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Network Effects, Compatibility Decisions, and Monopolization*

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1. Introduction

It is everyday experience that a user's surplus from a hardware-software system often depends positively on the total number of users of the same type of system. Obvious examples are personal-computer systems and compact-disk systems (with the disks as 'software'). These 'indirect' or 'market mediated network effects'[1] are due to the fact that software components are typically produced with relatively high fixed costs and (more or less) constant marginal costs. Then, with free market entry, a rising total system demand increases the number of differentiated software-component variants, and with a preference for a variety of software, this results in an increase in each user's surplus. As the significance of the network effects depends on the degree of compatibility between competing system variants, the compatibility decisions of the suppliers of system components are of central importance for market performance and welfare. In particular, the hardware suppliers' decisions on indirect horizontal (in)compatibility with competing hardware variants, i.e. on vertical (in)compatibility with software which is operable under competing hardware variants, are often decisive for the outcome of the system competition.[2]

The following analysis of the compatibility decision of a hardware supplier who is dominant due to a quality advantage takes up this issue. Among other things, it aims at showing how and when the dominant supplier can and will turn his quality advantage into a monopolization of the hardware

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1 For this terminology, see Katz / Shapiro (1985), p. 424, and Farrell / Saloner (1985), p. 70. See Holler / Knieps / Niskanen (1997), pp. 383 ff, for a classification of network effects.

2 For a classification of the various kinds of (in)compatibility, see Wiese (1997), pp. 285 ff. In the following, '(in)compatibility' always means 'indirect horizontal (in)-compatibility'.

market by making sure that software which is compatible with his hardware is incompatible with competing hardware, so that consumers of the competing hardware do not benefit from the network effects of his system variant.[3] We present a Hotelling model of the competition between two hardware suppliers who can, due to intellectual property rights attached to their interface specifications, unilaterally prevent compatibility. First, the duopolists simultaneously decide on (in)compatibility, and then, they compete in prices. The central feature of our Hotelling model with network effects is the asymmetry caused by the quality advantage. It is our main point that this vertical bias of the per se horizontal differentiation affects realized welfare considerably by inducing a price distortion which is not present in the symmetric model. While, in a symmetric set-up, compatibility is welfare optimal regardless whether prices are set by firms or by a social planner, in the asymmetric approach, the welfare optimality of compatibility is only guaranteed if prices are set by the social planner. This welfare-theoretical first-best nature of compatibility is, however, a purely theoretical result, because the determination and enforcement of welfare-optimal prices in hardware markets is, obviously, a project which is too ambitious to be promising. Therefore, we will use that welfare as a benchmark which results when the social planner can intervene only in the compatibility decisions. It turns out that against the background of this second-best welfare optimum, a monopolization via maintained incompatibility can be welfare superior to the coexistence of compatible variants both in cases where such a monopolization actually occurs and in cases where the suppliers prefer compatibility. Hence, both the prevention of a monopolization and the permission of compatibility agreements can be policy failures. Moreover, we will show that there are some cases where the coexistence of incompatible variants can be welfare superior to the coexistence of compatible variants as well.

The first stringent analysis of the private and social incentives for compatibility is Katz / Shapiro (1985). They, however, restrict themselves to discussing the case of intrinsically homogeneous network-effect goods.[4] A hor-

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3 An example of such a prevention of compatibility can be found in the context of one of several antitrust investigations of the US Department of Justice against Microsoft. There, Digital Research complained that it was being systematically discriminated against (compared with other software developing firms) when Microsoft disclosed details about new specifications of the interface between its (Microsoft's) operating system MS DOS and application programs, and that in this way Microsoft hindered Digital Research's ability to keep its operating system DR DOS compatible with MS DOS. See Baseman / Warren-Boulton / Woroch (1995), pp. 299 ff, for details. (In this example, the operating systems are the competing basic 'hardware' variants and the application programs are the 'software' components.)

4 Two recent approaches with intrinsically homogeneous network-effect goods are de Palma / Leruth (1996) and Economides / Flyer (1997). In both models, suppliers compete in quantities, and consumers differ in their valuation of the network effects. With given incompatibility, asymmetric market equilibria can occur where the sup-

izontal differentiation of the basic system component is assumed in Farrell / Saloner (1992), in Desruelle / Gaudet / Richelle (1996) and in Church / Gandal (1996). In the first two articles mentioned, however, the Hotelling approach is symmetric, and thus all of our central results concerning the effects of a vertical quality bias are not derived there. Moreover, while in Farrell / Saloner (1992) compatibility is provided by a converter, i.e. ex post (after production of hardware), in our model, compatibility is realized ex ante (or not at all). In Church / Gandal (1996), incompatibility is exogenously given, i.e. the compatibility decision is not analyzed. They show how a hardware as well as software supplying incumbent can deter entry by offering such a variety of software that his resulting installed base is large enough to make entry unprofitable for an incompatible competitor. That is, in their approach, there is a dominant supplier and this dominant supplier can monopolize the market. His dominance, however, stems from a first-mover advantage, not from a quality advantage, and he monopolizes the market via his installed base, not via deliberately chosen incompatibility. Their dominant supplier, for example, neither has the option of accommodating *compatible* entry, nor can he choose between the coexistence of compatible and of incompatible hardware variants.

The paper is organized as follows: after the basic model has been presented in Section 2, we discuss the price competition of the second stage of the game for given compatibility in Section 3 and for given incompatibility in Section 4. In Section 5, the profit-maximizing compatibility decisions are derived and compared with the welfare-theoretical first-best and second-best solutions. Finally, in Section 6, some conclusions are drawn.

2. The Model

2.1 Assumptions

There are two suppliers, D1 and D2, each producing one of two substitutive variants of the hardware component of a hardware-software system, V1 and V2, and selling them at prices p_1 and p_2, respectively. With regard to their production technology, their variants' locations in product space and the specification of the consumers' surplus, we follow the assumptions of Farrell / Saloner (1992) with the exception that, in our model, V1 has a quality advantage. In detail, our assumptions are as follows:

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plier of the larger network has a higher price and makes higher profits. However, in a symmetric set-up, i.e. with both suppliers having an equal chance of becoming the larger one, the duopolists always prefer compatibility. Only if for some exogenous reason one of both firms has a considerably higher chance of becoming the larger one, this firm will hinder compatibility whenever the general significance of the network effects is high: see Economides / Flyer (1997), pp. 23 f.

- The hardware variants are horizontally differentiated with V1 at the left-end point and V2 at the right-end point of the unit line. Furthermore, V1 has a systematic quality advantage which manifests itself in a higher basic willingness to pay a_j (j =1, 2) for V1, i.e. $a_1 > a_2$ holds. In the following, this quality advantage $a_1 - a_2$ is denoted as k and is exogenously given; we assume that it has resulted from an R&D competition in which both suppliers could achieve it with equal probability.[5]
- The specifications of both hardware-software interfaces are protected by intellectual property rights, so that compatibility only comes about if *both* duopolists prefer it. Moreover, the duopolists can only decide on (in)compatibility ex ante, and, therefore, compatibility causes no extra costs.
- Marginal costs of hardware production are constant and equal for both variants. Without loss of generality, we normalize these costs to zero. For simplicity, the same is assumed to be true with regard to the fixed costs of hardware production.
- As for the software markets, which are not explicitly modelled, we assume monopolistic competition with free entry and constant and equal marginal costs as well as equal fixed costs in the production of each software variant. Hence, in the case of incompatibility, the software variety of a system variant increases with rising demand for that system variant.[6]
- Consumers' general willingness to pay for a system variant is uniformly distributed along the unit line, and the horizontal alienation terms are linear in distance. With $0 \leq i \leq 1$ as a consumer's address on the Hotelling line, these alienation effects amount to $-mi$ with respect to V1 and to $-m\,(1-i)$ with respect to V2, where m can be seen as a measure of the extent of the horizontal differentiation.[7] With regard to the significance of the vertical quality advantage $k = a_1 - a_2$ in com-

[5] Alternatively, it can be explained by a systematic cost advantage of D1 in producing quality; in Appendix A, we provide some results for the case that, in a first stage of the game, 'qualities' a_1 and a_2 are produced with increasing marginal costs.

[6] See Chou/Shy (1990) and Church/Gandal (1992) where software markets are explicitly modelled. As we are not interested in the vertical aspects of compatibility per se, we follow Katz/Shapiro (1985) and Farrell/Saloner (1985 and 1992) in modelling indirect network effects simply by assuming a positive dependence of a user's surplus on the total number of users of compatible system variants.

[7] Using quadratic 'transportation costs' $-mi^2$ and $-m(1-i)^2$ does not change any of our central results; it would only raise consumers' surplus and total welfare both in the case of compatibility and in the case of incompatibility by a fixed amount of $m/6$ (compared to the linear specification).

parison with the extent of the horizontal differentiation, we require that $0 < k < m$ holds; i.e. despite the existence of a quality advantage, the differentiation is horizontal.[8]

- In line with the models of Farrell / Saloner and Katz / Shapiro, it is assumed that consumers' surplus is additive in the general willingness to pay for a system variant on the one hand, and in that part of the willingness to pay which is due to the network effects on the other hand. The underlying assumption is that the inherent product characteristics of a system variant and its network's size are poor substitutes.
- Consumers' surplus is a linear function in network size, and consumers do not differ in their valuation of network effects. Hence, with n as a measure of the general significance of the network effects and x_j $(j = 1, 2)$ as the demand for Vj (i.e.: its network size in the case of incompatibility), that part of the willingness to pay which is due to network effects can be expressed (for given incompatibility) as nx_j.[9]
- The total number of consumers is normalized to one, and a single consumer's demand is infinitesimal. Furthermore, each consumer purchases one (and only one) unit of hardware. Hence, the market is always covered, and the absolute demand for a system variant equals its market share, which in turn equals the variant's network size in the case of incompatibility. The covered-market assumption is equivalent to demanding that the surplus of those consumers who are indifferent between V1 and V2 is positive even in the case of a coexistence of incompatible variants. According to the results obtained in Section 4, this is fulfilled for $a_1 + a_2 > 3(m - n)$.

These assumptions taken together, in the case of incompatibility the surplus of a consumer with address i when purchasing V1 or V2 can be formulated as

$$s_{i1} = a_1 - m\,i + n\,x_1 - p_1 \quad \text{and} \tag{1}$$

$$s_{i2} = a_2 - m\,(1-i) + n\,x_2 - p_2 \quad \text{with } x_2 = 1 - x_1\,, \tag{2}$$

respectively. For given compatibility, both variants have a joint network of size one, i.e. $s_{i1} = a_1 - mi + n - p_1$ and $s_{i2} = a_2 - m(1-i) + n - p_2$ hold.

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[8] For $k > m$, in the case of incompatibility with $p_1 = p_2$ and equal network size, all consumers would choose V1, i.e. then the differentiation would be vertical.

[9] A more flexible approach which takes into account that network effects are sometimes significantly decreasing would be nx_j^z with $0 < z \leq 1$; see Appendix B for a short discussion of this case.

2.2 Demand Functions

In the case of compatibility, we obtain the address of those consumers who are indifferent between V1 and V2 by equating $a_1 - mi + n - p_1$ with $a_2 - m(1-i) + n - p_2$. As total demand is normalized to one and consumers are uniformly distributed along the unit line, this address is identical to the V1 market share. Taking into account that $0 \leq x_j \leq 1$ and $x_1 + x_2 = 1$ hold, we obtain[10]

$$x_j = \begin{cases} 0 & \text{if} \quad p_j \geq \pm k + m + p_\ell \\ 0.5 + \dfrac{p_\ell - p_j \pm k}{2m} & \text{if} \quad \pm k - m + p_\ell < p_j < \pm k + m + p_\ell \\ 1 & \text{if} \quad p_j \leq \pm k - m + p_\ell \end{cases} \tag{3}$$

with $j, \ell = 1, 2$ and $j \neq \ell$.

In the case of incompatibility, equating s_{i1} with s_{i2} leads to $x_j = 0.5 + (p_\ell - p_j \pm k)/[2(m-n)]$ (for $0 < x_j < 1$), and two cases have to be considered:

- If the horizontal differentiation dominates the network effects, i.e. if $n < m$ holds, this function is the inner branch of the demand function. Taking into account the boundaries, we obtain for this first case

$$x_j = \begin{cases} 0 & \text{if} \quad p_j \geq m - n \pm k + p_\ell \\ 0.5 + \dfrac{p_\ell - p_j \pm k}{2(m-n)} & \text{if} \quad n - m \pm k + p_\ell < p_j < m - n \pm k + p_\ell \\ 1 & \text{if} \quad p_j \leq n - m \pm k + p_\ell \,. \end{cases} \tag{4}$$

  Comparing Equation (4) with the demand function under compatibility makes clear that the price elasticity (in this first case) is higher under incompatibility than it is under compatibility. In other words, competition is more intensive when the system variants are incompatible. This is due to bandwagon effects induced by the network effects.

- If the network effects dominate the horizontal differentiation, i.e. if $n > m$ holds, the inner branch of Equation (4) is upward sloping (with respect to p_j) and turns out to be unstable for fixed prices. This becomes clear by inspection of the surplus of the indifferent consumers $s_{i=x_1,1} = a_1 + (n-m)x_1 - p_1$ and $s_{i=x_1,2} = a_2 + (n-m)(1-x_1) - p_2$: here, obviously, $\partial s_{i=x_1,1}/\partial x_1 = -\,\partial s_{i=x_1,2}/\partial x_1 = n - m$ holds. Hence, whereas for $n < m$, a perturbation leads to a stabilizing reaction of

[10] In the following, '±' means that a positive sign holds for the dominant supplier D1 and a negative sign for his competitor D2.

consumers, such perturbations induce destabilizing bandwagon effects for $n > m$. An exogenous rise in x_1, for instance, for $n < m$ leads to a lower surplus from V1 and to a higher surplus from V2 and, thus, to a subsequent fall in x_1 (the address of the indifferent consumers shifts to the left). In contrast, with $n > m$ it results in a higher surplus from V1 and a lower surplus from V2 and, thus, induces a further rise in x_1 (the address of the indifferent consumers shifts to the right). Hence, as for consumers' choice, in the case of dominating network effects interior equilibria could be ruled out.[11] From an evaluation of the consumers' surplus in the boundary states $x_1 = 1$ and $x_1 = 0$, it becomes clear that with $n > m$ either one of these two states is an equilibrium (for given prices) or both are equilibria. For example, $x_1 = 1$ (all consumers choose V1) is an equilibrium if consumers with address $i = 1$ (who have the lowest willingness to pay for V1) do not deviate, i.e. whenever $s_{11}(x_1 = 1) = a_1 - m + n - p_1$ is higher than $s_{12}(x_1 = 1) = a_2 - p_2$. Obviously, this condition is fulfilled for $p_1 - p_2 < n - m + k$. Analogously, $x_1 = 0$ (all consumers choose V2) is an equilibrium if consumers with address $i = 0$ (who have the lowest willingness to pay for V2) do not deviate, i.e. whenever $s_{02}(x_1 = 0) = a_2 - m + n - p_2$ is higher than $s_{01}(x_1 = 0) = a_1 - p_1$. Obviously, this condition is fulfilled for $p_1 - p_2 < m - n + k$. Hence, dominating network effects turn the market into a natural monopoly, and there is a 'de-facto standardization' either on V1 or on V2. From the conditions for the boundary equilibria, it becomes clear that both equilibria coexist for $m - n + k \leq p_1 - p_2 \leq n - m + k$. Here, a de-facto standardization on V1 is pareto superior to a de-facto standardization on V2 (due to $a_1 > a_2$). Therefore, we assume that in these cases, $x_1 = 1$ is the focal equilibrium. Hence, the 'demand function' of the dominant supplier D1 reads

$$x_1 = \begin{cases} 1 & \text{if} \quad p_1 \leq n - m + k + p_2 \\ 0 & \text{otherwise}\,. \end{cases} \tag{5}$$

We assume that the duopolists simultaneously commit to (in)compatibility in the first stage of the game and compete in prices in the second stage. In our analysis of the noncooperative market process, we restrict ourselves to the derivation of subgame-perfect Nash equilibria. Hence, in a first step, we compute the Nash equilibria of the price subgame given that compatibility

[11] In Section 4, we will prove that this also holds with regard to the price setting of the suppliers; there, it will be shown that with $n > m$, quantities on the upward sloping branch are profit minimizing.

has been established (in Section 3) and given that incompatibility has been maintained (in Section 4). Then (in Section 5) we deduce the profit-maximizing compatibility decisions of the duopolists.

3. Price Competition with Given Compatibility

In this section, we derive both Nash equilibria and welfare optima of the price subgame given that compatibility has been established in the first stage of the game. In order to clarify the influence of the existence of a quality advantage on profits and welfare, we start with a short discussion of the symmetric model.

In the absence of a quality advantage ($k = 0$) and with given compatibility, our model would be identical to the standard textbook model of horizontal product differentiation,[12] except for the fact that consumers' surplus and total welfare are higher due to the network effects. As is well known, in this symmetric benchmark model, there is a unique equilibrium with $x_j^c = 0.5$ (with c for 'compatibility') and equal prices for both variants. The computation of profits and welfare is straightforward. Maximizing $G_j = p_j x_j$ with x_j according to Equation (3) leads via the best-response functions $p_j = 0.5(m + p_\ell)$ to $p_j^c = m$ and $G_j^c = 0.5m$. As the market is always covered, absolute prices do not matter for total welfare. Hence, realized total welfare W^c is the sum of the cumulated basic willingness to pay $a = a_1 = a_2$ and the cumulated network effects n less the cumulated alienation effects. The latter are identical to the average distance between a consumer and his chosen variant multiplied with m, i.e. they amount to $0.25m$.

Obviously, *the existence of a quality advantage* ($k > 0$) will leave neither the relative price nor the market shares unchanged, and these changes will affect profits and realized total welfare. We can prove the following lemma:

Lemma 1. Given that compatibility has been established in the first stage of the game, individual profits and realized total welfare amount to

$$G_j^c = \frac{m}{2} \pm \frac{k}{3} + \frac{k^2}{18m} \quad \text{and} \tag{6}$$

$$W^c = \frac{a_1 + a_2}{2} + n - \frac{m}{4} + \frac{5k^2}{36m}\ , \tag{7}$$

respectively.

[12] See Tirole (1988), pp. 279 ff.

Proof. The first- and second-order conditions for the maximization of $G_j = p_j x_j$ with x_j according to Equation (3) are $\partial G_j / \partial p_j = x_j - 0.5 p_j / m = 0$ and $\partial^2 G_j / \partial p_j^2 = -1/m < 0$, respectively. The latter are, obviously, always fulfilled, and the former yield, via the best-response functions $p_j = 0.5(m \pm k + p_\ell)$, equilibrium prices

$$p_j^c = m \pm \frac{k}{3} \, .$$

Hence, the quality advantage induces a price difference of $2k/3$. Substituting this difference into Equation (3) results in equilibrium quantities

$$x_j^c = \frac{1}{2} \pm \frac{k}{6m} \, ,$$

and by multiplying p_j^c with x_j^c, we obtain equilibrium profits as stated in the lemma. Realized total welfare W^c consists of three components: the cumulated basic willingness to pay $a_1 x_1^c + a_2 x_2^c$, the cumulated network effects n, and the cumulated alienation effects $-0.5m\,(x_1^{c\,2} + x_2^{c\,2})$. By use of the equilibrium quantities, we obtain Equation (7).

Compared with the symmetric benchmark case, the existence of a quality advantage leads both to a higher price and to a higher market share of the dominant supplier and reduces both the price and market share of his competitor. Note that due to $0 < k < m$, all Nash equilibria are inside the interval $m < p_1^c < 4m/3$ and $2m/3 < p_2^c < m$, so that $1/2 < x_1^c < 2/3$ holds.

Considering *optimal welfare* for given compatibility, it is obvious that in the absence of a quality advantage, equal prices are optimal: they lead to equal market shares, which minimizes the cumulated alienation effects and, thus, maximizes total welfare. In our model with $k > 0$, market prices differ, and it is important for the understanding of our central welfare-theoretical results derived in Section 5 to note that this price difference is a price distortion. A social planner who is confronted with given compatibility would maximize $W = a_1 x_1 + a_2(1 - x_1) + n - 0.5m[x_1^2 + (1 - x_1)^2]$, which leads to welfare-optimal (wo) market shares of $x_j^{c,wo} = 0.5 \pm k/(2m)$ and, thus, to a total welfare which amounts to

$$W^{c,wo} = \frac{a_1 + a_2}{2} + n - \frac{m}{4} + \frac{k^2}{4m} \, . \tag{8}$$

Substituting $x_j^{c,wo}$ into Equation (3) shows that the realization of this optimum would require the enforcement of equal prices (a project which seems to us quite unrealistic).

4. Price Competition with Given Incompatibility

In this section, we derive both Nash equilibria and welfare optima of the price subgame given that incompatibility has been maintained in the first stage of the game. Again, we start with a discussion of the symmetric benchmark model.

In the absence of a quality advantage ($k = 0$) and with given incompatibility, there are two clear-cut fundamental cases (see Subsection 2.2): while for a dominating horizontal differentiation ($n < m$), the market outcome is always a duopoly, dominating network effects ($n > m$) definitely turn the market into a natural monopoly.

- That $n < m$ results in a symmetric duopoly becomes clear from the demand equation (4): with $k = 0$, neither of the suppliers can set a limit price. From the first-order conditions of profit maximization, we obtain the best-response functions $p_j = 0.5(m - n + p_\ell)$. The second-order conditions are $1/(n - m) < 0$, and this is, obviously, fulfilled for $n < m$. Hence, for these symmetric duopolistic Nash equilibria, $p_j^{in,d} = m - n$ and $G_j^{in,d} = 0.5\,(m - n)$ hold (with *in* for 'incompatibility' and *d* for 'duopolistic'). Since the price elasticity of demand increases with a rise in the general significance of the network effects n, the competition of incompatible variants *within* the market is more intensive, the higher this significance is, and, thus, a higher n results in lower prices and profits. Due to the splitting of consumers into two incompatible networks, realized total welfare amounts to $W^{in,d} = a + 0.5n - 0.25m$.
- In the case of $n > m$, the second-order conditions are not fulfilled, and interior Nash equilibria do not exist. Then, the market is a natural monopoly where the two coexisting equilibria 'de-facto standardization on V1' and 'de-facto standardization on V2' are not pareto ranked. We assume that in this case, 'nature' decides which supplier can monopolize the market via limit pricing, i.e. that the two suppliers have an equal chance of becoming the monopolist.[13] Hence, with a limit price of $n - m$ (see Equation [5]) and given risk neutrality, *expected* individual profits amount to $0.5(n - m)$. In contrast to the duopolistic case, with competition of incompatible variants *for* the market, the price increases with a rise in the general significance of the network effects. This is due to the fact that the limit price can be

[13] The underlying assumption is that in the absence of a quality advantage, exogenous factors (such as successful marketing campaigns) determine which equilibrium is focal before price competition.

higher, the more significant the value of the monopolist's network is for consumers. Considering realized total welfare, a monopolization (index m) leads, on the one hand, to a full exploitation of network effects, and, on the other hand, to a doubling of the cumulated alienation effects, i.e. $W^{in,m} = a + n - 0.5m$ holds.

The existence of a quality advantage $a_1 > a_2$ breaks the symmetry and, thus, for $n > m$, a de-facto standardization on V1 becomes either the focal or even the unique Nash equilibrium . Moreover, it is intuitively clear that with given incompatibility, a quality advantage is leveraged by the bandwagon effects, so that a monopolization is also possible for $n < m$. The following lemma holds:

Lemma 2. Given that incompatibility has been maintained in the first stage of the game,

- $n/m < 1 - k/(3m)$ *leads to the coexistence of incompatible variants with individual profits*

(9) $$G_j^{in,d} = \frac{m-n}{2} \pm \frac{k}{3} + \frac{k^2}{18\,(m-n)}$$

and realized total welfare

(10) $$W^{in,d} = \frac{a_1 + a_2}{2} + \frac{n}{2} - \frac{m}{4} + \frac{(5m-4n)k^2}{36(m-n)^2} \ .$$

- $n/m > 1 - k/(3m)$ *results in a de-facto standardization on the dominant supplier's variant V1 with profits and prices*

(11) $$G_1^{in,m} = p_1^{in,m} = n - m + k$$

and realized total welfare

(12) $$W^{in,m} = a_1 + n - \frac{m}{2} \quad \text{with} \quad a_1 = \frac{a_1 + a_2}{2} + \frac{k}{2} \ .$$

Proof. From the first-order conditions of the maximization of $G_j = p_j x_j$ with x_j according to Equation (4), we obtain the best-response functions $p_j = 0.5\,(m - n \pm k + p_\ell)$. The second-order conditions $1/(n-m) < 0$ make clear that these are best responses only for $n < m$. In this case, the equilibrium prices are

$$p_j^{in,d} = m - n \pm \frac{k}{3} \ .$$

Obviously, a duopolistic market structure requires that $n/m < 1 - k/(3m)$ holds (otherwise $p_2^{in,d}$ would be negative). Provided that this condition is fulfilled, equilibrium quantities result from substituting $p_j^{in,d}$ into Equation (4) as

$$x_j^{in,d} = \frac{1}{2} \pm \frac{k}{6(m-n)} ,$$

and by subsequent multiplication, we obtain equilibrium profits as stated in the lemma. Realized total welfare is the sum of the cumulated basic willingness to pay $a_1 x_1^{in,d} + a_2 x_2^{in,d}$, cumulated network effects $n(x_1^{in,d\,2} + x_2^{in,d\,2})$, and cumulated alienation effects $-0.5m(x_1^{in,d\,2} + x_2^{in,d\,2})$. Substituting equilibrium quantities leads to Equation (10). If the above condition is not fulfilled, i.e. if $n/m > 1 - k/(3m)$ holds, there is no duopolistic Nash equilibrium. For $1 - k/(3m) < n/m < 1$, the quality advantage is leveraged by the bandwagon effects to such an extent, that the market outcome is a monopoly, even though $n < m$ holds. According to Equation (4), the limit price $p_1^{in,m}$ and, thus, the profits of the monopolist are as stated in the lemma. For $n > m$, the non-existence of duopolistic equilibria is proven by the second-order conditions of profit maximization and our discussion of the stability of consumers' choice in Subsection 2.2. Here, the de-facto standardization on V1 is always a Nash equilibrium, and the limit price is (of course) again as stated above: see Equation (5). The calculation of realized total welfare $W^{in,m}$ is straightforward.

Considering *optimal welfare* for given incompatibility, with $k = 0$, a monopolization maximizes cumulated network effects $n(x_1^2 + x_2^2)$ but also maximizes (in absolute terms) cumulated alienation effects $-0.5m(x_1^2 + x_2^2)$, whereas a symmetric duopoly minimizes cumulated alienation effects but also minimizes cumulated network effects. By weighing up these two kinds of effects, it becomes clear that a symmetric duopoly is welfare optimal for $n < 0.5m$ and a monopolization otherwise. Hence, we can conclude that in the presence of a quality advantage, a de-facto standardization on V1 can be welfare optimal with $n < 0.5m$. Moreover, taking into account the leverage effect which is caused by the bandwagon effects in the case of incompatibility, we can presume that the distortion of duopoly prices is now aggravated (compared to the case of compatibility). Indeed, by maximizing the general welfare formula $W = a_1 x_1 + a_2(1 - x_1) + (n - 0.5m)[x_1^2 + (1 - x_1)^2]$, we can prove that a social planner who is confronted with given incompatibility would realize a de-facto standardization on V1 for $n/m > 0.5\,(1 - k/m)$ and a coexistence of incompatible variants otherwise. In the latter case, he would set a price difference $p_1 - p_2 = -kn/(m - 2n) < 0$ in order to induce market shares of $x_j^{in,d,wo} = 0.5 \pm k/[2(m - 2n)]$, and this would lead to

(13) $$W^{in,d,wo} = \frac{a_1 + a_2}{2} + \frac{n}{2} - \frac{m}{4} + \frac{k^2}{4(m-2n)^2} .$$

In the case of a monopolization, realized total welfare proves to be optimal.[14]

5. Compatibility Decisions

In this section, the Nash equilibria for the first stage of the game are derived and compared to welfare optima. Since we see interventions in the price formation as a purely theoretical policy measure, we focus on the comparison with second-best welfare optima, i.e. with that welfare level which results when the social planner intervenes only in the compatibility decisions.

In the absence of a quality advantage ($k = 0$), the suppliers have to decide whether to compete in a compatible or in an incompatible duopoly for $n < m$, and whether to compete in a compatible duopoly or to maintain incompatibility and compete for the market for $n > m$.

- In the case of a dominating horizontal differentiation, they establish compatibility, because this softens price competition and, thus, raises individual profits. As for realized total welfare, compatibility is always second-best optimal, because compared to an incompatible duopoly, it has the advantage of doubling the cumulated network effects.
- In the case of dominating network effects, the positive quantity effect of a monopolization (the monopolist doubles his sales) is exactly offset by the uncertainty concerning who will win. Hence, like in the first case, with regard to the compatibility decision only prices matter. Comparing prices under compatibility $p_j^c = m$ with the limit price of the monopolist $p_j^{in,m} = n - m$ makes clear that a monopolization occurs for $n > 2m$. As for realized total welfare, compatibility has the advantage of halving the cumulated alienation effects and, thus, is second-best welfare optimal.

In the presence of a quality advantage ($k > 0$), the decision on (in)compatibility is a decision on whether to compete in a compatible or in an incompatible duopoly for $n/m < 1 - k/(3m)$ and a decision on whether to compete within or for the market for $n/m > 1 - k/(3m)$ (see Lemma 2).

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14 The second-order condition of the maximization of total welfare with respect to x_1 reads $2n - m < 0$; i.e. for $n/m > 0.5$, market shares according to $x_j^{in,d,wo}$ as stated above lead to welfare minima. In the latter case, $x_1 = 1$ is always welfare optimal due to $a_1 > a_2$. As becomes clear from the formula for $x_j^{in,d,wo}$, this also is true for $n/m < 0.5$ provided that $k > m - 2n$ holds, i.e. for $n/m < 0.5(1 - k/m)$.

- In the case of $n/m < 1 - k/(3m)$, the market share of the hardware variant with the quality advantage is higher under incompatibility than under compatibility: from the proofs of Lemmas 1 and 2, we know that $x_1^c = 0.5 + k/(6m)$ and $x_1^{in,d} = 0.5 + k/[6(m-n)]$ hold. This is due to the fact that under incompatibility, a higher market share of V1 (caused by $a_1 > a_2$) also means a larger network size, so that some consumers who choose V2 under compatibility opt for V1 under incompatibility. Hence, whereas D2 always wants to establish compatibility, now the softening of competition under a move to compatibility is not necessarily sufficient for ruling out that D1 prevents compatibility. Moreover, considering realized total welfare, the decline of the V1 market share under a move to compatibility might question the welfare-theoretical desirability of this move.

- In the case of $n/m > 1 - k/(3m)$, the quality advantage of V1 makes the monopolization by D1 the focal equilibrium. Therefore, whereas under symmetry, a monopolization means for D1 expected profits of $0.5(n-m)$, it now means certain profits of $n - m + k$. Hence, in the presence of a quality advantage, the market is much more prone to a monopolization. This fact, however, must not necessarily be detrimental to realized total welfare, because a monopolization now leads to a higher cumulated basic willingness to pay. With the help of Lemmas 1 and 2, we can prove the following proposition:

Proposition 1.

- *For $n/m < 1.5 - 2k/(3m) + k^2/(18m^2)$, the suppliers make their variants compatible. This is second-best welfare optimal for $k/m < 0.6$ as well as for $k/m > 0.6$ insofar as $n/m < 1 - [5k/(36m)][k/m + \sqrt{(k/m)^2 + 2.88}]$ holds. Otherwise, we have to distinguish two cases (both with $k/m > 0.6$): for $1 - [5k/(36m)][k/m + \sqrt{(k/m)^2 + 2.88}] < n/m < 1 - k/(3m)$, the coexistence of incompatible variants is second-best welfare optimal, and for higher n/m, a monopolization by the dominant supplier is second-best welfare optimal.*

- *For $n/m > 1.5 - 2k/(3m) + k^2/(18m^2)$, the dominant supplier monopolizes the market via maintaining incompatibility. This is second-best welfare optimal for $k/m > 0.6$ but welfare inferior to compatibility for $k/m < 0.6$.*

Proof. According to Equations (6), (9), and (11), the changes in the dominant supplier's profits under a move to compatibility are $0.5n + [k^2/(18m)][1 - m/(m-n)]$ for $n/m < 1 - k/(3m)$ and $1.5m - n - 2k/3 +$

$k^2/(18m)$ for $n/m > 1 - k/(3m)$. In the first case, the change in profits is positive for $n/m < 1 - [k/(3m)]^2$, and this condition is, obviously, fulfilled. This proves that the decline in market share is overcompensated by the rise in price, so that the dominant supplier agrees to compatibility. In the second case, simple rearrangements show that a monopolization via maintaining incompatibility and setting the limit price pays off for $n/m > 1.5 - 2k/(3m) + k^2/(18m^2)$. This proves that a quality advantage makes the market more prone to a monopolization. In order to deduce the second-best welfare optima, we have to compare W^c according to Equation (7) with $W^{in,d}$ according to Equation (10) for $n/m < 1 - k/(3m)$ and with $W^{in,m}$ according to Equation (12) for $n/m > 1 - k/(3m)$. In the first case, some rearrangements of the borderline case $W^c = W^{in,d}$ lead to the quadratic equation $(n/m)^2 - \{2 - 2.5[k/(3m)]^2\}(n/m) + 1 - 3[k/(3m)]^2 = 0$, and evaluating this equation results in $W^c < W^{in,d}$ for $n/m > 1 - [5k/(36m)]$ $[k/m + \sqrt{(k/m)^2 + 2.88}]$. Given $n/m < 1 - k/(3m)$, this condition implies $k/m > 0.6$ as a necessary condition. In the second case, simple rearrangements show that $W^{in,m} > W^c$ holds for $k/m > 0.6$.

Note that the monopolization of the market in case of a sufficiently high general significance of the network effects n is a result which is very robust with respect to modifications of the model. It is due to the fact that the limit price positively depends on n while prices under compatibility do not depend on n. This is independent of the linear specification of the surplus function with respect to transportation costs and network size and holds under any continuous consumer distribution. However, with regard to the decision in favor of compatibility for $n/m < 1 - k/(3m)$, we cannot prove that it results for any nonlinear specification of the demand function. As for second-best welfare optima, it is noteworthy that due to the existence of a quality advantage, both a monopolization via maintaining incompatibility and the coexistence of incompatible variants can be welfare superior to compatibility. In our model with $a_1 > a_2$, a monopolization leads not only to higher cumulated alienation effects but also to a higher cumulated basic willingness to pay – and for $k/m > 0.6$, the latter overcompensates the former. The possible welfare superiority of a coexistence of incompatible variants is due to the fact that $x_1^{in,d} > x_1^c$ holds: the latter implies that under incompatibility the balance of cumulated alienation effects and cumulated basic willingness to pay can be higher than under compatibility – and for high $x_1^{in,d}$ (i.e. if the market is nearby a de-facto-standardization on V1), this can overcompensate the network-effect advantage of compatibility.[15] However, here again, we cannot preclude that the result concerning the compar-

[15] A numeric evaluation of the relevant parameter regime shows that $x_1^{in,d} \geq 0.9$ is a necessary condition for the welfare superiority of an incompatible duopoly.

ison between a compatible and an incompatible duopoly does not hold under a nonlinear specification of the demand function, whereas the eventual welfare superiority of a monopolization is a considerably robust result. In particular, the latter is independent of the linear specification of the surplus function. (As for robustness with respect to consumer distributions, see at the end of this section.)

Figure 1 gives an overview on when Nash equilibria are second-best welfare optimal and when policy interventions can be justified. There are four parameter regimes:

- If (for a given extent of the horizontal differentiation m) both the general significance of the network effects n and the quality advantage k are low (i.e. if $n/m < 1.5 - 2k/(3m) + k^2/(18m^2)$ and $k/m < 0.6$ hold), the suppliers establish compatibility, and this is second-best welfare optimal.
- If (for given m) both the general significance of the network effects and the quality advantage are high, the dominant supplier monopolizes the market via maintaining incompatibility, and this is second-best welfare optimal as well.
- If (for given m) the general significance of the network effects is high and the quality advantage is low, the dominant supplier monopolizes the market via maintaining incompatibility, whereas compatibility is the second-best welfare optimum. Here, intervening in favor of compatibility by enforcing a compulsory licensing of the intellectual property rights attached to the dominant supplier's interface specification makes sense.
- If (for given m) the general significance of the network effects is low and the quality advantage is high, the suppliers establish compatibility, but this is not always second-best welfare optimal. Rather, if the general significance of the network effects is not too low, maintaining incompatibility is the second-best welfare optimum. Here, the prohibition of compatibility arrangements can make sense. For most of the relevant parameter constellations, this would lead to a monopolization. However, there are also some constellations where such a policy intervention would lead to the coexistence of incompatible variants.

Hence, against the background of the symmetric model (where compatibility is always first- and second-best welfare optimal), it must be stressed that with a reasonable second-best welfare-theoretical standard, exclusionary strategies can be welfare improving and license contracts and related compatibility arrangements should be under the scrutiny of antitrust authorities. Of course, if policy interventions do not aim at maximizing total welfare but at maximizing cumulated consumers' surplus, quite different policy implications result. This is due to the fact that in most cases, the interests of suppliers (or of the dominant supplier) and consumers (as a whole) concerning (in)compatibility are conflicting. In the case of symmetry, this is obvious: there, suppliers opt for compatibility because $p_j^c > p_j^{in,d}$ holds or whenever $p_j^c > p_j^{in,m}$ holds, and they opt for incompatibility whenever $p_j^c < p_j^{in,m}$ holds. In the case of asymmetry, however, things can be different: due to the fact that with $k > 0$ the quantity effect of a monopolization is not offset by the uncertainty concerning who will be the monopolist, a monopolization can be profitable for the dominant supplier despite a limit price which is lower than his price under compatibility. Hence, there exits a parameter regime where not only the dominant supplier but also consumers (as a whole) are better off in a V1 monopoly (it reads $1.5 - 2k/(3m) + k^2/(18m^2) < n/m < 1.75 - k/(2m) - k^2/(36m^2)$).

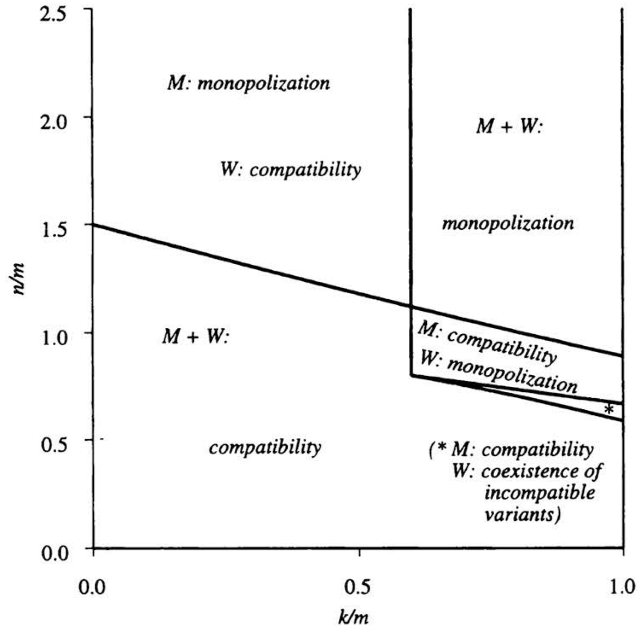

Figure 1: Market equilibria (*M*) and second-best welfare optima (*W*)

In order to derive the *first-best welfare optima* for endogenous (in)compatibility, we have to compare $W^{c,wo}$ according to Equation (8) with $W^{in,d,wo}$

according to Equation (13) for $n/m < 0.5(1 - k/m)$ and with $W^{in,m,wo} = W^{in,m}$ according to Equation (12) otherwise. It is straightforward to prove that compatibility is always first-best optimal. From this we can conclude that the fact that realized welfare under compatibility can be lower than realized welfare under incompatibility is not due to the quality advantage per se but caused indirectly by the induced price distortions.[16] The extent of these price distortions, however, depends on the assumed consumer distribution. It is well-known that for symmetric unimodal distributions, absolute prices are lower the more the distribution concentrates around the center $i = 0.5$. As this may imply a lower price difference (distortion), we cannot preclude that for sharply peaked distributions, compatibility is always second-best welfare optimal.

6. Conclusions

This paper presents an asymmetric Hotelling model with network effects in order to discuss the compatibility decision of a dominant hardware supplier whose hardware variant has a quality advantage. It is shown that he monopolizes the market via maintaining incompatibility whenever the general significance of the network effects is high and opts for compatibility otherwise. Furthermore, we have seen that the market is the more prone to a de-facto standardization, the higher the quality advantage is, and that due to a limit price which can be lower than the price under compatibility, consumers (as a whole) can be better off in an incompatible monopoly.

Our welfare analysis shows that as long as the quality advantage is low, compatibility is both the first-best and the second-best welfare optimum, so that policy recommendations are clear-cut: permit voluntary licensing agreements, and enforce compatibility whenever a supplier would choose to monopolize the market. However, if the quality advantage is high and the general significance of the network effects is not too low, in our model a monopolization via maintained incompatibility proves to be second-best welfare optimal. This welfare superiority of a monopolization holds both in cases where a monopolization actually occurs and in cases where the suppliers prefer compatibility. It is due to a price distortion which leads to a too low market share of the variant with the quality advantage under compatibility. Moreover, due to the same reason, there are some cases where the coexistence of incompatible variants is second-best welfare optimal.

[16] In particular, a negative sign of the difference $W^c - W^{in,m}$ (although $W^{c,wo} - W^{in,m}$ is always positive) is explained by the fact that W^c is by $k^2/9m$ lower than $W^{c,wo}$ due to the price distortions.

Hence, the central conclusion from our welfare analysis is that, in contrast to policy recommendations deduced from symmetric models or from the first-best welfare optima of the asymmetric model, per-se rules seem to be unsuitable for the problem at hand. In particular, a compulsory licensing of the intellectual property rights attached to interface specifications *whenever* the hardware market is monopolized can be wrong. Moreover, permitting compatibility agreements *whenever* suppliers apply for such a permission can be a policy failure as well. Therefore, whether compulsory licensing has to be enforced or not, and whether a licensing of intellectual property rights concerning interface specifications has to be prohibited or not, should only be decided after a careful analysis of the market's structure.

Appendix A: Endogenous Quality Advantage

In this appendix, we endogenize the 'qualities' a_1 and a_2 by assuming that they are produced with increasing marginal costs. The cost functions are $Q_j = 0.5 q_j a_j^2$ $(j = 1, 2)$ with $q_1 < q_2$; i.e. D1 has a systematic cost advantage which is, for example, due to a superior know-how (so that $a_1 > a_2$ is guaranteed). In the first stage of the game, the duopolists simultaneously choose their qualities, in the second stage, they decide on (in)compatibility, and in the third stage, they compete in prices. The costs of producing quality are assumed to be completely sunk, and qualities $a_j > 0$ are fixed irreversibly. We analyze only those cases in which the difference between q_2 and q_1 is restricted to values which lead to differences in profit-maximizing qualities k lower than m, so that the product differentiation remains horizontal (as in the main text). Then, it becomes clear from the results of our two-stage game (see Proposition 1 and Figure 1) that irrespective of the value of k (and, thus, of the values of q_1 and q_2) $n/m > 1.5$ always leads to a monopolization and $n/m < 8/9$ always leads to a coexistence of compatible variants. Moreover, it is straightforward to prove that for $8/9 < n/m < 1.5$, there exists no quality level $\bar{a}_1$ which could prevent the simultaneous entry of D2: solving $G_2^c = 0.5m - (\bar{a}_1 - a_2)/3 + (\bar{a}_1 - a_2)^2/(18m) - 0.5 q_2 a_2^2 = 0$ results in $\bar{a}_1 = 3m + a_2^c(1 + 3\sqrt{q_2 m})$, which implies $\bar{k} > m$. Obviously, given that D1 does not turn the product differentiation into a vertical one (what we have ruled out per assumption), he cannot prevent the simultaneous entry of D2. Hence, there are two cases:

- In the case of $n/m > 1.5$, D2 does not invest in quality ($a_2 = 0$), because D1 definitely monopolizes the market via maintaining incompatibility in the second stage. D1 maximizes $G_1^{in,m} = n - m + a_1 - 0.5 q_1 a_1^2$ (see Equation [11]), which results in $a_1^{in,m} = k^{in,m} = 1/q_1$.

- In the case of $n/m < 1.5$, both suppliers definitely opt for compatibility in the second stage, i.e. a compatible duopoly is guaranteed. Here, the marginal profits from producing quality are $\partial G_j/\partial a_j = 1/3 + (a_j - a_\ell)/(9m) - q_j a_j$ (with $j, \ell = 1, 2$ and $j \neq \ell$; see Equation [6]), and the second-order conditions are $q_j m > 1/9$. This leads, via the best-response functions $a_j = (3m - a_\ell)/(9q_j m - 1)$, to the Nash equilibria

$$a_j^c = \frac{\frac{2}{3}\left(\frac{3}{2}q_\ell m - \frac{1}{3}\right)}{q_j\left(\frac{3}{2}q_\ell m - \frac{1}{3}\right) + q_\ell\left(\frac{3}{2}q_j m - \frac{1}{3}\right)} .$$

Hence, $g_j m > 2/9$ must hold if the existence of a Nash equilibrium with positive qualities should be guaranteed. The quality advantage of V1 results as

$$k^c = \frac{m(q_2 - q_1)}{q_1\left(\frac{3}{2}q_2 m - \frac{1}{3}\right) + q_2\left(\frac{3}{2}q_1 m - \frac{1}{3}\right)} .$$

Of course, $\partial a_j^c/\partial q_j < 0$ and $\partial a_j^c/\partial q_\ell > 0$ hold, so that a higher difference $q_2 - q_1$ means a higher quality advantage k^c.

As for total welfare, the comparison of $a_1^{in,m}$ with a_1^c shows that $a_1^{in,m} > a_1^c$ and, thus, $k^{in,m} > k^c$ always hold. Hence, compared with our two-stage model with exogenous (and equal) k, a monopolization has an additional quality-level advantage. Furthermore, it has the advantage that no second quality has to be produced ($Q_2 = 0$). Both effects, however, might be overcompensated by the higher costs of producing the high quality $a_1^{in,m}$.

Appendix B: Decreasing Network Effects

In this appendix, we take into account that network effects are sometimes significantly decreasing. Then, in the case of incompatibility, that part of the willingness to pay which is due to the network effects can be expressed as nx_j^z with $0 < z < 1$. In the case of compatibility, both market equilibria and welfare optima are, obviously, independent of whether network effects are constant or decreasing. In the case of incompatibility, the price-demand function for Vj is $p_j = \pm k - 2mx_j + n[x_j^z - (1 - x_j)^z] + p_\ell$ with $\partial p_j/\partial x_j = -2m + zn[x_j^{z-1} + (1 - x_j)^{z-1}]$ (and with $j, \ell = 1, 2$ and $j \neq \ell$). For $z < 1$, $\lim_{x_j \to 0} \partial p_j/\partial x_j = \lim_{x_j \to 1} \partial p_j/\partial x_j = +\infty$ holds, i.e. for (very) small as well as for (very) high Vj market shares, the demand function is upward sloping and, hence, unstable. Furthermore, we obtain $\partial p_j/\partial x_j > 0$ for

$zn[x_j^{z-1} + (1 - x_j)^{z-1}] > 2m$, where the term on the left-hand side is a parabola with a minimum value of $4zn0.5^z$ (for $x_j = 0.5$). Hence, for $2zn0.5^z > m$, i.e. if $n/m > 2^z/(2z)$ holds, the demand function is upward sloping for all $0 \leq x_j \leq 1$. In this case, all results concerning market equilibria are qualitatively equivalent to those for $z = 1$ with $n/m > 1$. If $n/m < 2^z/(2z)$ holds, the demand function has a central downward-sloping branch and there are two cases: for $n < m$, points on this branch are unique equilibria, whereas for $n > m$, these equilibria coexist with two stable boundary equilibria (confer Subsection 2.2). In the first case, the results do not differ qualitatively from those derived for $z = 1$. The second case is a qualitatively new one; here, two stable de-facto standardization equilibria coexist with a stable duopolistic equilibrium. Whether there are parameter constellations for which the latter is relevant can only be decided by a numerical evaluation of the profit functions. Note, however, that the parameter space of this new case, $1 < n/m < 2^z/(2z)$, is small: for $z = 0.9$, we obtain $1 < n/m < 1.04$, and for $z = 0.5$ (which would be a very drastic assumption), we obtain $1 < n/m < 1.4$. Our central welfare-theoretical result, the possible welfare superiority of a monopolization, is not affected by the value of z, because neither in the case of compatibility nor in the case of a monopolization total welfare depends on z.

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Zusammenfassung

Diese Arbeit präsentiert ein asymmetrisches Hotelling-Modell mit Netzeffekten mit dem Ziel, die Kompatibilitätsentscheidung eines dominanten Hardwareanbieters zu untersuchen. Wir nehmen an, daß es zwei horizontal differenzierte Varianten der Hardwarekomponente eines Hardware-Software-Systems gibt, von denen eine einen Qualitätsvorteil hat. Unter anderem zeigen wir, unter welchen Umständen der dominante Anbieter den Markt mittels der Aufrechterhaltung von Inkompatibilität monopolisiert. Vor dem Hintergrund eines politikrelevanten wohlfahrtstheoretischen Maßstabs stellt sich heraus, daß eine solche Monopolisierung sowohl in Fällen, in denen sie tatsächlich eintritt, als auch in Fällen, in denen die Anbieter Kompatibilität bevorzugen, einer Koexistenz kompatibler Varianten hinsichtlich der Wohlfahrt überlegen sein kann.

Abstract

This paper presents an asymmetric Hotelling model with network effects in order to analyze the compatibility decision of a dominant hardware supplier. There are two horizontally differentiated variants of the hardware component of a hardware-software system, and one of the two has a quality advantage. Among other things, we show under what circumstances the dominant supplier monopolizes the market via maintaining incompatibility. Against the background of a reasonable welfare-theoretical second-best benchmark, it turns out that such a monopolization can be welfare superior to a coexistence of compatible variants both in cases where it actually occurs and in cases where the suppliers prefer compatibility.

JEL-Klassifikation: L12, L15, L41

Keywords: Compatibility, Monopolization, Network effects, Standardization