends on the complementary software for each platform. The literature defines this as an indirect network effect: demand for a platform increases in the availability and quality of complementary software; at the same time, platforms with higher demand attract more variety and higher quality software.^{2,3} It is the quality aspect of these indirect network effects that we study in this paper.

Indirect network effects can be driven by variety or quality. For example, during the early stages of the DVD technology, the DVD market was mostly driven by the variety of available titles. In

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* Corresponding author. Tel.: +1 847 467 3665.

E-mail addresses: s-markovich@kellogg.northwestern.edu (S. Markovich), johannes_moenius@redlands.edu (J. Moenius).

¹ Tel.: +1 909 748 8779.

² It is well established in the literature that whenever a short-lived product requires a compatible longer-lived product, network effects are present. We follow this literature and call the shorter-lived product software and the longer-lived hardware.

³ This is in contrast to direct network effects, where consumer utility directly depends on the number of other consumers, such as in telephone networks. Our model does not exhibit direct network effects. We therefore sometimes refer to indirect network effects simply as network effects to improve readability.

converse, Nintendo's dominance in the video-game market during the late 80s was mainly driven by the quality of the video-games Nintendo and its licensees offered (Sheff, 1994).⁴ Since network effects in the context of software variety are well understood (e.g. Church and Gandal, 1992), we focus on indirect network effects driven by quality upgrades, and study competition dynamics in these markets.

In general, software firms invest in quality upgrades based on expected future profits. Typically, competitors on all platforms respond with their own upgrades to prevent consumers from switching to another software provider (later on defined as a competitive effect), or even platform (later on defined as a network effect). Therefore, two main considerations drive the competitive behavior of software firms: the attractiveness – or simply strength – of the platform for which the firm produces relative to the competing platforms; and the strength of the firm relative to its competitors on the same platform.⁵ If platforms are of similar strength, firms on all platforms will compete fiercely for dominance, since a dominant platform is more likely to become the standard in the market – eliminating competition from other platforms entirely. However, it is unclear how firms on a lagging platform will behave. Will they increase their efforts in the hope to catch up or will they simply give up? Furthermore, will a lagging firm on a leading platform increase or decrease its efforts? Does that change if this firm was on a lagging platform?

There is a large literature on markets with network effects (e.g., Farrell and Saloner, 1985a,b, 1986, 1992; Katz and Shapiro, 1985, 1986, 1992; Church and Gandal, 1992; Bresnahan and Greenstein, 1999; Gandal et al., 1999; Gandal et al., 2000; Gandal and Dranove, 2003, among many others). While the empirical studies document the importance of network effects, the theoretical ones focus mainly on welfare and the long-run structure of the industry (i.e., standardization vs. variety). Note, however, that both empirical and theoretical models only analyze variety models. This paper takes a different approach. First, it analyzes competition in quality instead of variety. Second, it focuses on the short-run dynamics of those markets rather than the long-run (static) equilibria. We explicitly consider the competitive behavior of firms and its effect on within- as well as across-platform competition. We also contrast our findings to those of the previous literature on R&D investment. Finally, we study the effect of this competitive behavior on firms' market value.

Adapting the framework developed in Ericson and Pakes (1995), we analyze the effect of the overall market structure on software firms' incentives to compete in quality upgrades. We assume a market with two incompatible hardware technologies, where each software firm's investment affects the probability of a quality increase of its product in the next period. The combination of all firms' qualities then shape consumers' hardware and software choices, which in turn determine firms' market values. Firms' investments are a best response to each other based on expected quality upgrades. Consequently, market share changes through *ex post* successful quality upgrades influence *ex ante* competitive efforts. This is in contrast to the existing literature on network effects, where there is no difference between *ex ante* and *ex post* effects of market share changes. It is this difference that drives the following key results of our paper. We find that a firm that loses a

quality competition and falls behind can still see its market value increase. Its competitive efforts will be less than the leading firm's if it is on the lagging platform, but may be even higher than the leading firm's if those two firms are on the leading platform. Nevertheless, a firm that falls behind always weakens its platform. On a lagging platform, this leads to a higher probability of standardization. In contrast, on a leading platform, this leads to a higher probability of increased competition across platforms, since total investment on the lagging platform may be higher than on the leading platform. Once a platform falls far behind a competing platform that hosts equally strong firms, competition weakens and standardization becomes more likely. All this combined leads to a continuous development toward standardization, not a discontinuous “tipping”. This has an important policy implication: if firms on platforms compete in qualities, the more competitive the market, the more time policy-makers have should they want to interfere in the market.⁶

The mechanisms are as follows: indirect network effects tie together the fate of firms on the same platform. Network effects and competitive efforts of firms on the same platform are the higher the more equally strong platforms are. In this case, a firm wins additional market value while losing a quality competition: an upgrade by a competitor on the same platform attracts new customers to the platform, but not all of them buy from the winning firm. Thus, the losing firm receives a windfall increase in market share and market value, even while keeping its own quality unchanged. Within a given platform, competitive effects are stronger the more similar, in terms of quality levels, the firms on that platform are. Consequently, as long as platforms are equally strong, the network effect and the competitive effect lead to a prolonged, fierce competition. Once a platform has taken the lead the network effect wanes. However, if a platform leads, it reduces its level of investment and thus reduces competitive pressure on firms on the competing platform. This increases the probability of the lagging platform to catch up again. Therefore, gaining a lead is reversible and does not necessarily lead to standardization. This result is in contrast to the previous theoretical literature: we find neither excess inertia nor “tipping” towards standardization due to a small advantage of one platform over the other. However, once one platform falls sufficiently behind, less competitive market structures tend to persist and make standardization inevitable.

We contribute to three lines of literature: first, we add to the literature on dynamic platform competition. For the computer industry, Bresnahan and Greenstein (1999) provide an excellent descriptive taxonomy of platforms. We add to their insights by precisely tracing key trade-offs and details about the short-run mechanisms that drive the different kinds of competition. Second, we extend the analysis of Chou and Shy (1990) and Church and Gandal (1992) who model variety in the software market in order to study inertia and standardization. We find key differences in how network and competitive effects shape market outcomes when firms compete in quality. Finally we contrast our findings with Athey and Schmutzler (2001) to explain why the existence of platforms changes the patterns of investment in R&D.

The paper is organized as follows: in the next section, we introduce our model. We then present the first main result of our paper: network effects can lead to windfall profits in certain cases. We also trace the two main channels of this effect: an immediate change in market share and a change in the incentives to invest. The fourth section studies whether platforms reduce or intensify competition. The fifth section concludes.

⁴ McWhertor (2008) presents data that documents the dominant role of new and updated games for gaming console sales in Japan. Of the 26 game releases presented, roughly half are updates and sequels of earlier versions.

⁵ In models of network industries, the strength of platforms is reflected in the market structure. In static models, the market structure is sufficiently described by platforms' market shares. In dynamic models with quality competition, the market structure and thus the strength of a platform is reflected by a combination of its market share and its software firms' quality levels relative to their competitors on other platforms.

⁶ Note that the implications of these results are not restricted to computer software and hardware products, but rather apply to any market characterized by indirect network effects with quality upgrades in the complementary products. For an excellent description of detailed examples, see Gawer and Cusumano (2002).

2. The model

Following Markovich (2008), we adapt Ericson and Pakes (1995) to allow for dynamics in the demand side of the model. We assume a discrete-time infinite-horizon model. Consumers care about the set of software choices offered by a platform in terms of quality. Consumers derive utility from the software they purchase. Compatible hardware is only needed to operate the software; therefore we follow Church and Gandal (1992) and do not model the hardware market, but focus only on the software firms' decisions. We assume that consumers live forever and are forward-looking: they evaluate the benefits of available software on each hardware platform, as well as expected potential quality upgrades. They then choose hardware and software accordingly. Software producers develop knowledge that is specific to a platform and therefore cannot switch platforms. Consequently, software firms choose their strategies based on expectations about their own, their competitors', and their platform's performance.

The timing of the game is as follows: first, consumers simultaneously choose hardware, and software firms choose how much to invest in quality upgrades. The outcome of the investment is stochastic: the higher the amount invested this period, the higher the probability that a quality upgrade will be achieved in the next period. Firms then compete on prices and consumers buy either one unit of software or the outside good. Finally, nature determines the outcome of the firms' investment. It also determines whether an increase in the quality of substitute products has devalued the quality levels of all software producers on both platforms.

We assume that there are two incompatible platforms, where each platform can accommodate two software firms. Since the analysis for platform B is analogous, we only discuss platform A. Some definitions before proceeding:

- Let $Q = \{0, 1, 2, \dots, K\}$ be a finite set of quality levels for each firm. Let $a_j \in Q$ characterize firm j 's quality level when producing software compatible with platform A. The vectors $a \equiv (a_1, a_2)$ and $a' \equiv (a'_1, a'_2)$ represent the quality level of both firms on platform A in the current period and in the next period, respectively. The vectors b and b' are defined analogously.
- σ is the percentage of consumers who own a unit of hardware A.⁷ σ is a discrete variable with discretization step κ .
- The state $S \equiv (\sigma, a, b)$ represents the structure of the industry.

2.1. Consumers' choice

Consumers need complementary hardware to operate software. Each consumer cares about the hardware decisions of all other consumers since these decisions influence the incentives to provide complementary software: The more users buy hardware A, the higher the demand for software on this platform, and the more valuable is market-share on it. This leads to increased competition across software firms on this platform, resulting in lower prices or higher quality, thus benefiting consumers.

Consumers live forever. Every period one-half of the consumers on each platform replace their current hardware with a new unit.⁸ The utility a consumer gets from hardware depends on the quality and price of the software he uses with it. We assume that software provides services for a single period. The one-period utility consumer i gets from the consumption of hardware A and software 1 with quality level a_1 and price p_1^A is then $U_{1i}^A(a) - p_1^A = a_1 - p_1^A + \varepsilon_{1i}$, where ε_{1i} represents taste differences among consumers.⁹

⁷ Some authors refer to these shares as the "installed base" (e.g., Farrell and Saloner, 1986).

⁸ This assumption simplifies the market-share law of motion and avoids the need for additional state variables. The assumption does not affect the results qualitatively, but might slow the standardization process.

⁹ Note that the model can accommodate other utility functions, including ones that depend on platform size.

2.1.1. Software choice

Consumers can choose to purchase one unit of software or the outside good, which gives a utility of ε_{0i} . Consumers' preferences, ε_{0i} , ε_{1i} , and ε_{2i} are independently and identically distributed according to a type I extreme value distribution. The probability that consumer i purchases from firm 1 is then:

$$D_1(a_1, a_2; p_1, p_2) = \frac{\exp(a_1 - p_1)}{1 + \exp(a_1 - p_1) + \exp(a_2 - p_2)} \quad (1)$$

2.1.2. Hardware choice

The expected utility consumer i gets from purchasing hardware A is:

$$W_i^A(S) = E\{[U_{ij}^A(a) - p_j] | \sigma, a, b\} + \beta E\{E[U_{ik}^A(a') - p'_k] | \sigma, a, b\} + \varepsilon_i^A \quad (2)$$

where $E(U_{ij}^A(a))$ and $E(E[U_{ik}^A(a')])$ are the utilities the consumer expects to get from purchasing software $j \in \{1, 2, \dots, N\}$ in the current period and software $k \in \{1, 2, \dots, N\}$ in the next period, respectively. ε_i^A represents consumer i 's additional random utility from platform A (e.g., in the video games market, some consumers prefer Sony's Playstation, while others favor Microsoft's Xbox). Given the current state, $S = (\sigma, a, b)$, consumers appraise these expected utilities by forming expectations of future software quality levels, and future prices.¹⁰ Note that Eq. (2) reflects the fact that utility is mainly derived from software. However, once a consumer chooses a platform, he can only buy software compatible with this platform.

Consumer i will purchase hardware A if and only if it provides a higher expected utility than purchasing hardware B; that is, if and only if $W_i^A(S) - P^A > W_i^B(S) - P^B$, where P^A and P^B are hardware A's and B's prices, respectively. Assuming again that consumers' preferences, ε_i^k , are independently and identically distributed according to a type I extreme value distribution, the share Ψ of consumers that buy platform A is equal to¹¹:

$$\Psi(S; P^A, P^B) = \frac{\exp(W^A - P^A)}{\exp(W^A - P^A) + \exp(W^B - P^B)} \quad (3)$$

The law of motion of platform A's market share is then: $\sigma'(S; P^A, P^B) = \sigma/2 + \Psi(S; P^A, P^B)/2$. Since platform A's market share is discretized, market shares computed by the equation above might sometimes not be a multiple of the discretization step κ . In these cases, we take the weighted average of the two potential market shares within which σ' falls. This induces a transition probability for σ' , denoted by $\Lambda(S; P^A, P^B)$.

2.2. The software industry

We model the software market as a differentiated good oligopoly. Each firm produces only one type of software compatible with one of the platforms. Software firms invest in order to upgrade the quality of their product. Firms' profits are determined at the price competition stage.

2.2.1. Investment

Each firm's quality follows a Markov process. The firm's quality level tomorrow depends on its quality level today, its level of investment today, and the devaluation of quality through competition

¹⁰ Using properties of the logit distribution, $E\{E[U_{ij}^A(a') - p_j] | S\} = \sum_{\text{possible next states}} \ln\left(1 + \sum_{k, a'_k \neq 0} \exp(a'_k - p_k)\right)$. See Markovich (2008) for more details.

¹¹ When consumers make hardware decisions, they are not allowed to choose the outside good. This assumption simplifies the computation as it avoids the need for an additional state variable.

from substitute industries. Let a_j be firm j 's quality level today. The Markov process is then: $a_j = a_j + \tau_j - \nu$, where $\tau_j \in \{0, 1\}$ is the realization of firm j 's investment. We assume that the more a firm invests, the higher is the probability of a quality upgrade. In particular, if firm j invests x_j , the probability of successful investment is $p(\tau_j = 1) = \frac{x_j}{(1+x_j)}$. $\nu \in \{0, 1\}$ represents any technological advance in substitute markets that erodes the advantage held by software firms within the industry of interest. For example, looking at the video games market again, an advance in the computer games market would negatively affect Microsoft's Xbox as well as Sony's Playstation. Therefore, we measure the quality level of software relative to the quality of the outside good, and assume that innovation in substitute markets equally depreciates the quality of all software on both platforms. In each period the probability of an improvement in the quality of the outside good is $p(\nu = 1) = \delta$, where the realization of ν is independent of the software firms' investment level. Since in each period the probability that the quality level of all firms decreases by 1 is δ , the quality level of firm j , which invests x_j , rises by 1 in the next period with probability $(1 - \delta) \frac{x_j}{1+x_j}$.¹²

2.2.2. Software firms' investment problem

Each software firm solves an intertemporal maximization problem to determine its optimal investment. Let the state of the industry be $S = (\sigma, a, b)$, and $V_1^A(S)$ be the expected future payoff of software firm 1 on platform A. Firm 1 then solves the following Bellman equation:

$$V_1^A(S) = \sup_{x_1 \geq 0} \left[\pi_1(\sigma, a, p) - x_1 + \beta \sum_{\sigma', a', b'} V_1^A(S') \cdot \Lambda(\sigma' | S) \right. \\ \times \left(P(a'_1 | a_1, x_1, \nu = 0) P(a'_2 | a_2, x_2^A(S), \nu = 0) \right. \\ \times P(b'_1 | b_1, x_1^B(S), \nu = 0) P(b'_2 | b_2, x_2^B(S), \nu = 0) \\ \times (1 - \delta) + P(a'_1 | a_1, x_1, \nu = 1) P(a'_2 | a_2, x_2^A(S), \nu = 1) \\ \left. \left. \times P(b'_1 | b_1, x_1^B(S), \nu = 1) P(b'_2 | b_2, x_2^B(S), \nu = 1) \delta \right) \right] \quad (4)$$

where $\pi_1(\sigma, a, p)$ and x_1 are the current profits and investment level of firm 1 on platform A, respectively. x_2^A , x_1^B and x_2^B are defined analogously. According to Eq. (4), software firms earn current profits in the pricing game, $\pi_j(\sigma, a, p)$, plus the expected discounted value of future profits.

We assume that the pricing game is a static game with no future effects or dynamics. Software firms (on each platform) set prices oligopolistically based solely on the quality levels of firms on their own platform. Note, while this assumption prevents firms from pricing strategically and thus profits do not *directly* depend on software-qualities on the competing platform, they do so indirectly: Profits are also a function of the firm's own-platform market share, which in turn depends on the software-qualities on the competing platform.¹³ Demand is then determined according to Eq. (1). Assuming that marginal cost is constant at c , then for any vector of prices, the per-period profit of firm 1 on platform A is:

$$\pi_1(\sigma, a, p) = \sigma * M * D_1(a_1, a_2; p_1, p_2) * (p_1 - c) \quad (5)$$

where $M > 0$ is the total size of the market and σ is the percentage of consumers that own platform A.

¹² The probabilities that the firm's quality level will stay the same or decrease by one can be calculated analogously.

¹³ Preliminary considerations suggest that the interaction of strategic pricing and investment offer rich and interesting patterns. However, since consumers can costlessly switch platforms in our model after two periods, strategic pricing does not affect the principle features of our findings, but can affect how quickly the long-run equilibrium of our model is reached.

2.2.3. Equilibrium in the industry

A subgame perfect equilibrium for the above game consists of a collection of strategies that constitute a Nash equilibrium for every history of the game. We consider only Markov strategies — i.e., the class of strategies that depend only on the “payoff relevant” states. This means that the strategies are defined for every state of the game regardless of how this state has been reached. Formally, a Markov Perfect Equilibrium for the game is defined by the

- Investment strategies $x_j^h(S)$ for $j = 1, 2$; $h = A, B$ and every possible state S .
- Value functions $V_j^h(S)$ for $j = 1, 2$; $h = A, B$ and every possible state S .

Such that:

- (i) The strategies are optimal given the value functions $V_j^h(S)$.
- (ii) For every state S , the value functions describe the present value of profits realized when all firms play the equilibrium investment strategies.

While uniqueness cannot be guaranteed in general, our computations always lead to the same value and policy functions irrespective of the starting point and the particulars of the algorithm. See Markovich (2008) for details on the computational algorithm.

2.2.4. Parameterization

Since investment realization is a relatively slow process, we take a period to be one year and set the discount factor to be $\beta = 0.92$. In order to solve for the equilibrium numerically, the state space needs to be limited. This implies that the parameter K , the maximum quality level firms can achieve, can only assume a finite number of values. Since our profit function is bounded, K can be endogenously determined by the maximum quality level at which a monopolist stops investing. In our model, this point is reached at quality level $K = 6$. Beyond that, consumers will not sufficiently reward firms for additional investment in higher quality. This upper bound represents the maximum difference a software firm can obtain relative to any other player, including those producing the outside good. In other words, any player can always acquire knowledge from publicly available sources which allows it to be no further behind than $K = 6$ quality steps. Market size, M , is set to 10. For simplicity, we set the hardware prices, $P^A = P^B = 0$, and platform A's market share, σ , runs from 0% to 100% in increments of 5%.

In the remainder of the paper, we only present results where each platform starts with a market share of 50%. We choose the value of δ such that the long-run market structure is standardization. Markovich (2008) finds that the level of competition from substitute industries determines whether the long-run market structure is standardization or variety. In particular, if $\delta \geq 0.4$ the long-run market structure is standardization; otherwise, variety prevails in the market. Unless noted otherwise, we set the level of outside competition, δ , to 0.5. Changing δ to lower values, such that the long run market structure is variety, or to higher values so that standardization is attained faster, alters the specific numerical outcomes but does not fundamentally change the shapes of the figures and graphs presented or the mechanisms described below.¹⁴

3. Network effects and the market value of firms

Competition affects market structure, and thus market values of firms, differently in the presence of indirect network effects than it

¹⁴ Fig. 7 presents graphs for three different δ s. Figures for other δ s are available from the authors upon request.

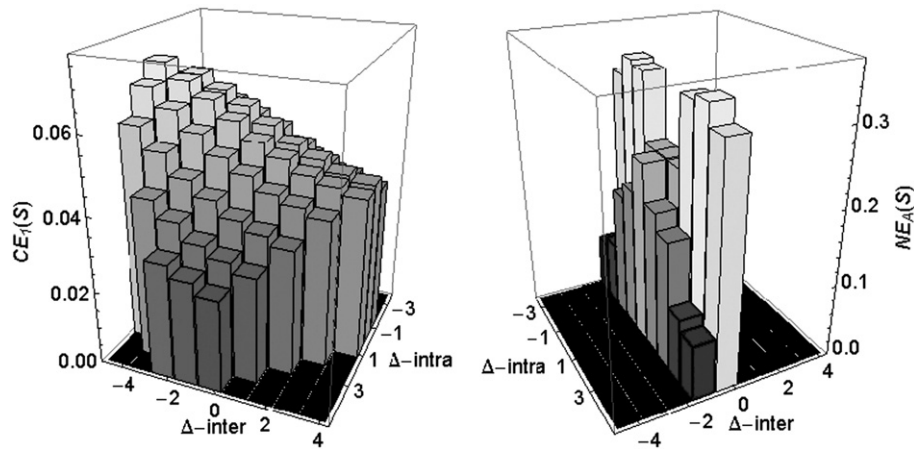


Fig. 1. Competitive- and network-effect.

does in their absence. In order to highlight these differences, we first identify how network effects and competitive effects are at work in our model. We then study the effect of successful quality upgrades on firms' market values. Since these are propelled by increases in market share and optimal investment of the upgrading firm, we discuss them next. Finally, we analyze whether network and competitive effects lead to more or less competitive market structures.

While Markovich (2008) finds that the long run market structure is determined by the strength of competition from the outside good market; we find that short-run dynamics are mainly affected by the intensity of competition within- and across-platforms. Previous literature has measured the intensity of competition by total investment (e.g. Grossman and Shapiro, 1987; Doraszelski, 2003). In our model, total investment in the industry is the highest when quality differences across platforms are zero. Total investment on a platform is the highest when quality differences between firms on the same platform are zero. Thus, quality differences within and across platforms indicate the intensity of competition on and across platforms, respectively. We therefore present all variables of interest as a function of these quality differences.

For all our graphs below, we set the quality level of both firms on platform B to 3. We define Δ -inter as the difference between the sum of qualities on platform A and the sum of qualities on platform B, 6. For example if the firms on platform A are at quality levels 4 and 3, the sum of their qualities is 7, which is ahead of platform B and Δ -inter = 1. If both firms on platform A are at quality level 2, platform A is behind and Δ -inter = -2. We define Δ -intra as the difference between the quality level of firm 1 and firm 2 on platform A. Using the examples above, Δ -intra = 1 in the first example and Δ -intra = 0 in the second. A complete list of quality combinations for all Δ -intra and Δ -inter used in the graphs can be found in the Appendix.

3.1. The competitive and network effects

We define the competitive and network effects analogously to Church and Gandal (1992): Fixing the distribution of consumers across platforms, a software firm can increase profits by winning market share from its competitor on the same platform or by attracting new consumers that previously bought the outside good. Holding the competing firm's quality and both platform's market share constant, we call the change in a firm's market share driven by its own quality upgrade, a *competitive effect* (hereafter CE). Conversely, holding the competing platform's quality fixed,

we call the change in a platform's market share driven by an increase in the quality level of one of its firms a *network effect* (hereafter NE). Recall that the quality level of both firms on platform B is fixed at 3, Fig. 1 plots the CE for firm 1 and the NE for platform A.

As Fig. 1 shows, the CE depends on all firms' quality levels, on both platforms. The CE is strongest when both firms on a platform are of the same strength (Δ -intra = 0). It decreases in absolute value as the quality differences between firms increase and increases as the platform falls behind. The market shares that sum to the CE stem from two sources: the firm's competitor on the same platform and the outside good. Recall that as Δ -inter increases, the sum of the quality levels on platform A increases. The higher the sum of quality levels on platform A, the lower is the market share of the outside good, leading to higher transfers of market-shares from the unsuccessful firm to the firm that successfully upgraded. So when platform A is behind, its firms' quality levels are low and thus most of the additional market-share of the successful innovator is transferred from the outside good. As platform A leads, more of the transferred market share comes from the second firm on the same platform.

The NE is much larger in our model than the CE, and exhibits a more subtle behavior. When a platform is far ahead or far behind, the NE is very small, and at times equals zero. When the platform is far behind, a one unit quality increase is not sufficient to grab market share from the competing platform and thus the NE is zero. In contrast, when the platform is far ahead it already enjoys almost 100% market share, consequently, the NE is again very small. When the platforms are close together, a one unit increase in quality affects consumers' expectation regarding the survival and success of the platform in the future, and thus the NE is positive and large.

The size of the NE strongly varies by market structure and is largest when the platforms are close together. When platform A is closely behind (Δ -inter = -1), the NE is the highest when firms on platform A are of equal quality. However, as firms on platform A jointly achieve the same or higher quality levels than on the reference platform B, the NE is highest when the firms on platform A have different quality levels. The intuition is as follows: Consumers care about software qualities in the current and the next period. Moreover, investment on a platform is highest when Δ -intra equals zero. These two factors have conflicting effects on the NE. While on the one hand, a relatively higher-quality software in the next period is more likely when there is at least one high quality software available today; on the

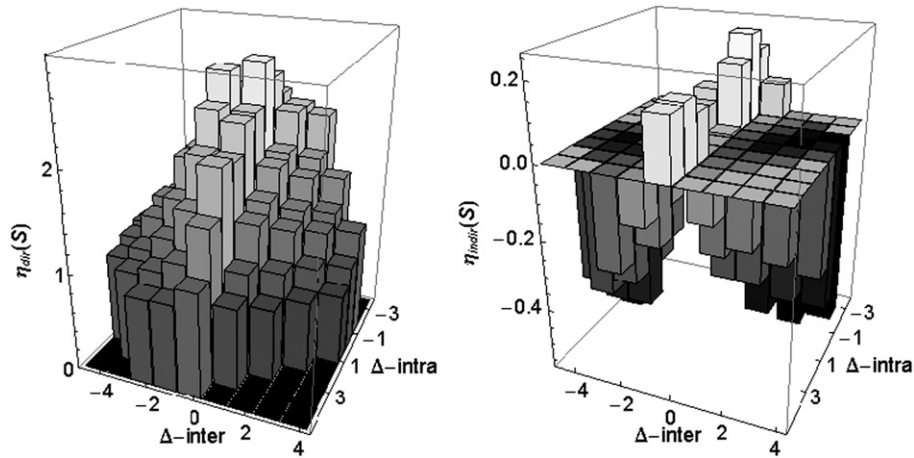


Fig. 2. Own- and cross-market-value elasticities with respect to quality upgrades.

other hand, when Δ -intra is large, total investment on a platform might not be sufficiently high to outpace the competing platform. Consequently, when Δ -inter = 0, consumers consider the future of both platforms to be sufficiently “bright”, and thus prefer the platform that offers the highest-quality software. This first effect also dominates if Δ -inter > 0. However, when platform A lags slightly behind, consumers discount the availability of a higher-quality software in favor of sufficiently high investment (Δ -intra = 0) and now the second effect dominates.

3.2. Winning while losing

Can a firm win while losing? If a competitor's quality upgrade leads to a positive change in market value of another firm, the answer is yes. The existence of indirect network effects suggests that this may be the case if two competitors produce software for the same platform. In particular, as Fig. 1 shows, in cases where the NE is large relative to the CE, a “win while lose” outcome may be possible. In order to analyze this effect, we define as follows: A firm's own market-value elasticity (hereafter “own elasticity”) is the percentage change in the firm's market value given a one percent change in its own quality level.¹⁵ A firm's cross market-value elasticity (hereafter “cross elasticity”) is the percentage change in a firm's market value given a one percent change in its competitor's quality level. Fig. 2 shows firm 1's own- and cross-elasticities, denoted $\eta_{dir}(S)$ and $\eta_{indir}(S)$ respectively, as a function of within and across platforms quality differences.

The left panel of Fig. 2 shows that the relative benefit from a quality upgrade is the higher the more firm 1 lags behind firm 2, unless firm 2 is at or close to the top of the quality ladder. This result is driven by an increase in the CE: closing in on a competitor on the same platform increases future prospects and with that, market value. The figure also shows that the NE influences firms' market value the most when overall qualities on both platforms are about the same (i.e., quality combinations of 3–3 and 4–2). This can be better seen in the right panel of Fig. 2: When the platforms' quality levels are far from each other, the NE is almost zero, and thus firm 1's market values are negatively affected by the CE. In contrast, when platforms are at similar

quality levels, the NE outweighs the CE and a quality upgrade by firm 2 leads to an increased market value of firm 1. Thus, a firm can win additional market value through its competitors' successful quality upgrade. In order to better understand this effect, the next two sections illustrate the short-run mechanisms of this windfall benefit.

3.3. The fight for market shares

When a firm succeeds in increasing the quality of its product, the following three effects shape the distribution of market shares: All else equal, (1) a quality upgrade by firm 1 on platform A draws customers from firm 2 on the same platform. This is a *business-stealing effect* (BS). (2) The upgrading firm also increases the size of the market by attracting customers that did not buy software before (i.e., who bought the outside good). We call this a *market-extension effect* (ME). (3) The upgrading firm also attracts more consumers to buy hardware A. This is the *network effect* (NE) discussed above. The *competitive effect*, CE, is then the sum of the business-stealing and market-extension effects. Since in every period only 50% of the consumers on each platform purchase new hardware, there exist a period 1 and a period 2 NE.¹⁶

In order to understand how these three effects interact, we study the effect of a one-time quality upgrade by firm 1. We start from a symmetric situation where all firms have the same quality level and as before, each hardware platform enjoys a market share of 50%. Now assume that firm 1 on platform A has successfully upgraded its quality. In addition, assume that the investment of all other firms (on both platforms) had failed and that in period 2 the quality levels of all firms are identical to period 1's qualities. Observing the quality upgrade, more consumers buy hardware A; the innovative firm thereby induces a NE immediately after the successful upgrade. In period 1, some of the consumers who switched to platform A might buy from firm 2. Therefore, both firms on platform A benefit from the higher attractiveness of their platform. At the same time, a larger share of consumers that now

¹⁵ Since our model can only handle discrete changes in qualities, the percentage changes for the elasticities have been calculated based on unit changes. For example, an increase from quality 4 to quality level 5 represents a 25% change.

¹⁶ More precisely, in our model consumers switch hardware on average every two periods. That is, while some switch after 1 period, others might keep their hardware for many periods. Consequently, the NE spreads over more than two periods. However, since after the first two periods the NE is marginal, we only focus on the first two periods.

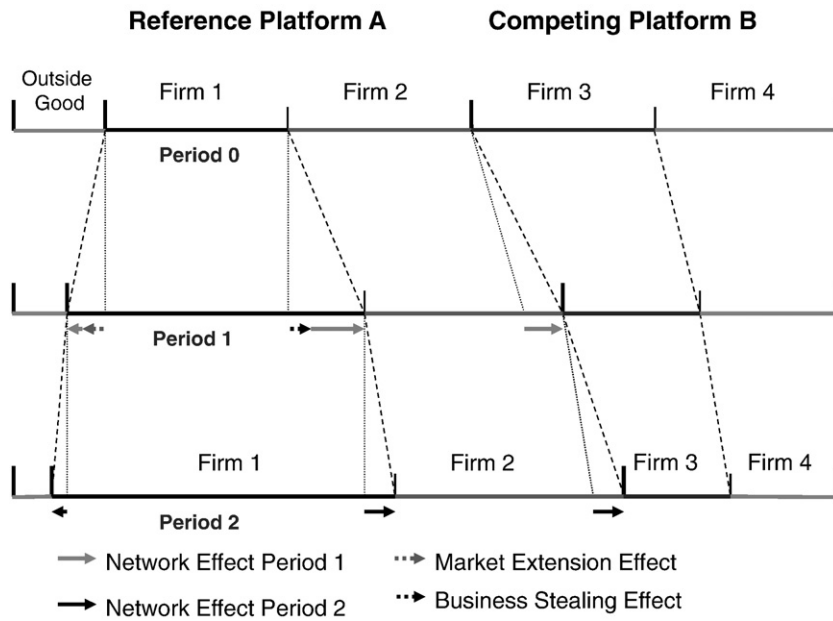


Fig. 3. Market-share transfers over two periods.

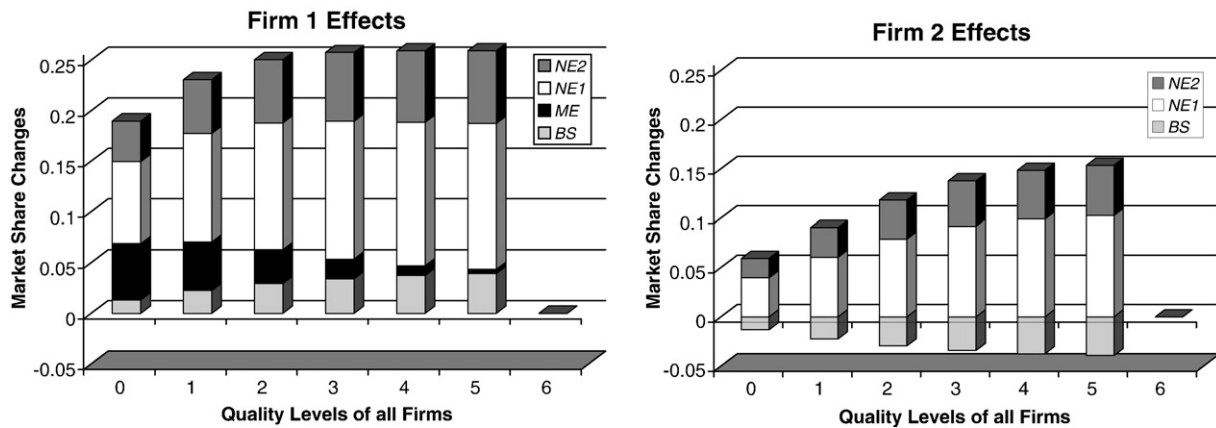


Fig. 4. Market-share transfers of a one-step quality upgrade of firm 1.

own hardware A buy software from the innovator. In other words, firm 1 wins market share within its platform from firm 2, as well as from the outside good. In the second period, additional consumers buy hardware A. This again benefits both firms. Since market shares within the platform have already been transferred to the innovator, we do not see a market-extension or a business-stealing effect in the second period. The only effect present in the second period is the *NE*, where consumers who switched to platform A choose to buy from firm 1, firm 2, or the outside good. Fig. 3 summarizes this process.

As Fig. 3 shows, a successful competitor on a platform steals market share from the less successful competitor during the first period (see dark dotted arrow in the graph), but it also increases the platform's overall attractiveness (*NE*). The net effect for the unsuccessful firm can therefore be *positive*. Furthermore, since in the second period more consumers switch to platform A, firms 1 and 2 enjoy an additional increase of market share during this period. Note that the speed of transfer of market shares depends on the durability of hardware. In our case, consumers are locked into the hardware they own, on average, for two periods; and thus the *NE* transfer extends

over two periods. A longer hardware life would spread the *NE* over more periods. In the short run, this protects the firms on the lagging platform, since it slows the transfer of market share from them to the innovator.¹⁷

Fig. 4 illustrates these three effects in the context of our model for different initial quality levels. Qualities of all firms before the quality upgrade are on the x-axis. Changes in market shares in response to a first period change in quality of firm 1 are on the y-axis. We denote the different effects as follows: *ME* = market-extension effect, *BS* = business-stealing effect, and *NE_t* = network effect, *t* = 1, 2.

Firm 1, the innovator, benefits from its own quality upgrade in the three ways described in Fig. 3: A positive *NE* that stretches out over

¹⁷ Note that for clarity of exposition, Fig. 3 combines the market share of the outside good on both platforms. Since the within-platform market-share of the outside good on platform A is smaller than on platform B – as a result of the market extension effect – the move of consumers from platform B to A decreases the overall share of the outside good within the whole market. Consequently, as Fig. 3 shows, the *NE* has a negative effect on the overall share of the outside good during both periods.

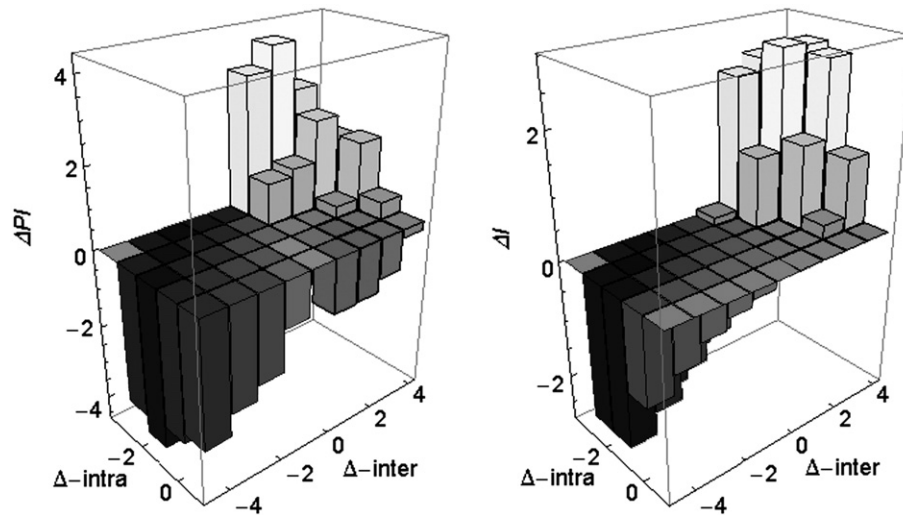


Fig. 5. Investment difference between followers and leaders.

two periods,¹⁸ a positive *BS* – gaining market-share from the competitor on the same platform, and a positive *ME* that induces customers who previously bought the outside good to buy software instead. As the quality of the goods offered increases, the outside-good market shrinks, and the *ME* decreases. When platforms start symmetrically, in our model the *NE* always outweighs the *BS*. That is, when all firms start with the same quality level, firm 2 always enjoys a net increase in overall market share from an innovation of firm 1. The relative sizes of the effects for firm 2 are depicted in the right panel, indicating that this net positive effect already occurs in period 1, independent of the quality levels at which firms start. This leads to immediate increases in profits as well as market values. The increase in market shares also increases a firm's incentives to invest. In expectation, this further improves firm 2's relative position and, consequently, its market value.

3.4. The effect of competition on investment

Investment enables firms to influence their position relative to other firms in the market.¹⁹ As with market-value, a firm's investment depends on three variables: (1) its own quality level, (2) its competitor's quality level on the same platform, and (3) the overall quality on the competing platform. When analyzing these three influences, we see the *CE* and *NE* at work exactly in the same way as before: When the quality levels of the two firms on a platform are similar, the *CE* encourages investment in a fight for future within-platform market share and profits. When platforms are similarly strong, the potential to win market share from the other platform provides additional incentives: through the *NE* firms seemingly “join efforts” and simultaneously increase investment to gain market share from the other platform. Consequently, total investment and thus expected technological progress is highest in perfectly symmetric market structures. Once quality differences across platforms increase, the *NE* wanes and the *CE* dominates. Since market shares on the other platform are out of reach or unattractive, the main incentive to invest is attracting customers on one's own platform. We return to this point in the next section.

In other words, similar quality levels both across and within platforms increase overall investment, but for different reasons: The *NE* encourages investment when quality differences across platforms decrease, while the *CE* encourages investment when quality differences within platforms decrease. The increase in market value of firm 1 due to its competitor's quality upgrade is therefore driven by two influences. The successful quality upgrade increases the market share of the reference platform, which benefits both firms 1 and 2. This also raises firm 1's incentives to invest, increasing its platform's as well as its own market share in expectation. The end result is an increase in its market value.

The analysis above shows that firms' investment depends on their relative position in the market. In contrast to most of the R&D literature, this however does not imply that a leading firm or platform always invests more than the lagging firm or platform.²⁰ To the contrary, in our model we frequently find lagging firms or platforms investing more than leading ones. In order to get a better understanding of these findings, we compare our setting with that of [Athey and Schmutzler \(2001\)](#), who identify conditions under which leaders always invest more than followers. Central to their setting is a profit function that must fulfill two conditions for, what they call, “weak increasing dominance” to hold; our profit function meets both conditions. However, a close examination of similarities and differences of both models identifies two key assumptions, which drive the divergence in our results. For the [Athey and Schmutzler's \(2001\)](#) predictions to hold, investment needs to be independent of the state and investors must not be too farsighted. Both conditions are not satisfied in our model: As we explained above, investment in our model is state dependent because of the *NE* and *CE*. Moreover, firms choose the level of investment that maximizes discounted future profits over the entire expected lifetime of the firm, taking *all possible future investment opportunities* into account. These differences in assumptions induce lagging platforms and lagging firms to invest more than their respective leaders.

The left panel of [Fig. 5](#) displays investment differences between the lagging platform and the leading platform (ΔPI). The right panel shows the analogous differences for firms on the same platform (ΔI).²¹ Positive values indicate that the follower invests more than the leader. Recall that in the graphs, firms' qualities on

¹⁸ The *NE* is larger in the first period because of the replacement pattern of hardware in the model: each period, 50% of the consumers on a particular platform buy new hardware. Since the size of the second platform is smaller in the second period, the share of the 50% of consumers on this platform that buy new hardware is now smaller relative to all consumers than in the first period.

¹⁹ For a detailed analysis of optimal investment behavior, see [Markovich and Moenius \(2006\)](#).

²⁰ We would like to thank the editor, Roman Inderst, for drawing our attention to this issue.

²¹ Since the graphs are symmetric along $\Delta\text{-intra} = 0$, we only show the cases where $\Delta\text{-intra} \leq 0$.

platform B are fixed at (3,3), and that platform A lags behind platform B if Δ -inter is negative. Firm 1 lags behind firm 2 if Δ -intra is negative. That is, positive values in the graph when Δ -inter > 0 indicate that platform B (the laggard) is investing more than platform A; positive values when Δ -inter < 0 indicate that platform A (the laggard) is investing more than platform B. The left panel shows that the lagging platform invests more than the leading platform when quality differences on the leading platform are large (Δ -intra negative and large) or when the leading platform is far ahead of the lagging platform (Δ -inter positive and large). When firms' qualities are the same as in the case of (3,3) the CE on this platform is strong, while it is weak when firms' qualities are far apart. When the CE is strong on the lagging platform and weak on the leading platform firms on the lagging platform can win substantial market-shares from the leading platform and the outside good. The lagging platform also has good prospects to gain the lead itself soon. Thus firms on the lagging platform invest more than firms on the leading platform. A strong NE, however, can outweigh the weak CE on the leading platform; resulting in a larger investment on the leading platform. As the NE wanes, the CE dominates once more and firms on the lagging platform again invest more than firms on the leading platform. When Δ -inter < 0 the CE on the leading platform is strong, as both of its firms have a quality level of 3. As the graphs show, if the CE is strong on both platforms the lagging platform is unlikely to invest more than the leading platform: it requires a strong CE on the lagging and a weak CE on the leading platform for the laggard to invest more than the leader. Consequently, we do not observe cases where a lagging platform invests more than the leader when Δ -inter < 0.

A quite similar pattern emerges for firms on the same platform (Fig. 5, right panel): lagging firms invest more than leaders only when platform A leads; i.e., when their platform is well established. In these cases, the lagging firm invests more than the leading firm when quality differences on its platform are large (Δ -intra negative and large) or when its platform is far ahead of the lagging platform (Δ -inter positive and large). Interestingly, in general, the larger Δ -intra and thus the weaker the CE, the larger will be the difference between the lagging and the leading firm's investment. The intuition behind this result is as follows: If the leading firm is far ahead, it cannot win much additional market-share from the lagging firm. Moreover, each additional increase in Δ -intra offers lower additional market share and thus lowers the leader's additional profits from investment. A stronger lead can even be counterproductive for the leader, since, as the left panel shows, investment on the lagging platform may then be higher than on the leading platform and thus may weaken the leading platform as a whole. The opposite is true for the lagging firm: today's increase in quality opens up the opportunity of additional increases in the future. Increases in the lagging firm's quality strengthen the platform overall.

The mechanism on the lagging platform is quite different: most of the market share that can be won is on the other platform. The leader cannot win much market share from the lagging firm. This, however, is not a disincentive to invest. To the contrary, a stronger lead implies a stronger platform overall, thus inducing the leading firm to invest even more. It is therefore an additional incentive to invest, and not counterproductive as in the case of the leading platform. Finally, the lagging firm faces a larger threat to be eliminated by competition from the outside good – decreasing its incentive to invest. Consequently, on the lagging platform the leader always invests more than the follower.

In summary, state dependence of investment decisions through the NE and the CE, and the fact that firms take all possible future states in their investment decisions into account are the defining

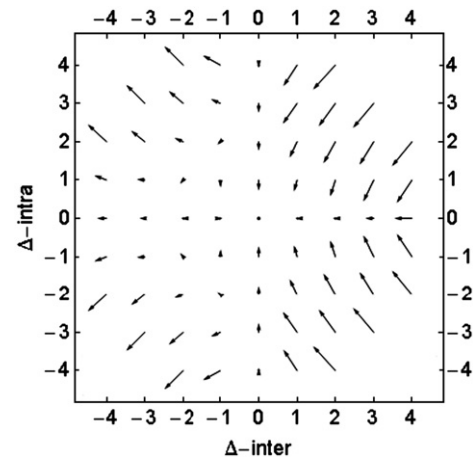


Fig. 6. Two-periods ahead vector field of weakly increased competition.

features in our model that lead to substantial departures from the findings in the previous literature on R&D investment. In our model, both lagging firms as well as firms on lagging platforms can invest more than their leading counterparts. This has substantial consequences on whether competition will likely increase or decrease as firms progress. We will investigate this issue in the next section.

4. Do network effects lead to a more or less competitive market structure?

The preceding analysis shows that competitive efforts are the highest when quality differences within and across platforms are at their lowest. Moreover, when quality differences on the leading platform are large, lagging firms and platforms can invest more than their leading counterparts. This suggests that the NE and CE should lead to more competitive market structures. This is in contrast to the existing literature, where the NE generally leads to standardization, which eliminates competition across platforms. We investigate our hypothesis by studying the effect of current quality differences within and across platforms on future quality differences. Since hardware market shares take time to adjust, we look at the probabilities that quality differences weakly decrease (i.e., either decrease or stay the same), implying equally or more competitive market structures, over the next two periods as a function of current quality differences within and across platforms (Fig. 6).²²

In order to study the above, we use a vector field diagram. Arrows toward Δ -intra = 0 indicate that intra-platform competition will likely increase. Arrows toward Δ -inter = 0 indicate that inter-platform competition will likely increase. All other types of arrows can be explained analogously. The length of each arrow indicates the probability of (weakly) increased competition.

Figure 6 shows the following pattern: first, in many cases, either inter- or intra-platform competition is likely to increase. In particular, there are sets of market structures where an increase in competition across platforms is likely. Second, the symmetric equilibrium, where Δ -intra and Δ -inter are both equal to zero, has a high probability of persistence. Finally, standardization onto the leading platform's hardware is more likely, the more firms on the

²² The graphs that plot probabilities of one period ahead look very similar to the ones displayed here.

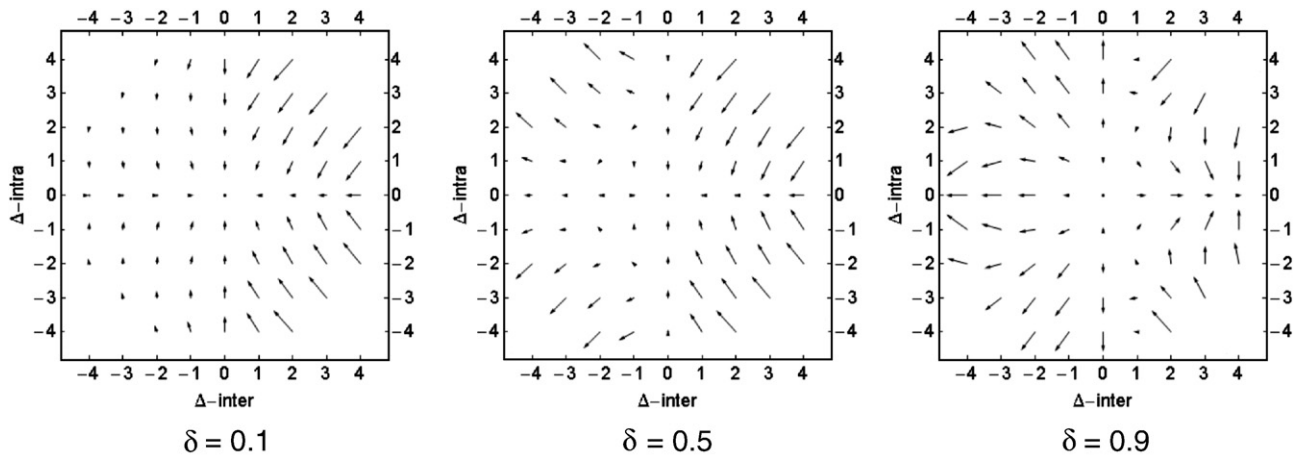


Fig. 7. Two-periods ahead vector field of weakly increased competition for $\delta = 0.1, 0.5$ and 0.9 .

lagging platform are of dissimilar strength and the farther ahead the leading platform. However, “tipping” towards standardization due to a small quality advantage of one platform over the other does not generally exist in our model.

We will now study this graph in more detail. As before, we reference the platform of interest as platform A, and the competing platform as platform B. For Δ -intra, when firms on platform A lead, sustained or increased competition within a platform is always more likely than lower levels of competition. Being ahead implies a larger market share for platform A. This in turn leads to a higher incentive to invest for both firms on platform A. Consequently, the probability that one firm falls behind is low. Moreover, as shown in the preceding section, in this case lagging firms frequently invest more than leading firms, thus increasing competition within platform. Conversely, when platform A is behind, a smaller platform market share reduces incentives to invest. This, in turn, increases the probability that one firm falls behind, which then weakens the platform further and increases the probability of standardization on the leading platform B. We, consequently, see a large number of arrows pointing toward lower levels of competition. When both firms are at the same quality level, it is impossible to increase within-platform competition, so changes in the competitive situation can only happen toward the other platform.

Similar forces drive the changes in quality differences across platforms. Nevertheless, the symmetry observed for Δ -intra does not hold for Δ -inter. The intuition behind this is as follows. Consider first the case when within-platform competition is strong (Δ -intra = 0). When platforms are of equal strength, the NE is large and thus ensures that the market structure remains at a similar level of competitiveness

as firms have high incentives to invest. The more platform A lags behind, the more across-platform competition decreases, as consumers flock to the leading platform. Furthermore, the more platform A lags behind, the lower the quality level of its firms. Consequently, its firms have low incentives to invest in upgrades; resulting in a low probability of survival for platform A. Interestingly, since platform B has relatively high quality firms and thus has a high probability of survival, the same effects lead to *increased* competition across platforms when platform A is ahead: as the NE wanes, firms on platform A reduce their investment, thus platform B has a higher probability to catch up.²³ We see similar patterns when intra-platform differences exist (Δ -intra > 0). They actually reinforce the mechanisms we just described, since in either case a large Δ -intra weakens the platform it occurs on, and may even lead to lower investment of firms on the leading platform relative to those on the lagging platform. This relationship is driven by the CE: competitive efforts are highest when firms are of similar strength, which increases the probability of winning the competition across platforms. If the CE is high on the lagging platform but low on the leading platform, the higher competitive efforts on the lagging platform may lead to increased competition.

Given our parameterization, the symmetric industry structure is not sustainable in the long run. Sooner or later, one of the firms on one of the platforms might have a string of bad luck. Once this bad luck opens a large enough gap in firms' qualities, the industry will reach states where competition decreases. The industry would then snowball and standardize on the leading platform.

This snowball effect can be best seen by comparing our vector field graph for different δ s. The result is displayed in Fig. 7: The left panel depicts the case of $\delta = 0.1$, when variety is the long run outcome. As a reference, we repeat the graph for $\delta = 0.5$ in the middle panel. The right panel shows the outcome for $\delta = 0.9$, when standardization is attained fast (Markovich, 2008). While in the left panel there is no path towards standardization, the right panel depicts many of them. Nevertheless, in the right panel arrows pointing toward the center indicate that the path towards standardization may lead first through more competitive market structures.

This discussion implies that the more competitive the market, the longer it would take the market to standardize on one of the platforms. In order to illustrate this effect, using the symmetric state (0.5;3;3;3,3) as our point of comparison, Fig. 8 shows the probability

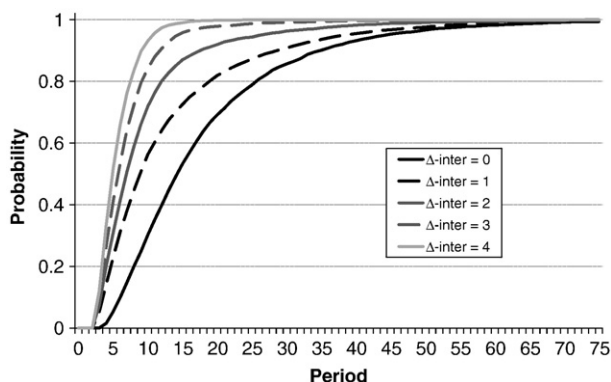


Fig. 8. Probability of standardization.

²³ Note that this asymmetry is present regardless of the reference values chosen for Δ -intra and Δ -inter.

of standardization as a function of the number of periods and the level of competition across the platforms as measured by Δ -inter.

The figure demonstrates that the higher the inter-platform competition the longer the convergence process. For example, when Δ -inter = 0 the probability that the market standardizes on one of the platforms after 10 periods is 0.3. This probability goes up to 0.56 for Δ -inter = 1; 0.72 for Δ -inter = 2; and is higher than 0.9 for Δ -inter = 4. This suggests that the more competitive the market the more time policy-makers have, should they choose to intervene.

4.1. Discussion

As Markovich (2008) shows, standardization or coexistence of platforms depends on the level of competition from the substitute markets. Focusing on a specific parameter value, $\delta = 0.5$, we complement this long-run result with an explanation of short-run mechanisms that take place during the process. Firms base their investment decisions solely on expected discounted future profits. Profit expectations depend on a firm's current quality level and the quality levels of its competitors on the same as well as on the competing platform, which in-turn determine market shares. If there are no quality differences within platforms and both platforms start with the same market shares, total investment on the leading platform is always higher than on the platform that lags behind. The competitive effect induces competitors on the leading platform to fight for that large overall market share, increasing investment on that platform. Competitors on the lagging platform have to wait for one or more periods until they can gain the platform lead – lowering discounted future profit expectations and thus inducing lower investment on the lagging platform. This favors standardization. Furthermore, the more similar are the quality levels on one platform, the more firms invest. This again strengthens the platform, regardless of whether it is ahead or behind. Moreover, lower levels of investment produce more uneven outcomes, since the probability that only one firm on a platform succeeds increases with lower levels of investment. This is again in favor of the leading platform, since levels of investment are higher on this platform.

Given these forces that favor the leading platform, why do we still observe comparatively high probabilities of weakly stronger competition? The intuition behind this result is two fold: First, when one platform gets far ahead, it does not consider the second platform as a relevant competitor. Investment on this platform falls and firms on the lagging platform may jointly invest more than those on the leading platform, increasing the chance of catch-up. Moreover, high levels of investment also tend to cement the current within-platform structure: since high investment leads to a high probability of success, close competitors stay close, while existing within-platform differences are likely to increase. Once the leading platform achieves a relatively large lead, investment on the leading platform falls. As a result, the probability of an increase in within platform differences increases. The increase in quality differences on the leading platform may result in firms on the lagging platform to jointly invest more than the firms on the leading platform. Consequently, catch-up is more likely when quality differences are large on the leading platform but small on the lagging platform.

These observations can be summarized as follows: in our model, the *NE* increases as quality differences across platforms decrease. The *NE* generally induces higher competitive efforts for all players. The *CE* increases as quality differences within platforms decrease: the closer the quality levels are, the higher the investment on a platform. Increased investment, however, leads to persistence of the existing competitive situation. Consequently, the *NE* and the *CE* are *aligned* with each other, and combined they *slow down* the forces toward standardization in situations where all software firms produce

similar qualities. Moreover, when the *CE* on the lagging and the leading platform differ, this difference works as a catalyst: If it is in favor of the lagging platform, it increases competition; if it is in favor of the leading platform, it accelerates the path towards standardization.

It is worthwhile to compare these results to the literature on indirect network effects with respect to increased variety instead of quality upgrading. There are three major differences between our results and this literature. First, in our model, *ex ante* expectations about market share changes through both the *NE* and *CE* align the competitive efforts of firms. In variety models, the *NE* and *CE* always work in opposite directions. Second, in our model, the *NE* is the strongest when platforms are roughly equally strong and competition is most intense. For example, in Church and Gandal (1992), the closest paper to ours, it is the exact opposite: the *NE* is the weakest when platforms host equal numbers of varieties. Therefore, in their model the *NE* only matters when its magnitude is relatively insignificant. Third, in our model, when firms and platforms are equally strong, both the *NE* and *CE* are strong. This helps foster the *persistence* of market structure and allows shifts in platforms' market shares to be *reversible*. In variety models, neither persistence nor reversibility exists when platforms compete with equal strength: Even a small advantage of one platform induces *all* new entrants to join the stronger platform, a process generally referred to as tipping. The discussion above, therefore, strongly suggests that industry analysis in the presence of indirect network effects requires identifying the major source of innovation: increases in variety (like CDs and DVDs) or quality upgrades (like software).

5. Conclusions

In this paper, we study how the existence of incompatible hardware platforms influences competition among software firms. We analyze two drivers of competition: quality levels on the same platform and quality levels across platforms. Within platforms, we find that indirect network effects tie together the fate of firms on the same platform. This tie is stronger the more equally strong the platforms are. When network effects are strong, firms on the same platform increase their competitive efforts due to a quality upgrade of a firm on their platform. In this case, a firm may receive a windfall increase in market value as a result of its competitor's upgrade. Network effects are weak when there are large quality differences across platforms. The competitive effect is stronger the lower the quality levels of firms on a platform and the more similar firms on that platform are. The network effect, the competitive effect, and the delay in the replacement of hardware all favor prolonged, fierce competition as long as platforms are equally strong. Consequently, we do not find an equivalent to the tipping result of the variety literature. If a platform leads in terms of quality, it reduces its level of investment and thus reduces competitive pressures for the competing platform as do large differences in quality levels on the leading platform. Excess inertia therefore can also be overcome in our model without extraordinary effort.

Since an analytical model would not allow us to address the complexity of these issues or acquire insights comparable to the ones we found, we use numerical methods for our analysis. This type of analysis can be further used to study additional issues that appear once innovative activities and dynamics are taken into account in industries with network effects. For instance, how do incentives to invest change when both hardware and software can experience quality upgrades? What if software firms are not restricted to one platform? What is the role of vertical integration? In particular, what if, as in the literature on two-sided markets, platforms were sponsored and both hardware and software could be priced dynamically? We intend to address some of these issues in our future research.

Appendix A. Quality levels of software firms on platform A

		Δ -inter								
		-4	-3	-2	-1	0	1	2	3	4
Δ -intra	-4	n.a.	(0,4), n.a.	(0,4)	(1,5), (0,4)	(1,5)	(2,6), (1,5)	(2,6)	n.a., (2,6)	n.a.
	-3	(0,3), n.a.	(0,3)	(1,4), (0,3)	(1,4)	(2,5), (1,4)	(2,5)	(3,6), (2,5)	(3,6)	n.a., (3,6)
	-2	(0,2)	(1,3), (0,2)	(1,3)	(2,4), (1,3)	(2,4)	(3,5), (2,4)	(3,5)	(4,6), (3,5)	(4,6)
	-1	(1,2), (0,1)	(1,2)	(2,3), (1,2)	(2,3)	(3,4), (2,3)	(3,4)	(4,5), (3,4)	(4,5)	(5,6), (4,5)
	0	(1,1)	(2,2), (1,1)	(2,2)	(3,3), (2,2)	(3,3)	(4,4), (3,3)	(4,4)	(5,5), (4,4)	(5,5)
	1	(2,1), (1,0)	(2,1)	(3,2), (2,1)	(3,2)	(4,3), (3,2)	(4,3)	(5,4), (4,3)	(5,4)	(6,5), (4,5)
	2	(2,0)	(3,1), (2,0)	(3,1)	(4,2), (3,1)	(4,2)	(5,3), (4,2)	(5,3)	(6,4), (5,3)	(6,4)
	3	(3,0), n.a.	(3,0)	(4,1), (3,0)	(4,1)	(5,2), (4,1)	(5,2)	(6,3), (5,2)	(6,3)	n.a., (6,3)
	4	n.a.	(4,0), n.a.	(4,0)	(5,1), (4,0)	(5,1)	(6,2), (5,1)	(6,2)	n.a., (6,2)	n.a.

Reference cells on platform B are (3,3) for the clear cells of the table and (3,4) and (2,3) for the top and bottom values in the shaded cells of the table, respectively. Values calculated from the shaded cells are the averages of the two values provided. Cells for which data was not available (n.a.) were not included in the calculations and graphs. Note that graphs that depict changes have additional cells with n.a. data in the bottom right corner of the table.

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